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THE PLANET JUPITER.

As seen with the 26-inch telescope at Washington, 1875, June 24.

AMERICAN SCIENCE SERIES, BRIEFER COURSE.

ASTRONOMY

BY

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PREFACE.

The present treatise is a condensed edition of the *Astronomy* of the American Science Series. The book has not been shortened by leaving out anything that was essential, but by omitting some of the details of practical astronomy, thus giving to the descriptive portions a greater relative extension.

The most marked feature of this condensation is, perhaps, the omission of most of the mathematical formulæ of the larger treatise. The present work requires for its understanding only a fair acquaintance with the principles of algebra and geometry and a slight knowledge of elementary physics. The space which has been gained by these omissions has been utilized in giving a fuller discussion of the more elementary parts of the subject, and in treating the fundamental principles from various points of view.

A familiar and secure knowledge of these is essential to the students' real progress. The full index makes the work of value as a reference-book to a student who has studied it and put it aside.

As in the larger work, the matter is given in two sizes of type. It will be found that the larger type contains a course practically complete in itself, and that the matter of the smaller type is chiefly explanatory of the former. It is highly desirable, however, that the book should be *read* as a whole, while the actual class-work may be confined to the subjects treated in the larger type, if the class is pressed for time. A celestial globe, and a set of star-maps (Proctor's "New Star-Atlas" is as good as any), will be found to be of use in connection with the study; and if the class has access to a small telescope, even, much can be learned in this way. A mere opera-glass will suffice to give a correct notion of the general features of the moon's surface, and a very small telescope, if properly used, will do the same for the larger planets.

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ASTRONOMY.

INTRODUCTION.

Astronomy Defined.—Astronomy (αστήρ—a star, and νόμος—a law) is the science which has to do with the heavenly bodies, their appearances, their nature, and the laws governing their real and their apparent motions.

In approaching the study of this the oldest of the sciences depending upon observation, it must be borne in mind that its progress is most intimately connected with that of the race, it having always been the basis of geography and navigation, and the soul of chronology. Some of the chief advances and discoveries in abstract mathematics have been made in its service, and the methods both of observation and analysis once peculiar to its practice now furnish the firm bases upon which rest that great group of exact sciences which we call Physics.

It is more important to the student that he should become penetrated with the spirit of the methods of astronomy than that he should recollect its minutiæ; and it is most important that the knowledge which he may gain from this or other books should be referred by him to its true sources. For example, it will often be necessary to speak of certain planes or circles, the ecliptic, the equator, the meridian, etc., and of the relation of the apparent positions of stars and planets to them; but his labor will be useless if it has not succeeded in giving him a precise notion of these circles and planes as they exist in the sky, and not merely in the figures of his text-book. Above all, the study of this science, in which not a single step could have been taken without careful and painstaking observation of the heavens, should lead its student himself to attentively regard the phenomena daily and hourly presented to him by the heavens.

Does the sun set daily in the same point of the horizon? Does a change of his own station affect this and other aspects of the sky? At what time does the full moon rise? Which way are the horns of the young moon pointed? These and a thousand other questions are already answered by the observant eyes of the ancients, who discovered not only the existence, but the motions, of the various planets, and gave special names to no less than fourscore stars. The modern pupil is more richly equipped for observation than the ancient philosopher. If one could have put a mere opera-glass in the hands of HIPPARCHUS the world need not have waited two thousand years to know the nature of that early mystery, the Milky Way, nor would it have required a GALILEO to discover the phases of *Venus* and the spots on the sun.

Astronomy furnishes the principles and the methods by means of which thousands of ships are navigated with safety and certainty from port to port; by which the dimensions of the earth itself are fixed with high precision; by which the distances of the sun, the planets, and the brighter stars are measured and determined. The details of these methods cannot be given in an elementary work; but the general principles and even the spirit of the special methods can be entirely mastered by the faithful student. All the attention which he can bring will be richly rewarded by the insight he will gain into the noblest of the physical sciences.

How to Study Astronomy.—There are a few principles of Mathematics, of Geography, of Physics, which must be clearly understood by the student commencing astronomy, so that he may go on with advantage. They are all quite simple, but they must be entirely fixed in the mind, in order that the attention may be directed to the *astronomical* principle and not diverted by an attempt to recollect a fact from another science. Any patience and concentration which the student may bestow upon them at the outset should be rewarded by the facility with which they will enable him to grasp the more interesting portions of the subject. The few definitions which are given in italics should be memorized in the words of the text. In all other cases it is preferable that the student should give his own explanations in his own words.

First we will go briefly over some of the essential mathematical principles alluded to.

Angles: their Measurement.—*An angle is the amount of divergence of two right lines.* For example, the angle between the two right lines S^1E and S^2E is the amount of divergence of these lines. The angle S^3ES^4 is the amount of divergence of the two lines S^3E and S^4E. The eye sees at once that the angle S^3ES^4 in the figure is greater than the angle S^1ES^2, and that the angle S^2ES^3 is greater than either of them.

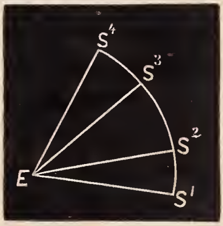

Fig. 1.

In order to compare them and to obtain their numerical ratio, we must have a unit-angle.

The unit angle is obtained in this way: The circumference of any circle is divided into 360 equal parts. The points of division are joined with the centre. The angles between any two adjacent radii are called *degrees*. In the figure, S^1ES^2 is about 12°, S^3ES^4 is about 22°, S^2ES^3 is about 30°, and S^1ES^4 is about 64°. The vertex of the *angle* is at the centre E: the *measure of the angle* is on the circumference $S^1S^2S^3S^4$, or on any other circumference drawn from E as a centre.

In this way we have come to speak of the length of one three-hundred-and-sixtieth part of any circumference as a degree, because radii drawn from the ends of this part make an angle of 1°.

For convenience in expressing the ratios of different angles we have subdivided the degree into minutes and seconds. The degree is too large a unit for some of the purposes of astronomy, just as the metre is too large a unit for use in the machine-shop, where fine work is concerned.

$$\begin{aligned} \text{One circumference} &= 360^\circ = 21600' = 1296000'' \\ 1^\circ &= 60' = 360'' \\ 1' &= 60'' \end{aligned}$$

When we wish to express smaller angles than seconds, we use decimals of a second. Thus one-quarter of a second is 0″.25; one quarter of a minute is 15″.

The Radius of the Circle in Angular Measure.—If R is the radius of a circle, we know from geometry that 1 circumference $= 2\,\pi\,R$, where $\pi = 3.1416$. That is,

$$2\,\pi\,R = 360^\circ = 21600' = 1296000''$$

$$\text{or} \qquad R = 57^\circ.3 = 3437'.7 = 206264''.8.$$

By this we mean that if a flexible cord equal in length to the radius of any circle were laid round the circumference of that circle, and if two radii were then drawn to the ends of this cord, the angle of these radii would be $57°.3$, $3437'.7$, or $206264''.8$.

It is important that this should be perfectly clear to the student.

For instance, how far off must you place a foot-rule in order that it may subtend an angle of 1° at your eye? Why, 57.3 feet away. How far must it be in order to subtend an angle of a minute? 3437.7 feet. How far for a second? 206264.8 feet, or over 39 miles.

Again, if an object subtends an angle of 1° at the eye, we know that its diameter must be $\frac{1}{57.3}$ as great as its distance from us. If it subtends an angle of $1''$, its distance from us is over 200,000 times as great as its diameter.

The instruments employed in astronomy may be used to measure the angles subtended at the eye by the diameters of the heavenly bodies. In other ways we determine their distance from us in miles. A combination of these data will give us the actual dimensions of these bodies in miles. For example, the sun is about 93,000,000 miles from the earth. The angle subtended by the sun's diameter at this distance is $1922''$. What is the diameter of the sun in miles?

An idea of angular dimensions in the sky may be had by remembering that the angular diameters of the moon and of the sun are about $30'$. It is 180° from the west point to the east point counting through the point immediately overhead. How many moons placed edge to edge would it take to reach from horizon to horizon? The student may guess at the answer first and then compute it.

Perhaps a more convenient measure is the apparent distance apart of the "pointers" in the Great Dipper, which is 5°. (See Fig. 7, page 24.)

Plane Triangles.—The angles of which we have been speaking are angles in a plane. In any plane triangle there are three sides and three angles—six parts. If any three of these parts (except the three angles) are given we can construct the triangle. If the three angles alone are given we can make a triangle which shall be of the right *shape*, and that is all.

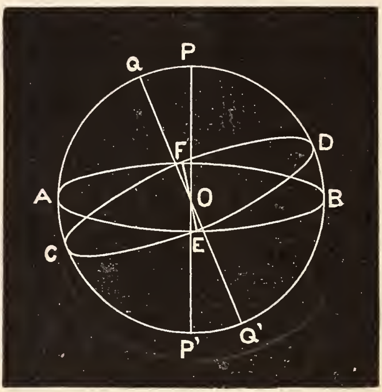

FIG. 2.

Spherical Triangles.—Besides plane angles and triangles, we have to do with those drawn on the surface of a sphere—spherical triangles. This is necessary since the heavenly bodies are spherical in shape, and since they are seen projected against the concave surface of the sky.

The Sphere: its Planes and Circles.—In the figure, *O* is the centre of the sphere and *ABE* is one of its circles. Suppose a plane *AB* passing through the centre and cutting the sphere into two *hemispheres*. It will intersect the surface of the sphere in a circle $AEBF$ which is called a *great circle* of the sphere. *A great circle of the sphere is one cut from the surface by a plane passing through the centre of the sphere.* Suppose a right line POP' perpendicular to this plane. The points P and P' in which it intersects the surface of the sphere are everywhere 90° from the circle $AEBF$. They are the *poles* of that circle. The poles of the great circle $CEDF$ are Q and Q'.

The following relations exist between the angles made in the figure:

I. The angle POQ between the poles is equal to the inclination of the planes to each other.

II. The arc BD which measures the greatest distance between the two circles is equal to the arc PQ which measures the angle POQ.

III. The points E and F, in which the two great circles intersect each other, are the poles of the great circle $PQACP'Q'BD$ which passes through the poles of the first circle.

The Spherical Triangle.—In the last figure there are several spherical triangles, as EDB, FAC, $ECP'Q'B$, etc. In astronomy we need consider only those whose sides are formed by arcs of great circles. The angles of the triangle are angles between two arcs of great circles; or what is the same thing, they are angles between the two planes which cut the two arcs from the surface of the sphere.

In spherical triangles, as in plane, there are six parts, three angles and three sides. Having any three parts the other three can be constructed.

The sides as well as the angles of spherical triangles are expressed in degrees, minutes, and seconds. If the student has a globe before him, let him mark on it the triangle whose angles are

$$A\ 128°\ 44'\ 45''.1,$$
$$B\ \ 33°\ 11'\ 12''.0,$$
$$C\ \ 18°\ 15'\ 31''.1,$$

and whose sides are (a is opposite to A, b to B, c to C.)

$$a = 10°, \quad b = 7°, \quad c = 4°.$$

Power of the Eye to see Small Objects.—When a round object subtends an angle of 1′ (that is, when it is about 3437 of its own diameters away), it is just at the limit of visibility, under ordinary circumstances. At the Transit of *Venus* in 1874, the planet *Venus* was between the earth and the sun, and appeared as a small black spot, just visible to the naked eye, projected on the sun's face. It was 67″ in diameter.

If two such discs are nearer together than 1′ 12″, few eyes can distinguish them as two distinct objects. If a body is long and narrow, its angular dimensions (width) may be reduced to 10″ or 15″ before it is indistinguishable to the eye. For example, a spider line hanging in the air.

If an object is very much brighter than the background on which it is seen, there is no limit below which it is necessarily invisible. Its visibility depends, in such a case, only on its brightness. It is probable that the diameters of the brightest stars subtend an angle no greater than 0″.01.

Latitude and Longitude of a Place on the Earth's Surface. Geography teaches us that the earth is a sphere. Positions on its surface are defined by giving their latitude and longitude. According to geography, *the latitude of a place on the earth's surface is its angular distance north or south of the equator.*

The longitude of a place on the earth's surface is its angular distance east or west of a given first meridian.

If P in the figure is the north pole of the earth, the latitude of the point B is 60° north; of Z it is 30° north; of I it is $27°\frac{1}{2}$ south. All places having the same latitude are situated on the same *parallel of latitude.* In the figure the parallels of latitude are represented by straight lines.

All places having the same longitude are situated on the

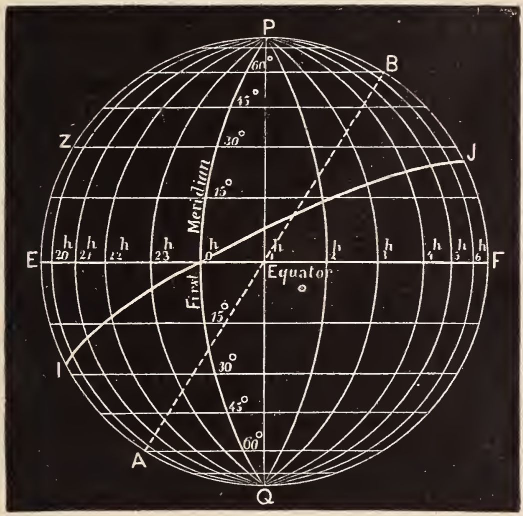

Fig. 3.

same *meridian.* We shall give the astronomical definitions of these terms further on.

It is found convenient in astronomy to modify the geographical definition of longitude. In geography we say that Washington is 77° west of Greenwich, and that Sydney (Australia) is 151° east of Greenwich. For astronomical purposes it is found more convenient to count the longitude of a place from the first meridian (usually Greenwich) always towards the west. Thus Sydney is 209° west of Greenwich. $360° - 151° = 209°$.

The earth turns on its axis once in 24 hours. In this time a point on its surface moves through 360 degrees, or such a point moves *at the rate* of 15° per hour. 360 divided by 24 is 15.

Hence we may express the longitude of a place either in time or arc. Washington is $5^h\ 8^m$ west of Greenwich, and Sydney is $13^h\ 56^m$ west of Greenwich.

It is also indifferent which first meridian we choose. We may refer all longitudes to Paris, to Berlin, or to Washington. Sydney is $8^h\ 48^m$ west of Washington, and Greenwich is $18^h\ 52^m$ west of Washington.

In the figure, suppose F to be west of the first meridian. All the places on the straight line PQ have a longitude of 15° or 1 hour; all on the curve $P5^hQ$ have a longitude of 75° or 5 hours; and so on.

The difference of longitude of any two places on the earth is the angular distance between the terrestrial meridians passing through the two places.

Thus Washington is 77° west of Greenwich, and Sydney is 209° west of Greenwich. Hence Sydney is 132° west of Washington, and this is the difference of longitude of the two places.

SYMBOLS AND ABBREVIATIONS

SIGNS OF THE PLANETS, ETC.

☉	The Sun.	♂	Mars.
◍	The Moon.	♃	Jupiter.
☿	Mercury.	♄	Saturn.
♀	Venus.	♅	Uranus.
⊕ or ♁	The Earth.	♆	Neptune.

The asteroids are distinguished by a circle enclosing a number, which number indicates the order of discovery, or by their names, or by both, as (100) ; *Hecate.*

SIGNS OF THE ZODIAC.

Spring signs.	1. ♈ Aries.		Autumn signs.	7. ♎ Libra.	
	2. ♉ Taurus.			8. ♏ Scorpius.	
	3. ♊ Gemini.			9. ♐ Sagittarius.	
Summer signs.	4. ♋ Cancer.		Winter signs.	10. ♑ Capricornus.	
	5. ♌ Leo.			11. ♒ Aquarius.	
	6. ♍ Virgo.			12. ♓ Pisces.	

The Greek alphabet is here inserted to aid those who are not already familiar with it in reading the parts of the text in which its letters occur:

Letters.	Names.	Letters.	Names.
Α α	Alpha	*Ν ν*	Nu
Β β	Beta	*Ξ ξ*	Xi
Γ γ	Gamma	*Ο ο*	Omicron
Δ δ	Delta	*Π π ϖ*	Pi
Ε ε	Epsilon	*Ρ ρ*	Rho
Ζ ζ	Zeta	*Σ σ ς*	Sigma
Η η	Eta	*Τ τ*	Tau
Θ ϑ θ	Theta	*Υ υ*	Upsilon
Ι ι	Iota	*Φ φ*	Phi
Κ κ	Kappa	*Χ χ*	Chi
Λ λ	Lambda	*Ψ ψ*	Psi
Μ μ	Mu	*Ω ω*	Omega

THE METRIC SYSTEM.

THE metric system of weights and measures being employed in this volume, the following relations between the units of this system most used and those of our ordinary one will be found convenient for reference :

MEASURES OF LENGTH.

1 kilometre	= 1000 metres	= 0·62137 mile.
1 metre	= the unit	= 39·370 inches.
1 millimetre	= $\frac{1}{1000}$ of a metre	= 0·03937 inch.

MEASURES OF WEIGHT.

1 kilogramme	= 1000 grammes	= 2·2046 pounds.
1 gramme	= the unit	= 15·432 grains.

The following rough approximations may be memorized :

The kilometre is a little more than $\frac{6}{10}$ of a mile, but less than $\frac{5}{8}$ of a mile.

The mile is $1\frac{6}{10}$ kilometres.

The kilogramme is $2\frac{1}{5}$ pounds.

The pound is less than half a kilogramme.

One metre is 3·3 feet.

One metre is 39·4 inches.

CHAPTER I.

THE RELATION OF THE EARTH TO THE HEAVENS.

The Earth's Shape and Dimensions.

The earth is a globe whose dimensions are gigantic when compared with our ordinary and daily ideas of size.

Its shape is nearly a sphere, as has been abundantly proved by the accurate geodetic surveys which have been made by various nations.

Of its size we may get a rough idea by remembering that at the present time it requires about three months to travel completely around it.

To these familiar facts we may add two propositions which are fundamental in astronomy.

I. *The earth is completely isolated in space.* The most obvious proof of this is that men have visited nearly every part of the earth's surface without finding anything to the contrary.

II. *The earth is one of a vast number of globular bodies, familiarly known as stars and planets, moving according to certain laws and separated by distances so immense that the magnitudes of the bodies themselves are insignificant in comparison to these distances.* The first conception which the student of astronomy has to form is that of living on the surface of a spherical earth which, although it seems of immense size to him, is really but a point in comparison with the distances which separate him from the stars which he nightly sees in the sky.

The Celestial Sphere.

When we look at a star at night we seem to see it set against the dark surface of a hollow sphere in whose centre we are.

All the stars seem to be at the same distance from us. When we stop to consider, we see that it is quite possible that some one of the many stars visible may be nearer than some other, but as we have no immediate method of knowing which of two stars is the nearer, we are driven to speak of their *apparent* positions just as if they were bright points studded over the inner surface of a large hollow globe, and all at the same distance from us. The radius of this globe is unknown. We do not, however, think of any of the stars as beyond the surface and shining through it. We therefore suppose the radius of the sphere to be equal to or greater than the distance of the remotest star.

Students generally fail at the outset to realize two very important facts in relation to the celestial sphere. First, that for all the purposes of our present knowledge the relative positions of the stars on its surface do not vary. Maps were made of these positions centuries ago which are as correct now as old maps of portions of the earth. The motions of the earth present different portions of the celestial sphere to our observation at different times, and one who has not thought at all of the subject might by that fact be led to suppose that changes are taking place in the relative positions of the stars themselves. Most people, however, know that they can find the same groups of stars

—"constellations," as they are called—in different directions from the observer's location on the earth, night after night; the difference in the directions being due to the earth's motions. Reflection on the foregoing will help the student to realize the second important fact alluded to in the beginning of this paragraph—that for most practical purposes of astronomy the earth may be regarded as a point

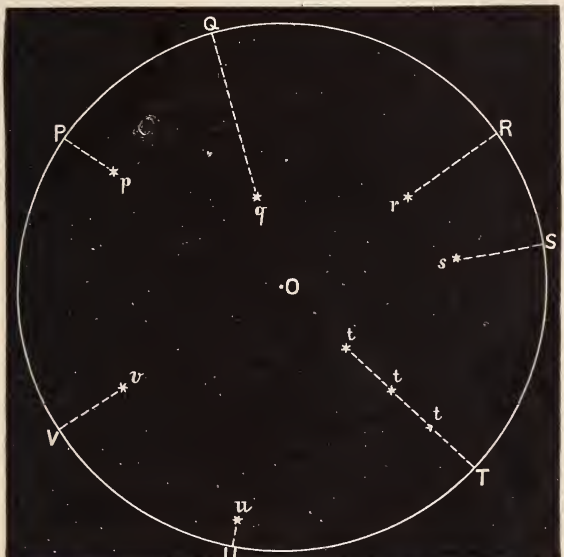

FIG. 4.

in the centre of a hollow globe whose inside surface is spotted over with the stars, that hollow globe corresponding to the celestial sphere. In fact ingenious instruments to illustrate some of the truths of astronomy have been made of large globes of glass or other transparent substances, with the stars painted in their unvarying positions on the inside surface, and the earth suspended at the centre by supports rendered as nearly invisible as possible.

Suppose an observer at the point O in the figure. If he sees a star at the point Q it is clear that the real star may be anywhere in space on the line OQ, as at q for example, and still appear to be at Q.

Again, stars which appear to be at the points P, V, U, T, S, R, may in fact be anywhere on the lines OP, OV, OU, OT, OS, OR. Thus, if there were three stars along the line OT, they would all be *projected* at the point T of the celestial sphere, and would appear as one star.

The celestial sphere is the surface upon which we imagine the stars to be projected.

The *projection* of a body upon the celestial sphere is the point in which this body appears to be, when seen from the earth. This point is also called the *apparent position* of the body. Thus to an observer at O, T is the apparent position of any of the stars whose true positions are t, t, t. Hence it follows that *positions on the celestial sphere represent the directions of the heavenly bodies from the observer, but have no necessary relation to their distances.*

If the observer changes his position, the apparent positions of the stars will also change.

We need some method of describing the apparent positions of stars on the celestial sphere; to do this we imagine a number of great circles to be drawn on its surface, and to these circles we refer the apparent positions of the stars.

A consideration of Fig. 2 will show the correctness of the following propositions, which it is necessary should be clearly understood:

I. Every straight line through the observer, when produced indefinitely, intersects the celestial sphere in two opposite points.

II. Every plane through the observer intersects the sphere in a great circle.

III. For every such plane there is one line through the observer's position which intersects the plane at right angles. This line meets the sphere at the poles of the great circle which is cut from the sphere by the plane.

Example: $P\,P'$, Fig. 2, is a line through O perpendicular to the plane $A\,B$. P, P' are the poles of $A\,B$.

IV. Every line through the centre has one plane perpendicular to it, which plane cuts the sphere in a great circle whose poles are the intersection of the line with the sphere.

Example: The line $Q\,Q'$ has one plane $C\,D$ through O perpendicular to it, and only this one.

The Horizon.

A level plane touching the spherical earth at the point where an observer stands is called the horizon of that observer.

This plane cuts the celestial sphere in a great circle, which is called the *celestial horizon.* The celestial horizon is therefore the boundary between the visible and the invisible hemispheres to that observer.

The Vertical Line.—The vertical line of any observer is the direction of a plumb-line where he stands. This line is perpendicular to his horizon. It intersects the celestial sphere in two points, called the *zenith* and the *nadir* of that observer.

The zenith of an observer is the point where his vertical line cuts the celestial sphere above his head, *The nadir of an observer is the point where his vertical line cuts the celestial sphere below his feet.*

The zenith and nadir are the poles of the horizon.

Vertical Planes and Circles.—A vertical plane with respect to any observer is a plane which contains his vertical line. It must pass through his zenith and nadir and must be perpendicular to his horizon.

A vertical plane cuts the celestial sphere in a *vertical circle.*

As soon as we imagine an observer to be at any point on the earth's surface his horizon is at once fixed; his zenith and nadir are also fixed. From his zenith radiate a number of vertical circles which cut the celestial horizon perpendicularly, and unite again at his nadir. This is a system of lines and circles which every person carries about with him, as it were, and which may serve him for lines to which to refer the apparent position of every star which he sees.

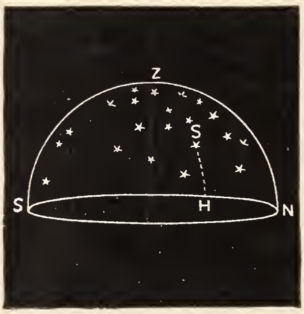

Fig. 5.

Some one of these vertical circles will pass through any and every star visible to this observer.

The altitude of a heavenly body is its elevation above the plane of the horizon measured on a vertical circle through the star.

The zenith distance of a star is its angular distance from the zenith measured on a vertical circle.

In the figure, ZS is the zenith distance (ζ) of S, and HS (a) is its altitude. ZSH is an arc of a great circle;

the vertical circle through the star. $ZSH = a + z = 90°$, and $z = 90° - a$ or $a = 90° - z$.

The altitude of a star in the zenith is 90°; half way from the zenith to the horizon it is 45°; in the horizon it is 0°.

The azimuth of a star is the angular distance from the point where the vertical circle through it meets the horizon, to the north (or south) point of the horizon.

In the figure, NH is the azimuth of S. The azimuth of a star in the east or west is 90°.

The prime vertical of an observer is that one of his vertical circles which passes through his east and west points.

Co-ordinates of a Star.—The apparent position of a heavenly body is completely fixed by means of its altitude and azimuth. If we know the altitude and azimuth of a star we can point to it.

If, for example, its azimuth is 20° from north towards the west and if its altitude is 30°, we can point to the star by measuring an angle of 20° from the north point towards the west, which will fix the foot of a vertical circle through the star. The star itself will be on the vertical circle, 30° above the horizon.

This point, and this alone, will correspond to the position of the star as determined by its altitude and azimuth.

Numbers (or quantities) which exactly define the position of a body are called its co-ordinates.

Hence altitude and azimuth form a pair of co-ordinates which fix the apparent position of a star on the celestial sphere.

It must be remembered that these two co-ordinates give only the position of the *projection* of the star on the celestial sphere, and give no knowledge of its distance from the observer. The body may be any where on the line defined by the position on the celestial sphere and the place of the observer.

If we also know the distance of the star from the observer, we know every possible fact as to its place in space.

Thus, three *co-ordinates suffice to fix the absolute position of a body in space;* two *co-ordinates suffice to determine its apparent position on the celestial sphere.*

These propositions suppose the place of the observer to be fixed, since the altitude and azimuth refer to an observer in some one definite position. If the observer should change his place, the star remaining fixed, the apparent position of the star on the celestial sphere would change to him, owing to his own motion. The numbers which express this apparent position—the altitude and azimuth of the star—would also change.

But wherever the observer is, if he has these two coordinates for a star, the apparent place of the star is fixed *for him.*

The Horizon.—Since the earth is spherical in form, and the horizon is a plane touching this sphere, every different place must have a different horizon. Wherever an observer goes on the earth's surface he carries an horizon, a zenith, and a nadir with him, and a set of vertical circles to which he can refer the positions of all the stars he sees. If he stays at a fixed point on the earth's surface his horizon is always fixed with relation to his vertical line. But the earth on which he stands is turning round its axis, and his horizon being tangent to the earth is moving also, and the vertical line moves with it. The stars stay in the same absolute places from year to year. The earth on which the observer stands is turning round from west to east. His horizon is thus brought successively to the east of the various stars, which thus appear to rise higher and higher above it.

The earth continues its motion, and the plane of his horizon finally approaches the same stars from the west and they set below it, only to repeat this phenomenon with every rotation of the earth.

The horizon appears to each observer to be the stable thing, and the motion is referred to the stars. As a matter of fact it is the stars that stand still and the horizon which moves below them, causing them to appear to rise, and then above them, causing them to appear to set.

The Diurnal Motion.

The diurnal motion is that apparent motion of the sun, moon, and stars from east to west in consequence of which they rise and set.

We call it the diurnal motion because it repeats itself from day to day. The diurnal motion is caused by a daily rotation of the earth on an axis passing through its centre called the *axis of the earth.*

This axis intersects the earth's surface in two opposite points called the *north and south poles of the earth.* If the earth's axis be prolonged in both directions, it meets the celestial sphere in two points which are called the *poles of the celestial sphere* or the *celestial poles.* The north celestial pole corresponds to the north end of the earth's axis; the south celestial pole to the south end.

The plane of the equator is that plane which passes through the earth's centre perpendicular to its axis. This plane intersects the earth's surface in a great circle of the earth's sphere which is called the *earth's equator* (*e q* in Fig. 6).

This plane intersects the celestial sphere in a great circle of this sphere which is called the *celestial equator* or *equinoctial* (EQ in Fig. 6).

The celestial equator is everywhere half way between the two celestial poles and thus 90° from each. The celestial poles are thus the poles of the celestial equator.

Apparent Diurnal Motion of the Celestial Sphere.—The

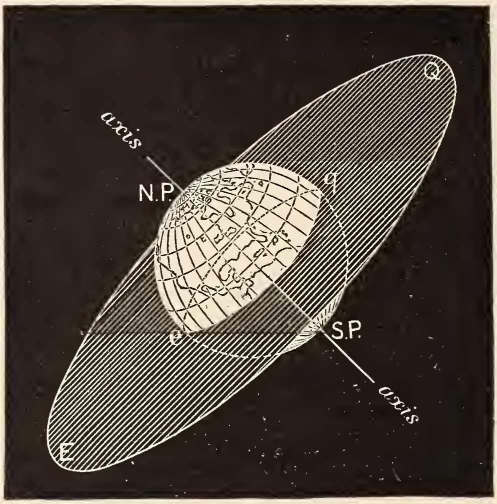

FIG. 6.

observer on the earth is unconscious of its rotation, and the celestial sphere appears to him to revolve from east to west around the earth, while the earth appears to remain at rest. The case is much the same as if he was on a steamer which is turning round, and as if he saw the harbor-shores, the ships, and the houses apparently turning in an opposite direction.

So far as appearances are concerned, it is quite the same thing whether we conceive the earth to be at rest and the heavens to turn about it, or whether we conceive the stars to remain at rest and the earth to move on its axis. We can explain all the phenomena of the diurnal motion in either way. We must, however, remember that it really is the earth which turns on its axis and successively presents to the observer different parts of the celestial sphere. The parts to his east are just coming into view (rising above his horizon). The parts to his west are about to disappear, (setting below his horizon).

Since the diurnal motion is an apparent rotation of the celestial sphere about a fixed axis, it follows that there must be two points of this sphere that remain at rest; namely, the two celestial poles. Moreover, since the celestial poles are opposite points, one pole must be above the horizon and therefore a visible point of this sphere, and the other pole must be below the horizon and therefore invisible.

The celestial pole visible to observers in the northern hemisphere is the north pole. To locate its place in the sky let the student look at the northern sky on any clear evening.

He will see the stars somewhat as they are represented in the figure.

In fact Fig. 7. shows the stars as they will appear to an observer in the month of August in the early hours of the evening. But the configurations of the stars can be recognized at any other time.

The first star to be identified is *Polaris,* or the *Pole Star.* It may be found by means of the *Pointers,* two stars in the constellation *Ursa Major,* familiarly known as the *Great*

Dipper. The straight line through these stars, as shown in the figure, passes near *Polaris*. *Polaris* is $1\frac{1}{4}$ degrees from the true pole. There is no star exactly at the pole itself.

The altitude of the pole-star above the horizon of any place is equal to the latitude of the place, as will be shown

Fig. 7.

hereafter. Hence in most parts of the United States the north pole is from 30° to 45° above the horizon. In England it is 51°, in Norway 60°.

The north-polar distance of a star is its angular distance from the north celestial pole.

The following laws of the diurnal motion will now be clear:

I. *Every star in the heavens appears to describe a circle around the pole as a centre in consequence of the diurnal motion.*

II. *The greater the star's north-polar distance the larger is the circle.*

III. *All the stars describe their diurnal orbits in the same interval of time, which is the time required for the earth to turn once on its axis.*

The circle which a star appears to describe in the sky in consequence of the diurnal motion of the earth is called the *diurnal orbit* of that star.

These laws can be proved by observation. The student can satisfy himself of their correctness in any clear night.

If the star's north-polar distance is less than the altitude of the pole, the circle which the star describes will not meet the horizon at all, and the star will therefore neither rise nor set, but will simply perform an apparent diurnal revolution round the pole. Such stars are shown in the figure. The apparent diurnal motion of the stars is in the direction shown by the arrows in the cut. Below the pole the stars appear to move from left to right, west to east; above the pole they appear to move from east to west.

The circle within which the stars neither rise nor set is called *the circle of perpetual apparition.* The radius of this circle is equal to the altitude of the pole above the horizon, or to the north polar distance of the north point of the horizon.

As a result of this apparent motion each individual constellation changes its configuration with respect to the horizon. That part of the constellation which is highest when the group is above the pole becomes lowest when it is below the pole. This is shown in the figure, which represents a supposed constellation at different times of the night as it revolves round the pole. The *culmination* of a star occurs when it is at its highest point above the horizon. The point of culmination is midway between the points of rising and setting.

If the polar distance of a star exceeds the altitude of the

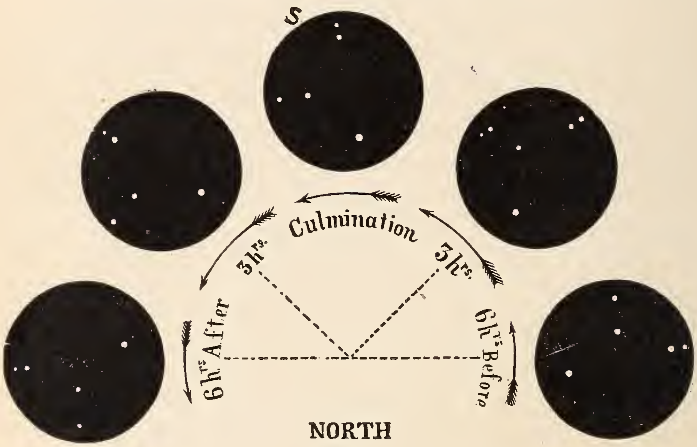

Fig. 8.

pole, the star will dip below the horizon for a part of its diurnal orbit, and the greater the polar distance of the star the longer it will be below the horizon.

A star whose polar distance is 90° lies on the celestial equator, and one half of its diurnal orbit is above and one half below the horizon.

The sun is in the celestial equator about March 21st and September 21st of each year, so that at these times the days and nights are of equal length. This is why the celestial equator was formerly called the equinoctial.

Looking further south at the celestial sphere, we shall see stars which rise a little to the east of the south point of the horizon and set a little to the west of this point, being above the horizon but a short time. The south pole is as far below the horizon of any place as the north pole is above it. Hence stars near the south pole never rise in our latitudes. The circle within which stars never rise is called *the circle of perpetual occultation.*

It is clear that the positions of the circles of perpetual apparition and occultation depend upon the position of the observer upon the earth, and hence that they will change their positions as the observer changes his.

By going to Florida we may see groups of stars which are not visible in the latitude of New York.

The Meridian.—The *plane of the meridian of an observer is that one of his vertical planes which contains the earth's axis.* Being a vertical plane it must contain the zenith and nadir of the observer; as it contains the earth's axis it must contain the north and south celestial poles.

Different observers have different meridian planes, since they have different zeniths.

The *terrestrial meridian* of an observer is the line in which the plane of his meridian intersects the surface of the earth. It is his north and south line.

It follows that if several observers are due north and south of each other, they have the same terrestrial meridian.

The *celestial meridian* of an observer is the great circle cut from the celestial sphere by the plane of that observer's meridian. Persons on the same terrestrial meridian have the same celestial meridian.

Terrestrial meridians are considered as belonging to the places through which they pass. For example, we speak of the meridian of Greenwich or of the meridian of Washington, and by this we mean the (terrestrial or celestial) meridian lines cut out by the meridian plane of the Royal Observatory at Greenwich or the Naval Observatory at Washington.

The Diurnal Motion in Different Latitudes.

As we have seen, the celestial horizon of an observer will change its place on the celestial sphere as the observer travels

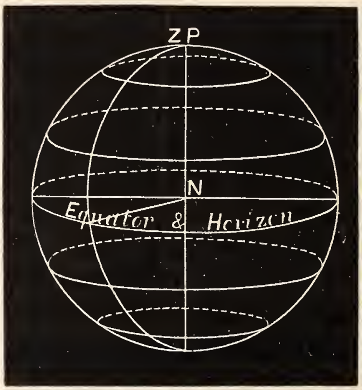

Fig. 9. The Parallel Sphere.

from place to place on the surface of the earth. If he moves directly toward the north his zenith will approach the north pole; but as the zenith is not a visible point, the motion will be naturally attributed to the pole, which will seem to approach the point overhead. The new apparent position of the pole will change the aspect of the observer's sky, as the higher the pole appears above the horizon the greater the circle of perpetual apparition, and therefore the greater the number of stars which never set.

If the observer is at the north pole his zenith and the pole itself will coincide: half of the stars only will be visible, and these will never rise or set, but appear to move around in circles parallel to the horizon. The horizon and the celestial equator will coincide. The meridian will be indeterminate since Z and P coincide; there will be no east and west line, and no direction but south. The sphere in this case is called a *parallel sphere.* (See Fig. 9.)

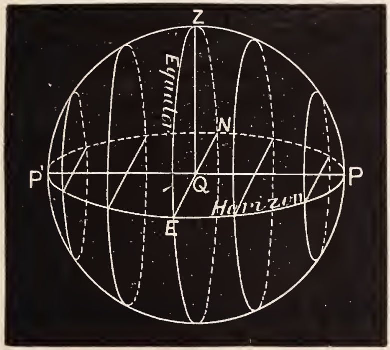

FIG. 10.—THE RIGHT SPHERE.

If instead of travelling to the north the observer should go toward the equator, the north pole would seem to approach his horizon. When he reached the equator both poles would be in the horizon, one north and the other south. All the stars in succession would then be visible, and each would be an equal time above and below the horizon. (See Fig. 10.)

The sphere in this case is called a *right sphere,* because the diurnal motion is at right angles to the horizon. If now the observer travels southward from the equator, the south pole will become elevated above his horizon, and in the southern hemisphere appearances will be reproduced which we have already described for the northern, except that the direction of the motion will, in one respect, be different. The heavenly bodies will still rise in the east and set in the west, but those near the equator will pass north of the zenith instead of south of it, as in our latitudes. The sun, instead of moving from left to right, there moves from right to left. The bounding line between the two directions of motion is the equator, where the sun culminates north of the zenith from March till September, and south of it from September till March.

If the observer travels west or east of his first station, his zenith will still remain at the same angular distance from the north pole as before, and as the phenomena caused by the earth's diurnal motion at any place depend only upon the altitude of the elevated pole at that place, these will not be changed except as to the times of their occurrence. A star which appears to pass through the zenith of his first station will also appear to pass through the zenith of the second (since each star remains at a constant angular distance from the pole), but later in time, since it has to pass through the zenith of every place between the two stations. The horizons of the two stations will intercept different portions of the celestial sphere at any one instant, but the earth's rotation will present the same portions successively, and in the same order, at both.

Correspondence of the Terrestrial and Celestial Spheres.

We have seen that the altitude of the pole above the horizon of any observer changes as the observer changes his place on the earth's surface. The exact relation of the altitude of the pole and the horizon of any observer is expressed in the following Theorem: *The altitude of the celestial pole above the horizon of any place on the earth's surface is equal to the latitude of that place.*

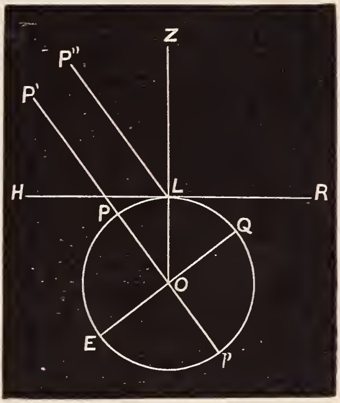

Fig. 11.

Let L be a place on the earth $P E p Q$, $P p$ being the earth's axis and $E Q$ its equator. Z is the zenith of the place, and $H R$ its horizon. $L O Q$ is the latitude of L according to ordinary geographical definitions; *i.e.*, it is the angular distance of L from the equator. Prolong $O P$ indefinitely to P' and draw $L P''$ parallel to it. P' and P'' are points on the celestial sphere infinitely distant from L. In fact they appear as *one* point since the dimensions of the earth are vanishingly small compared with the radius of the celestial sphere, which may be taken as large as we please. We have then to prove that $L O Q = P'' L H$. $P O Q$ and $Z L H$ are right angles, and therefore equal. $Z L P'' = Z O P'$ by construction. Hence $Z L H - Z L P'' = P O Q - Z O P'$, or the latitude of the point L is measured by either of the equal angles $L O Q$ or $P'' L H$.

If we denote the latitude by φ it follows that the *N.P.D.* (north-polar distance) of Z is $90° - \varphi$. As an observer moves to various parts of the earth, his zenith changes position with him. In every position the *N.P.D.* of his zenith is $90° - \varphi$. If he is at the equator his φ is 0° and his zenith is 90° from the north pole, which must therefore be in his horizon. If he is at the north pole, $\varphi = + 90°$ and the *N.P.D.* of his zenith is 0°, or his zenith coincides with the north pole. If he is at the south pole ($\varphi = - 90°$) the *N.P.D.* of his zenith is $90° - (- 90°)$ or 180°. That is, his zenith is 180° from the north pole, or it must coincide with the south pole; and so in other cases.

All this has just been shown (pages 28–30) in another way, but it is of the first importance that it should be not only clear but familiar to the student. When he sees any astronomical diagram in which the north pole and the horizon are laid down he can at once tell for what latitude this diagram is constructed. The elevation of the pole above the horizon measures the latitude of the observer, to whose station this particular diagram applies.

Change of the Position of the Zenith of an Observer by the Diurnal Motion.—In Fig. 12 suppose $n\,e\,s\,q$ to represent the earth and $N\,E\,S\,Q$ the celestial sphere. The earth, as we know, is rotating on the axis $N\,S$. We have now to inquire what are the real circumstances of this motion. The apparent phenomena have been previously described. Remember that the vertical line of an observer is (practically) that of a radius of the earth passing through his station. If the observer is at n his zenith is at N. As the earth revolves the zenith will revolve also. If the observer is in 45° north latitude, he is carried round by the rotation of the earth in a small circle of the earth's surface whose plane is perpendicular to the earth's axis. This is the parallel of 45°, so called, and is indicated in the figure. His zenith is always directly above him, and therefore his zenith must describe each day a circle $M L$ on the celestial sphere corresponding to this parallel on the earth; that is,

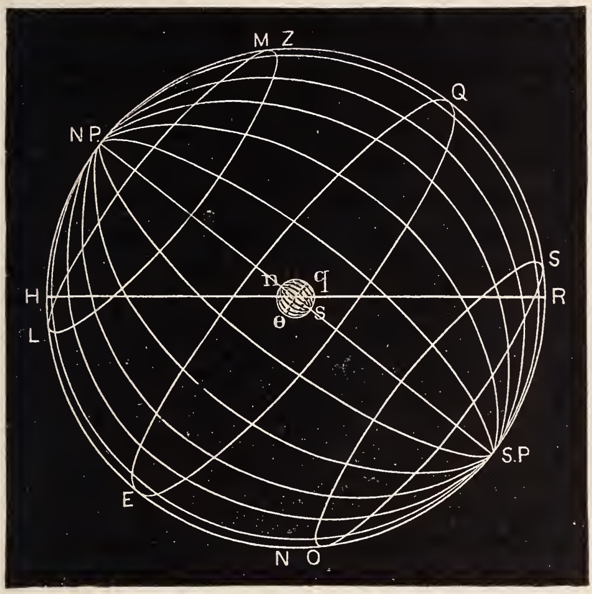

FIG. 12.

a circle half way between the celestial pole and the celestial equator. Now, suppose the observer to be on the equator $e q$. His zenith will then be 90° from either pole. As the earth revolves on its axis his zenith will describe a *great* circle $E Q$ on the celestial sphere. This circle is the celestial equator. An observer at 45° south latitude will have a parallel $S O$ marked out on the celestial sphere by the motion of his zenith due to the earth's rotation, and so on. Thus, for each parallel of latitude on the earth we have a corresponding circle on the celestial sphere, and each of these latter circles has its poles at the celestial poles.

Not only are there circles of the celestial sphere which correspond to parallels of latitude on the earth, but there are also celestial meridians corresponding to the various terrestrial meridians. The plane of the meridian of any place contains the zenith of that place and the two celestial poles. It cuts from the earth's surface the terrestrial meridian and from the celestial sphere that great circle which we have defined as the celestial meridian. To fix the ideas let us suppose an observer at some one point of the earth's surface. A north and south line on the earth at that point is the visible representative of his terrestrial meridian. A plane through the centre of the earth and that line contains his zenith, and cuts from the celestial sphere the celestial meridian. As the earth rotates on its axis his zenith moves around the celestial sphere in a parallel as $Z L$ in the last figure. Suppose that the east point is in front of the picture, the west point being behind it. Then as the earth rotates the zenith Z will move along the line $Z L$ from Z towards L. The celestial meridian always contains the celestial poles and the point Z, wherever it may be. Hence the arcs of great circles joining $N.P.$ and $S.P.$ in the figure are representatives of the celestial meridian of this observer, at different times during the period of the earth's rotation. They have been drawn to represent the places of the meridian at intervals of 1 hour. That is, 12 of them are drawn to represent 12 consecutive positions of the meridian during a semi-revolution of the earth. In this time *Z* moves from *Z* to *L*. In the next semi-revolution *Z* moves from *L* to *Z*, along the other half of the parallel *ZL*. In 24 hours the zenith *Z* of the observer has moved from *Z* to *L* and from *L* back to *Z* again. The celestial meridian has also swept across the heavens from the position *N.P., Z, Q, S, S.P.* through every intermediate position to *N.P., L, E, O, S.P.*, and from this last position back to *N.P., Z, Q, S, S.P.* The terrestrial meridian of the observer has been under it all the time. This real revolution of the celestial meridian is incessantly repeated with every revolution of the earth. The sky is studded with stars all over the sphere. The celestial meridian of any place approaches these various stars from the west, passes them, and leaves them. This is the *real* state of things. *Apparently* the observer is fixed. His terrestrial and celestial meridians seem to him to be fixed, not only with reference to himself, as they are, but to be fixed in space. The stars appear to him to approach his celestial meridian from the east, to pass it, and to move away from it towards the west. When a star crosses the celestial meridian it is said to *culminate.* The passage of the star across the meridian is called the *transit* of that star. This phenomenon takes place successively for each observer on the earth. Suppose two observers, A and B, A being one hour (15°) east of B in longitude. This means that the angular distance of their terrestrial meridians is 15° (see page 10). From what we have just learned it follows that their celestial meridians are also 15° apart. When B's meridian is *N.P., Z, Q, R, S.P.*, A's will be the first one (in the figure) beyond it; when B's meridian has moved to this first position, A's will be in the second, and so on, always 15°

(1 hour) in advance. A group of stars which has just come to A's meridian will not pass B's for 1 hour. When they are on B's meridian they will be 1 hour west of A's, and so on. Notice also that A's zenith is always 15° east of B's.

The same stars will successively rise, culminate, and set to each observer, but the phenomena will be presented to the eastern observer sooner than to the other.

CHAPTER II.

THE RELATION OF THE EARTH TO THE HEAVENS—(*Continued.*)

THE CELESTIAL SPHERE.

Systems of Co-ordinates.—The great circles of the celestial sphere which pass through the two celestial poles are called *hour-circles*. Each hour-circle is the celestial meridian of some place on the earth.

The hour-circle of any particular star is that one which passes through the star at the time. As the earth revolves, different hour-circles, or celestial meridians, come to the star.

In Fig. 13 let O be the position of the earth in the centre of the celestial sphere $NZSD$. Let Z be the zenith of the observer at a given instant, and P, p, the celestial poles. By definition $PZSpnNP$ is his celestial meridian. (Each of these points has a name; let the student give the names in order.) NS is the horizon of the observer at the instant chosen. PON is his latitude. If P is the north pole, he is in latitude 34° north. (See page 31.)

$ECWD$ is the celestial equator; E and W are the east and west points. The earth is turning from W to E. That is, the celestial meridian which at the instant chosen in the picture contains PZp was in the position $PDRp$ twelve hours earlier.

P C, *P B*, *P V*, *P D* are parts of hour-circles. If *A* is a star, *P B* is the hour-circle of that star. As the earth turns *P B* turns with it, and directly *P B* will have moved away from *A* towards the top of the picture and soon *P V* will pass through the star *A*, which stands still. When it does, *P V* will be the hour-circle of *A*. At the instant chosen *P B* is the hour-circle of *A*. The stars inside the circle *N K* are always above the observer's horizon. *l m* is

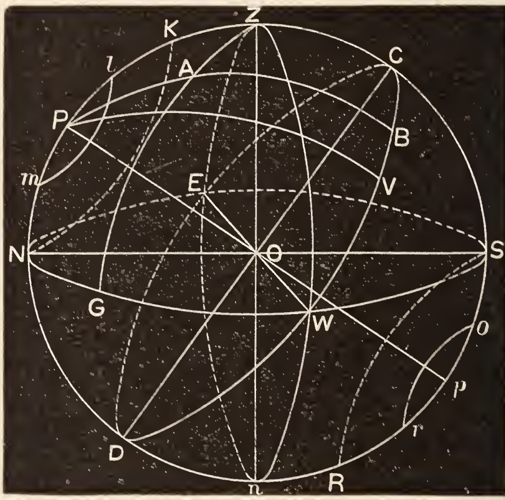

FIG. 13.

half of the diurnal orbit of one of the north stars. All the stars inside the circle *S R* are perpetually invisible to the observer. *o r* is half of the orbit of one of these southern stars. The north-polar distance of all those stars perpetually above the horizon is less than or equal to *P N*; the south-polar distance of all the stars perpetually invisible is less than or equal to *p S*, which is equal to *P N*.

Altitude and Azimuth.—ZG is the vertical circle of the star A at the instant chosen for making the picture. In a few moments Z will have moved eastwards and a new vertical circle will have to be drawn. GA is the altitude of A at the instant; in a few moments it will be less. For as Z moves towards the eastward, NWS, the western horizon of the observer, will move upwards (in the drawing) and come nearer to A, which stands still. Therefore the altitude of A will diminish progressively. It is now GA.

The *azimuth* of A is now NG, counted from the north point. It will change as Z changes. Having the altitude and azimuth of A at the instant, the observer at O can find it in the sky. (See page 18.)

North-Polar Distance and Hour-Angle.—The north-polar distance of A is PA. This will serve as one of a pair of co-ordinates to point out the apparent position of A in the sky.

The *hour-angle of a star is the angular distance between the celestial meridian of the place and the hour-circle of that star.* The hour-angle is counted from the meridian towards the west from 0° to 360°, or from 0^h to 24^h. The hour-angle of A, at this instant, is ZPB. The hour-angle of a star K is 0°.

The hour-angle is *measured* by the arc of the equator between the celestial meridian and the foot of the hour-circle through the star. The arc CB measures the hour-angle of A at the instant. Directly, Z will have moved away to the east and C will move away also along the dotted part of the line representing the equator, $WCED$.

Having the two co-ordinates PA and CB, the observer at O can find the star A. It will be noticed that these two co-ordinates, polar distance and hour-angle, differ in one respect from the two co-ordinates altitude and azimuth. *Both* the latter change as the earth revolves on its axis. Of the former only one changes; viz., the hour-angle. The polar distance of a star remains the same, since it is the distance from a fixed point, the pole, to a fixed point, the star.

Right Ascension and North-Polar Distance.—We can devise a pair of co-ordinates *neither* of which shall change as the earth revolves. This will clearly be convenient, for this pair of co-ordinates will be the same for every observer and for every hour of the day, whereas the others vary with the time, and with the situation of the observer.

To select such a pair we have simply to use fixed points in the celestial sphere to count from. The north pole will do for one of these, and the north-polar distance of the star will serve for one co-ordinate. This is measured, for the star A, on the hour-circle PB. Let us choose some fixed point V on the equator to measure our other co-ordinate from, and let us always measure it on the equator towards the east from 0° to 360° (from 0^h to 24^h). That is, from V through B, C, E, D, W, successively.

VB is the *right ascension* of A. *The right ascension of a star is the angular distance of the foot of the hour-circle through the star from the vernal equinox, measured on the celestial equator, towards the east.*

Exactly what the vernal equinox is we shall find out later on; for the present it is sufficient to define it as a certain fixed point on the celestial equator.

If we have the right ascension and north-polar distance of a star, we can point it out. Thus VB and PA define the position of A. As long as the pole, the star, and the vernal equinox do not move relatively to each other these two co-ordinates fix the position of the star. Their relative positions are not affected by the rotation of the earth, nor by the position of the observer upon its surface. He may be in any latitude or any longitude, and his zenith may be anywhere in the whole sky, but the right ascension and the north-polar distance of each star remain the same nevertheless.

The right ascension of the star K is VC. Of a star at E it is VCE; of a star at D it is $VCED$; of a star at W it is $VCEDW$, and so on.

Right Ascension and Declination.—Sometimes in place of the north-polar distance of a star it is convenient to use its *declination.*

The declination of a star is its angular distance north or south of the celestial equator.

The declination of A is BA, which is 90° *minus* PA.

The relation between N. P. D. and δ is

$$\text{N. P. D.} = 90^\circ - \delta; \quad \delta = 90^\circ - \text{N. P. D.}$$

North declinations are $+$; South declinations are $-$.

The declination of Z is CZ. CZ is equal to PN, since each is equal to $90^\circ - PZ$. PN measures the latitude of the observer whose zenith is Z. (See page 31.)

The latitude of a place on the earth's surface is measured by the declination of its zenith.

This is the definition of the latitude which is used in astronomy.

Co-ordinates of a Star.—In what has gone before we have seen that there are various ways of expressing the apparent positions of stars on the surface of the celestial sphere. That one most commonly used in astronomy is to give the right ascension and north-polar distance (or declination) of the star. The apparent position of the star is fixed by these two co-ordinates. If we know its distance also, the absolute position of the star in space is fixed by the three co-ordinates. Thus we have a complete method of describing the positions of the heavenly bodies.

Co-ordinates of an Observer.—To describe the position of an observer on the surface of the earth we have to give his latitude and longitude. His latitude is the declination of his zenith; his longitude is the fixed angle between his celestial meridian and the celestial meridian of Greenwich (or Washington). Declination in the sky is analogous to Latitude on the earth. Right ascension in the sky is analogous to Longitude on the earth. Both of these co-ordinates depend upon the position of his zenith, since his longitude is nothing but the angular distance of his zenith west of the zenith of Greenwich.

All this is extremely simple, but if it is clearly understood the student has it in his power to answer a great many interesting questions for himself.

We know, for example, that the sun is in the equator and at the vernal equinox on March 21st of each year.

The student can determine for himself what appearances will be presented on that day next year. He may proceed in this way: Draw a circle to represent the celestial sphere. Take a point, P, of it to be the position of the north pole in the sky. If the observer lives in a place whose latitude is φ degrees north, his zenith will be $90^\circ - \varphi$ from the north pole measured towards the south. Measure off $90^\circ - \varphi$ on the circle from P. The end of that arc is the zenith of that observer, Z. PZ is an arc of his celestial meridian. Measure from P through Z 90°, and the end of that arc is on the equator, Q say. Join P with the centre, O, of the circle. This line is the direction of the celestial pole. Join O and Q, and this line (perpendicular to PO) is the direction of that point of the equator which is highest above his horizon. Draw the line ZO; this is the vertical line. Through O draw NOS perpendicular to ZO. This is the north and south line of his horizon. Draw the ovals which represent (in perspective) the circles of the equator and of the horizon. Assume a point, V, of the celestial equator. On March 21st of each year the sun is there. When the sun is at the highest point Q of the equator it is noon to this observer. The sun is on his meridian. Six hours before this time the sun will rise to him; six hours after he will set. It requires twenty-four hours for the point V to be apparently carried all round the equator, and the sun appears to go with the point. Three months later the sun is about 90° of right ascension and has a north-polar distance of 66½°. The student can determine in the same way the circumstances under which the sun will appear to him to move on the 21st of next June when its north-polar distance is 66½°.

The example that is here given is not for the purpose of teaching the student what the motion of the sun is; that will be considered in its proper order in this book. But it is to show him that if he wishes to know about it he can find out for himself.

When he reads about the midnight sun that is visible in the Arctic regions he can verify the facts for himself. Let him construct the diagram we have described for a place whose latitude is 80° north and see what sort of a diurnal orbit the sun will describe on the 21st of June when its N. P. D. is 66½°.

Relation of Time to the Sphere.

Sidereal Time.—The earth rotates uniformly on its axis; that is, it turns through equal angles in equal intervals of time.

This rotation can be used to *measure* any intervals of time when once a unit of time is agreed upon. The most natural and convenient unit is a day. There are various kinds of days, and we have to take them as they are.

A sidereal day is the interval of time required for the earth to rotate once on its axis. Or what is the same thing, it is the interval of time between two consecutive transits of any star over the same celestial meridian. The sidereal day is divided into 24 sidereal hours; each hour is divided into 60 minutes; each minute into 60 seconds. In making one revolution the earth turns through 360°, so that

$$24 \text{ hours} = 360°; \text{ also,}$$
$$1 \text{ hour} = 15°;\ 1° = 4 \text{ minutes.}$$
$$1 \text{ minute} = 15';\ 1' = 4 \text{ seconds.}$$
$$1 \text{ second} = 15'';\ 1'' = 0.066 \text{ second.}$$

When a star is on the celestial meridian of any place its hour-angle is zero, by definition (see page 39). It is then at its transit or culmination.

As the earth rotates, the meridian moves away (eastwardly) from this star, whose hour-angle continually increases from 0° to 360°, or from 0 hours to 24 hours. Sidereal time can then be directly measured by the hour-angle of any star in the heavens which is on the meridian at an instant we agree to call sidereal 0 hours. When this star has an hour-angle of 90°, the sidereal time is 6 hours; when the star has an hour-angle of 180° (and is again on the meridian, but invisible unless it is a circumpolar star), it is 12 hours; when its hour-angle is 270°, the sidereal time is 18 hours; and, finally, when the star reaches the upper meridian again, it is 24 hours or 0 hours. (See Fig. 13, where $E\,C\,W\,D$ is the apparent diurnal path of a star in the equator. It is on the meridian at C.)

Instead of choosing a *star* as the determining point whose transit marks sidereal 0 hours, it is found more convenient to select that point in the sky from which the right ascensions of stars are counted—the vernal equinox—the point V in the figure. The fundamental theorem of sidereal time is: *The hour-angle of the vernal equinox, or the sidereal time, is equal to the right ascension of the meridian;* that is, $C\,V = V\,C$.

To avoid continual reference to the stars, we set a clock so that its hands shall mark 0 hours 0 minutes 0 seconds at the transit of the vernal equinox, and regulate it so that its hour-hand revolves once in 24 sidereal hours. Such a clock is called a sidereal clock.

Solar Time.—Time measured by the hour-angle of the sun is called *true* or *apparent* solar time. *An apparent solar day* is the interval of time between two consecutive transits of the sun over the upper meridian. The instant of the transit of the sun over the meridian of any place is the *apparent noon* of that place, or local apparent noon.

When the sun's hour-angle is 12 hours or 180°, it is local apparent midnight.

The ordinary sun-dial marks apparent solar time. As a matter of fact, apparent solar days are not equal. The reason for this will be fully explained later. Hence our clocks are not made to keep this kind of time, for if once set right they would sometimes lose and sometimes gain on such time.

Mean Solar Time.—A modified kind of solar time is therefore used, called *mean solar time.* This is the time kept by ordinary watches and clocks. It is sometimes called civil time. *Mean solar time* is measured by the hour-angle of the mean sun, a fictitious body which is imagined to move uniformly in the heavens. The law according to which the mean sun is supposed to move enables us to compute its exact position in the heavens at any instant, and to define this position by the two co-ordinates right ascension and declination. Thus we know the position of this imaginary body just as we know the position of a star whose co-ordinates are given, and we may speak of its transit as if it were a bright material point in the sky. *A mean solar day* is the interval of time between two consecutive transits of the mean sun over the upper meridian. *Mean* *noon* at any place on the earth is the instant of the mean sun's transit over the meridian of that place. Twelve hours after local mean noon is local *mean midnight.* The mean solar day is divided into 24 hours of 60 minutes each. Each minute of mean time contains 60 mean solar seconds. Astronomers begin the mean solar day at noon, which is 0 hours, and count round to 24 hours.

We have thus three kinds of time. They are alike in one point: each is measured by the hour-angle of some body, real or assumed. The body chosen determines the kind of time, and the absolute length of the unit—the day. The simplest unit is that determined by the uniformly rotating earth—the sidereal day; the most natural unit is that determined by the sun itself—the apparent solar day, which, however, is a variable unit; the most convenient unit is the mean solar day, and this is the one chosen for use in our daily life.

Comparative Lengths of the Mean Solar and Sidereal Day.—As a fact of observation, it is found that the sun appears to move from west to east among the stars, about 1° daily, making a complete revolution around the sphere in a year. It requires $365\frac{1}{4}$ days to move through 360°.

Hence an apparent solar day will be longer than a sidereal day. For suppose the sun to be at the vernal equinox exactly at sidereal noon (0 hours) of Washington time on March 21st; that is, the vernal equinox and the sun are both on the meridian of Washington at the same instant. In 24 sidereal hours the vernal equinox will again be on the same meridian, but the sun will have moved eastwardly by about a degree, and the earth will have to turn through this angle and a little more in order that the sun shall again be on the Washington meridian, or in order that it may be apparent noon on March 22d. For the meridian to overtake the sun requires about 4 minutes of sidereal time. The true sun does not move, as we have said, uniformly. The mean sun is supposed to move uniformly, and to make the circuit of the heavens in the same time as the real sun. Hence a mean solar day will *also* be longer than a sidereal day, for the same reason that the apparent solar day is longer. The exact relation is:

$$
\begin{aligned}
1 \text{ sidereal day} &= 0 \cdot 997 \text{ mean solar day,} \\
24 \text{ sidereal hours} &= 23^{h}\ 56^{m}\ 4^{s} \cdot 091 \text{ mean solar time,} \\
1 \text{ mean solar day} &= 1 \cdot 003 \text{ sidereal days,} \\
24 \text{ mean solar hours} &= 24^{h}\ 3^{m}\ 56^{s} \cdot 555 \text{ sidereal time,}
\end{aligned}
$$

and

$$366 \cdot 24222 \text{ sidereal days} = 365 \cdot 24222 \text{ mean solar days.}$$

Local Time.—When the mean sun is on the meridian of a place, as Boston, it is mean noon at Boston. When the mean sun is on the meridian of St. Louis, it is mean noon at St. Louis. St. Louis being west of Boston, and the earth rotating from west to east, the local noon of Boston occurs before the local noon at St. Louis. In the same way the local sidereal time at Boston at any given instant is expressed by a larger *number* than the local sidereal time of St. Louis at that instant.

The sidereal time of mean noon is given in the astronomical ephemeris for every day of the year. It can be found within ten or twelve minutes at any time by remembering that on March 21st it is sidereal 0 hours about noon, on April 21st it is about two hours sidereal time at noon, and so on through the year. Thus, by adding two hours for each month, and four minutes for each day after the 21st day last preceding, we have the sidereal time at the noon we require. Adding to it the number of hours since noon, and one minute more for every fourth of a day on account of the constant gain of the clock (4^m daily), we have the sidereal time at any moment.

Example.—Find the sidereal time on July 4th, 1881, at 4 o'clock A.M. We have:

	h	m
June 21st, 3 months after March 21st; to be × 2,	6	0
July 3d, 12 days after June 21st; × 4,	0	48
4 A.M., 16 hours after noon, nearly ⅔ of a day,	16	3
	22	51

This result is within a minute of the exact value.

Relation of Time and Longitude.—Considering our civil time which depends on the sun, it will be seen that it is noon at any and every place on the earth when the sun crosses the meridian of that place, or, to speak with more precision, when the meridian of the place passes under the sun. In the lapse of 24 hours the rotation of the earth on its axis brings all its meridians under the sun in succession, or, which is the same thing, the sun appears to pass in succession over all the meridians of the earth. Hence *noon* continually travels westward at the rate of 15° in an hour, making the circuit of the earth in 24 hours. The difference between the time of day, or the *local time* as it is called, at any two places will be in proportion to their difference of longitude, amounting to one hour for every 15 degrees of longitude, four minutes for every degree, and so on. *Vice versa*, if at the same real moment of time we can determine the local times at two different places, the difference of these times multiplied by 15 will give the difference of longitude.

The longitudes of places are determined astronomically on this principle. Astronomers are, however, in the habit of expressing the longitude of places on the earth like the right ascensions of the heavenly bodies, not in degrees, but in hours. For instance, instead of saying that Washington is 77° 3′ west of Greenwich, we commonly say that it is 5 hours 8 minutes 12 seconds west, meaning that when it is noon at Washington it is 5 hours 8 minutes 12 seconds after noon at Greenwich. This course is adopted to prevent the trouble and confusion which might arise from constantly having to change hours into degrees and the reverse.

Where does the Day Change?—A question frequently asked in this connection is, Where does the day change? It is, we will suppose, Sunday noon at Washington. That noon travels all the way round the earth, and when it gets back to Washington again it is Monday. Where or when did it change from Sunday to Monday? We answer, wherever people choose to make the change. Navigators make the change occur in longitude 180° from Greenwich. As this meridian lies in the Pacific Ocean, and meets scarcely any land through its course, it is very convenient for this purpose. If its use were universal, the day in question would be Sunday to all the inhabitants east of this line, and Monday to every one west of it. But in practice there have been some deviations. As a general rule, on those islands of the Pacific which were settled by men travelling east the day would at first be called Monday, even though they might cross the meridian of 180°. Indeed the Russian settlers carried their count into Alaska, so that when our people took possession of that territory they found that the inhabitants called the day Monday when they themselves called it Sunday. These deviations have, however, almost entirely disappeared, and with few exceptions the day is changed by common consent in longitude 180° from Greenwich.

Determinations of Terrestrial Longitudes.

Owing to the rotation of the earth, there is no such fixed correspondence between meridians on the earth and among the stars as there is between latitude on the earth and declination in the heavens. The observer can always determine his latitude by finding the declination of his zenith, but he cannot find his longitude from the right ascension of his zenith with the same facility, because that right ascension is constantly changing. To determine the longitude of a place, the element of time as measured by the diurnal motion of the earth necessarily comes in. Consider the plane of the meridian of a place extended out to the celestial sphere so as to mark out on the latter the celestial meridian of the place. Take two such places, Washington and San Francisco for example; then there will be two such celestial meridians cutting the celestial sphere so as to make an angle of about forty-five degrees with each other in this case. Let the observer imagine himself at San Francisco. Then he may conceive the meridian of Washington to be visible on the celestial sphere, and to extend from the pole over toward his south-east horizon so as to pass at a distance of about forty-five degrees east of his own meridian. It would appear to him to be at rest, although really both his own meridian and that of Washington are moving in consequence of the earth's rotation. Apparently the stars in their course will first pass the meridian of Washington, and about three hours later will pass his own meridian. Now it is evident that if he can determine the interval which the star requires to pass from the meridian of Washington to that of his own place, he will at once have the difference of longitude of the two places by simply turning the interval in time into degrees at the rate of fifteen degrees to each hour.

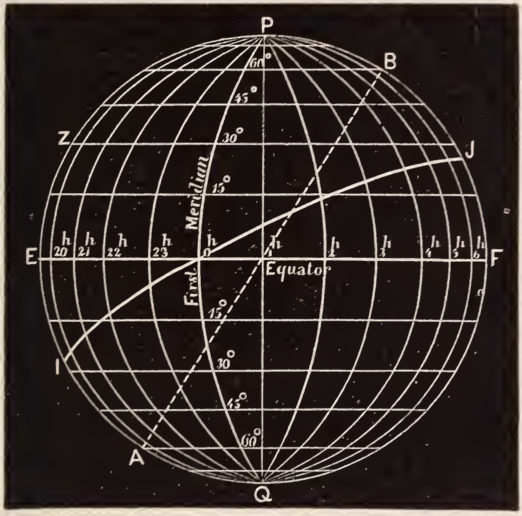

FIG. 14.

The difference of longitude between any two places depends upon the angular distance of the terrestrial (or celestial) meridians of these two places and not upon the motion of the star or sun which is used to determine this angular difference, and hence the longitude of a place is the same whether expressed as the difference of two sidereal or of two solar times. The longitude of Washington west from Greenwich is $5^h\ 8^m$ or 77°, and this is in fact the ratio of the angular distance of the meridian of Washington from that of Greenwich, to 24 hours or 360°. The angle between the two meridians is $\frac{77}{360}$ of 24 hours, or of a whole circumference.

It is thus plain that *the difference of longitude of any two places is the same as the difference of their simultaneous local times;* and this whether the local times spoken of are both sidereal or both solar.

Methods of Determining the Difference of Longitude of Two Places on the Earth.

Every purely astronomical method depends upon the principle we have just laid down.

It is of vital importance to seamen to be able to determine the longitude of their vessels. The voyage from Liverpool to New York is made weekly by scores of steamers, and the safety of the voyage depends upon the certainty with which the captain can mark the longitude and latitude of his vessel upon the chart.

The method used by a sailor is this: with a sextant (see Chapter III.) the local time of the ship's position is determined by an observation of the sun. That is, on a given day he can set his watch so that its hands point to twelve hours when the sun is on his meridian on that day. He carries a chronometer (which is merely a very fine watch) whose hands point always to Greenwich time. Suppose that when the ship's time is 0^h or noon the Greenwich time is $3^h\ 20^m$. Evidently he is west of Greenwich $3^h\ 20^m$, since that is the difference of the *simultaneous* local times, and since the Greenwich time is later. Hence he is somewhere on the meridian of 50° west. If he has determined the altitude of the pole or the declination of his zenith in any way, then he has his latitude also. If this should be 45° north, the ship is in the regular track between New York and Liverpool, and he can go on with safety.

When the steamer *Faraday* was laying the direct cable she got her longitude every day by comparing her ship's time (found by observation on board) with the Greenwich time telegraphed along the cable and received at the end of it which she had on her deck. Longitudes may be determined in the same way on shore.

From an observatory, as Washington, the beats of a clock are sent out by telegraph along the lines of railway; at every railway station and telegraph office the telegraph sounder beats the seconds of the Washington clock. Any one who can set his watch to the local time of his station and who can compare it with the signals of the Washington clock (which are sent at Washington noon, daily except Sunday) can determine for himself the difference of the simultaneous local times of Washington and of his station, and thus his own longitude east or west from Washington.

Methods of Determining the Latitude of a Place on the Earth.

Latitude from Circumpolar Stars.—In the figure suppose Z to be the zenith of the observer, $HZRN$ his me-

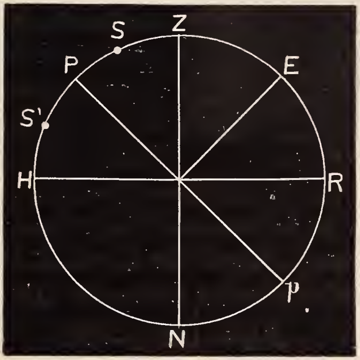

Fig. 15.

ridian, P the north pole, HR his horizon. Suppose S and S' to be the two points where a circumpolar star crosses the meridian, as it moves around the pole in its apparent diurnal orbit. $PS = PS'$ is the star's north-polar distance, and $PH = \varphi =$ the observer's latitude.

$$\frac{ZS + ZS'}{2} = ZP = 90^\circ - \varphi.$$

Therefore $$\varphi = 90^\circ - \frac{ZS + ZS'}{2}.$$

We can measure ZS and ZS', the zenith distances of the star in the two positions, by the meridian circle or by the sextant, as will be explained in the next chapter. Hence having these zenith distances we have the latitude of the place.

Latitude by the Meridian Altitude of the Sun or a Star.—In the figure let Z be the observer's zenith, P the pole, and Q the intersection of the celestial equator with the meridian HZH. The altitude of the star S is measured when the star is on the meridian. It is known to be on the meridian when we find its altitude to be a maximum. From the measured altitude of the star S we deduce its zenith distance $ZS = z = 90^\circ - HS$. Its declination is taken from a catalogue of stars if it is a star, or from the *Nautical Almanac* if it is the sun. In either case the declination QS is known.

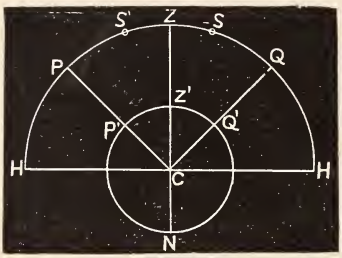

Fig. 16.

$$ZQ = QS + ZS;$$
$$\varphi = \delta + z.$$

If the body culminates north of the zenith at S',

$$ZQ = QS' - ZS;$$
$$\varphi = \delta - z.$$

This is the method uniformly employed at sea, where the altitude of the sun at apparent noon is daily measured.

Parallaxes and Semidiameters of the Heavenly Bodies.

The apparent position of a body on the celestial sphere remains the same as long as the observer is fixed, as has been shown (see page 20). If the observer changes his place and the star remains in the same position, the ap-

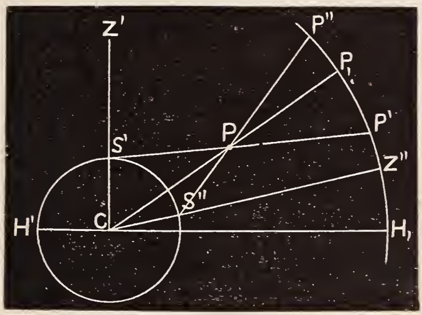

Fig. 17.

parent position of the star will change. To show this let CH' be the earth, C being its centre. S' and S'' are the places of two observers on the surface. Z' and Z'' are their zeniths in the celestial sphere $H'P''$. P is a star. S' will see P in the apparent position P'. S'' will see P in the apparent position P''. That is, two different observers see the same object in two different apparent positions. If the observer S' moves along the surface directly to S'', the apparent position of P on the celestial sphere will appear to move from P' to P''.

This change is due to the *parallax* of P.

The parallax of a body due to a change in the position of the observer, is the alteration in the apparent position of the body caused by that change.

If the observer at S' could move to the centre of the earth along the line $S'C$, the apparent position of P would move from P' to $P_{\prime}$. If the observer at S'' could move from S'' to C along $S''C$, the apparent position of P would move from P'' to $P_{\prime}$.

In the triangle $PS'C$ the following parts are known:

$$CP = \varDelta = \text{the geocentric distance of } P,$$
$$CS' = \rho' = \text{the radius of the earth at } S',$$

and the angle $S'PC = P'PP_{\prime}$ is the *parallax* of P.

For the change of apparent position of P from P' to $P_{\prime}$ is due to the change of the point of observation from S' to C.

Similarly the angle $S''PC = P''PP_{\prime}$ is the parallax of P relative to a change of the observer fıom S'' to C.

Horizontal Parallax.—Clearly the parallax of P differs for observers differently situated on the earth, and it is necessary to take some standard parallax for each observer. Such a standard is the *horizontal parallax.* Suppose P to be in the horizon of the observer S'; then $Z'S'P$ will be 90°, as will also the angle $PS'C$. In the triangle $S'PC$ three parts will then be known and the horizontal parallax (the angle at P when P is in the horizon) can be found. It will be the same for the observer at S''. When P is in the horizon of S'', $Z''S''P$ is a right angle, as is also $PS''C$. CP and CS'' are known and thus the horizontal parallax of P is determined.

If CP, the distance of P, increases, other things remaining the same, the parallax of P will diminish.

The student can prove this for himself by drawing the figure on the same scale as here given, making CP larger. The angles at P (the parallaxes) will become smaller and smaller the larger CP is taken. Hence the magnitude of the parallax of a star or a planet depends upon its distance from us.

Suppose an observer at the point P looking at the earth's radius $S'C$. The angle subtended by that semidiameter is the same as the parallax of P. Hence we may say that *the parallax of a body with reference to an observer on the earth is measured by the angle subtended by that semidiameter of the earth which passes through the observer's station.*

As the point P is carried further and further away from the earth, the angle subtended by $S'C$, for example, becomes less and less. If P were at the distance of the moon, this angle would be about 57′; if at the distance of the sun, it would be about $8\frac{1}{2}''$. $S'C$ is roughly 4000 miles; it subtends an angle of 57′ at the distance of the moon. 70 miles would subtend an angle of about 1′, and 3437′ would be about 240,000 miles. This is the distance of the moon from the earth. (See pages 4, 5.)

Again, 4000 miles subtends an angle of 8″.5 at the distance of the sun. 470.7 miles would subtend an angle of 1″, and 206,264″.8 would be 97,000,000 miles, and this is about the distance of the sun. By taking the exact values of the radius of the earth and of the solar parallax, this distance is found to be about 93,000,000 miles.

The example shows the method of calculating the sun's distance when we have two things accurately given: first, the dimensions of the earth; and second, the parallax of the sun.

Annual Parallax.—We have seen that for the moon the parallax is about 1°; for the sun it is only 8″; for some of the more distant planets it is considerably less.

For *Jupiter* it is about 2″; for *Saturn* less than 1″; for *Neptune* about 0″.3.

Let us remember what this means. It means that 4000 miles, the earth's radius, would subtend at the distance of *Neptune* an angle of only $\frac{3}{10}$ of a single second of arc.

The parallax of the moon is determined by observation, and the observations consist in measuring the angle which the radius of the earth *would* subtend if viewed from the moon's centre. 57′ is an angle large enough to be determined quite accurately in this way. There would be but a small *per cent* of error. Even 8″, the sun's parallax, can be measured so as to have an error of not more than 2 or 3 *per cent.*

But this method will not do to measure anything much smaller than 8″. The parallax of a fixed star, for example, is not $\frac{1}{200000}$ part as large as the sun's parallax: and this is too minute a quantity to be deduced by these methods. We therefore use for distant bodies a parallax which does not depend on the radius of the earth, but upon the radius of the earth's *orbit* around the sun.

The annual parallax of a body is the angle subtended at the body by the radius of the earth's orbit seen at right angles.

For example, in Fig. 18 suppose that C now represents the sun, around which the earth S' moves in the nearly circular orbit $S'S''H'$. $S'C$ is no longer 4000 miles as in the last example, but it is 93,000,000 miles. Suppose P to be, again, a body whose *annual parallax* is $S'P\,C$ (supposing $PS'C$ to be a right angle).

Some of the nearest fixed stars have an annual parallax of nearly 1″. Hence the nearest of them are not nearer than 206,264 times 93,000,000 miles. The greater number of them have a parallax of not more than $\frac{1}{10}''$.

Hence their distances cannot be less than

$$10 \times 206{,}264 \times 93{,}000{,}000 \text{ miles.}$$

To the student who has understood the simple rules given on pages 4 and 5 these deductions will be plain.

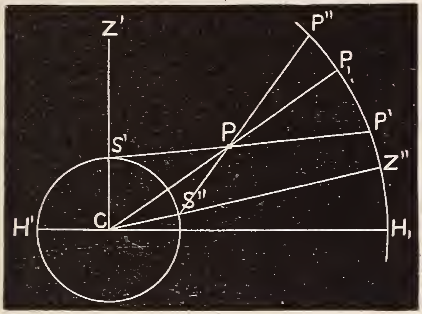

Fig. 18.

Semidiameters of the Heavenly Bodies.—The angular semidiameter of the sun as seen from the earth is 961″. Hence its diameter is 1922″. Its real diameter in miles is therefore about 880,000, as its distance is 93,000,000 miles.

The angular semidiameter of the moon as seen from the earth is about $15\frac{1}{2}'$. Hence its real diameter is about 2000 miles, its distance being about 240,000 miles.

In the same way, knowing the distance of any planet and measuring its angular semidiameter, we can compute its dimensions in miles.

CHAPTER III.

ASTRONOMICAL INSTRUMENTS.

General Account.—In a general way we may divide the instruments of astronomy into two classes, *seeing* instruments and *measuring* instruments.

The seeing instruments are telescopes; they have for their object either to enable the observer to see faint objects as comets or small stars, or to enable him to see brighter stars with greater precision than he could otherwise do. How they accomplish this we shall shortly explain. The measuring instruments are of two classes. The first class measures *intervals of time.* The second measures *angles.* A clock is a familiar example of the first class; a divided circle of the second.

Let us take these in the order named.

The Refracting Telescope.—The refracting telescope is composed of two essential parts, the *object-glass* or *objective* and the *eye-piece.*

The object-glass is for the sole purpose of collecting the rays of light which emanate from the thing looked at, and for making an *image* of this thing at a point which is called the *focus* of the objective.

The *eye-piece* has for its sole object to magnify the image so that the angular dimensions of the thing looked at will appear greater when the telescope is used than when it is not.

For example, in the figure suppose *BI* to be a luminous surface. Every point of it is throwing off rays of light in straight lines in every possible direction. Let us consider the point *I*. The rays from *I* proceed in every direction in which we can draw a straight line through *I*. Suppose all such straight lines drawn. Let *OO′* be the *objective* of a telescope pointed towards *BI*. All the rays from *I* which fall on *OO′* lie between the lines *IO*, and *IO′*. No others can reach the objective, and all others which proceed from *I* are wasted so far as seeing *I* with this particular telescope is concerned.

FIG. 19.

The action of the convex lens *OO′* is to bend every ray which passes through it towards its axis *BA*. *IO* is bent down to *OI′*; *IO′* is bent up to *O′I′*; and so for every other ray except the ray from *I* through the *centre* of *OO′* which is bent neither up nor down, but which goes straight on to *I′* and beyond.

Every one of the rays of light sent out by *I* between the limits *IO* and *IO′* finally passes through *I′*. *I* is a point of light, and so is *I′*. The point *I′* is the *focus* of *OO′* with respect to *I*.

Similarly *B* sends out light in every direction. Only those rays which chance to fall between *BO* and *BO′* are useful for seeing *B* with this particular telescope. Every one of this bundle of rays comes to a *focus* on the intersection of the lines I'..... and BA. In the same way every point of the *object* BI has a corresponding *image* on the line I'...... somewhere between I' and the axis BA. I'...... is the *focal plane* of the objective with respect to the object BI, and the image of BI lies in this focal plane. The objective has now done all it can; it has gathered every possible ray from the object BI and presents every one of these rays concentrated in an image of this object in the focal plane at I'......

Notice two things: first, the *image* is inverted with respect to the object; I is above B; the image of I is below the image of B; second, the rays from B...... I do not stop at I'......, but go on indefinitely to the left, always diverging from the image.

The Eye-piece.—The eye-piece is essentially a microscope which is simply to magnify the angular dimensions of the object as it is seen in the telescope; that is, to magnify the image. To see well with a microscope it must be close to the thing magnified. It cannot be placed near to BI in general, for BI may be a mile or ten millions of miles away. So the place to put it is near to the *image* of BI, a little above the focal plane I'...... in the figure.

The eye must be placed a little further above still, at such a position as to see well with the eye-piece. That is, close to it. Now fix an objective in one end of a tube and an eye-piece in the other end and you have a refracting telescope. The more powerful the microscope used as an eye-piece the higher the magnifying power of the combination. We increase the magnifying power of any telescope by changing the eye-piece.

The Objective.—As a matter of fact the objective is usually made of two glasses like the figure, where the arrow shows the direction in which the rays come to it from the object. If we use a single objective we find that the image of the object is *colored;* that is, of different colors from its natural tints. We find that by using a double objective made of two different kinds of glass this can be corrected. This is explained in Optics under the head of Achromatism or Chromatic Aberration.

FIG. 20.

Light-gathering Power.—It is not merely by magnifying that the telescope assists the vision, but also by increasing the quantity of light which reaches the eye from the object at which we look. Indeed, should we view an object through an instrument which magnified but did not increase the amount of light received by the eye, it is evident that the brilliancy would be diminished in proportion as the surface of the image was enlarged, since a constant amount of light would be spread over an increased surface; and thus, unless the light were very bright, the object might become so darkened as to be less plainly seen than with the naked eye. How the telescope increases the quantity of light will be seen by considering that when the unaided eye looks at any object, the retina can only receive so many rays as fall upon the pupil of the eye. By the use of the telescope it is evident that as many rays can be brought to the retina as fall on the entire object-glass. The pupil of the human eye, in its normal state, has a diameter of about one fifth of an inch, and by the use of the telescope it is virtually increased in surface in the ratio of the square of the diameter of the objective to the square of one fifth of an inch; that is, in the ratio of the *surface* of the objective to the *surface* of the pupil of the eye. Thus, with a two-inch aperture to our telescope, the number of rays collected is one hundred times as great as the number collected with the naked eye.

With a	5-inch	object-glass	the	ratio is		625 to 1
"	10 "	"	"	"		2,500 to 1
"	15 "	"	"	"		5,625 to 1
"	20 "	"	"	"		10,000 to 1
"	26 "	"	"	"		16,900 to 1

When a minute object, like a small star, is viewed, it is necessary that a certain number of rays should fall on the retina in order that the star may be visible at all. It is therefore plain that the use of the telescope enables an observer to see much fainter stars than he could detect with the naked eye, and also to see faint objects much better than by unaided vision alone. Thus, with a 26-inch telescope we may see stars so minute that it would require the collective light of many thousands to be visible to the unaided eye.

Eye-piece.—In the skeleton form of telescope before described the eye-piece as well as the objective was considered as consisting of but a single lens. But with such an eye-piece vision is imperfect, except in the centre of the field, from the fact that the image does not throw rays in every direction, but only in straight lines away from the objective. Hence the rays from near the edges of the focal image fall on or near the edge of the eye-piece, whence arises distortion of the image formed on the retina, and loss of light. To remedy this difficulty a lens is inserted at or very near the place where the focal image is formed, for the purpose of throwing the different pencils of rays which emanate from the several parts of the image, toward the axis of the telescope, so that they shall all pass nearly through the centre of the eye-lens proper. These two lenses are together called the eye-piece.

There are some small differences of detail in the construction of eye-pieces, but the general principle is the same in all.

The figure shows an eye-piece drawn accurately to scale. *O I* is one of the converging pencils from the object-glass which forms one point (*I*) of the focal image *I a*. This image is viewed by the *field-lens F* of the eye-piece as if it were a real object, and the shaded pencil between *F* and *E* shows the course of these rays after deviation by *F*. If there were no *eye-lens E*, an eye properly placed beyond *F* would see an image at $I'a'$. The eye-lens *E* receives the pencil of rays, and deviates it to the observer's eye placed at such a point that the whole incident pencil will pass through the pupil and fall on the retina, and thus be effective. As we saw in the figure of the refracting telescope,

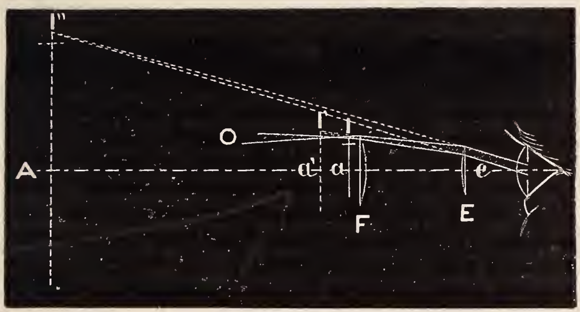

Fig. 21.

every point of the object produces a pencil similar to *OI*, and the whole surfaces of the lenses *F* and *E* are covered with rays. All of these pencils passing through the pupil go to make up the retinal image. This image is referred by the mind to the distance of distinct vision (about ten inches), and the image AI'' represents the dimension of the final image relative to the image *aI* as formed by the objective, and $\frac{A\,I''}{a\,I}$ is evidently the magnifying power of this particular eye-piece used in combination with this particular objective.

Reflecting Telescopes.—As we have seen, one essential part of a refracting telescope is the objective, which brings all the incident rays from an object to one focus, forming there an image of that object. In reflecting telescopes (reflectors) the objective is a mirror of speculum metal or silvered glass ground to the shape of a paraboloid. The figure shows the action of such a mirror on a bundle of parallel rays, which, after impinging on it, are brought by reflection to one focus *F*. The image formed at this focus may be viewed with an eye-piece, as in the case of the refracting telescope.

The eye-pieces used with such a mirror are of the kind already described. In the figure the eye-piece would have to be placed to

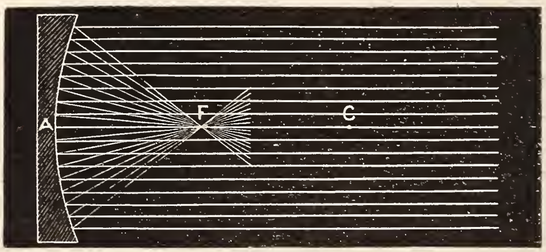

FIG. 22.

the right of the point *F*, and the observer's head would thus interfere with the incident light. Various devices have been proposed to remedy this inconvenience, of which the most simple is to interpose a small plane mirror, which is inclined 45° to the line *AC*, just to the left of *F*. This mirror will reflect the rays which are moving towards the focus *F* down (in the figure) to another focus outside of the main beam of rays. At this second focus the eye-piece is placed and the observer looks into it in a direction perpendicular to *AC*.

The Telescope in Measurement.—A telescope is generally thought of only as an instrument to assist the eye by its magnifying and light-gathering power in the manner we have described. But it has a very important additional function in astronomical measurements by enabling the astronomer to point at a celestial object with a certainty and accuracy otherwise unattainable. This function of the telescope was not recognized for more than half a century after its invention, and after a long and rather acrimonious contest between two schools of astronomers. Until the middle of the seventeenth century, when an astronomer wished to determine the altitude of a celestial object, or to measure the angular distance between two stars, he was obliged to point his sextant or other measuring instrument at the object by means of "pinnules." These served the same purpose as the sights on a rifle. In using them, however, a difficulty arose. It was impossible for the observer to have distinct vision both of the object and of the pinnules at the same time, because when the eye was focused on either pinnule, or on the object, it was necessarily out of focus for the others. The only way to diminish this difficulty was to lengthen the arm on which the pinnules were fastened so that the latter should be as far apart as possible. Thus TYCHO BRAHE, before the year 1600, had measuring instruments very much larger than any in use at the present time. But this plan only diminished the difficulty and could not entirely obviate it, because to be manageable the instrument must not be very large.

About 1670 the English and French astronomers found that by simply inserting fine threads or wires exactly in the focus of the object-glass, and then pointing it at the object, the image of that object formed in the focus could be made to coincide with the threads, so that the observer could see the two exactly superimposed upon each other. When thus brought into coincidence, it was obvious that the point of the object on which the wires were set was in a straight line passing through the wires, and through the centre of the object-glass. So exactly could such a pointing be made, that if the telescope did not magnify at all (the eye-piece and object-glass being of equal focal length), a very important advance would still be made in the accuracy of astronomical measurements. This line, passing centrally through the telescope, we call the *line of collimation* of the telescope, $A\ B$ in Fig. 19. If we have any way of determining it, it is as if we had an indefinitely long pencil extended from the earth to the sky. If the observer simply sets his telescope in a fixed position, looks through it and notices what stars pass along the threads in the eye-piece, he knows that all those stars lie in the axis of collimation of his telescope at that instant.

By the diurnal motion a pencil-mark, as it were, is thus drawn on the surface of the celestial sphere among the stars, and the direction of this pencil-mark can be determined with far greater precision by the telescope than with the naked eye.

Chronometers and Clocks.

We have seen that it is important for various purposes that an observer should be able to determine his local time (see page 52). This local time is determined most accurately by observing the transits of stars over the celestial meridian of the place where the observer is. In order to determine the moment of transit with all required accuracy, it is necessary that the time-pieces by which it is measured shall go with the greatest possible precision. There is no great difficulty in making astronomical measures to a second of arc, and a star, by its diurnal motion, passes over this space in one fifteenth of a second of time (see page 44). It is therefore desirable that the astronomical clock shall not vary from a uniform rate more than a few hundredths of a second in the course of a day. It is not, however, necessary that it should always be perfectly correct; it may go too fast or too slow without detracting from its character for accuracy, if the intervals of time which it tells off—hours, minutes, or seconds—are always of exactly the same length, or, in other words, if it gains or loses exactly the same amount every hour and every day.

The time-pieces used in astronomical observation are the chronometer and the clock.

The *chronometer* is merely a very perfect watch with a balance-wheel so constructed that changes of temperature have the least possible effect upon the time of its oscillation. Such a balance is called a *compensation* balance.

The ordinary house-clock goes faster in cold than in warm weather, because the pendulum-rod shortens under the influence of cold. This effect is such that the clock will gain about one second a day for every fall of 3° Cent. (5°.4 Fahr.) in the temperature, supposing the pendulum-rod to be of iron. Such changes of rate would be entirely inadmissible in a clock used for astronomical purposes. The astronomical clock is therefore provided with a *compensation* pendulum, by which the disturbing effects of changes of temperature are avoided.

The *correction* of a clock is the quantity which it is necessary to add to the indications of the hands to obtain the true time. Thus if the correction of a sidereal clock is $+ 1^m 10^s.07$ and the hands point to $21^h 13^m 14^s.50$, the correct sidereal time is $21^h 14^m 24^s.57$.

The *rate* of a clock is the daily change of its correction; *i.e.*, what it gains or loses daily.

The Transit Instrument.

The *Transit Instrument* is used to observe the transits of stars over the celestial meridian. The times of these

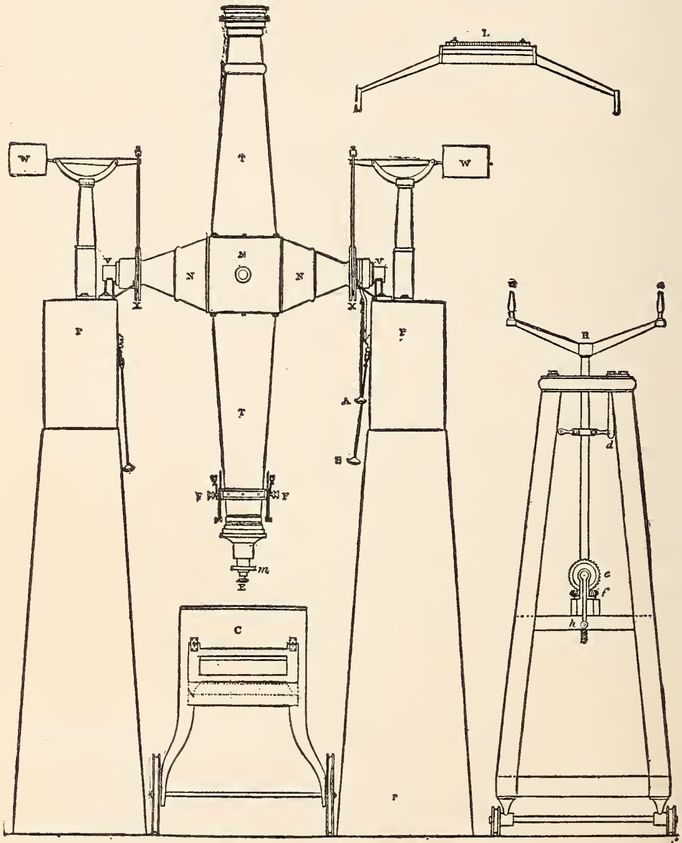

Fig. 23.

transits are noted by the sidereal clock, which is an indispensable adjunct of the transit instrument.

It consists essentially of a telescope TT mounted on an axis VV at right angles to it. The ends of this axis terminate in accurately cylindrical pivots which rest in metallic bearings VV which are shaped like the letter Y, and hence called the Y's.

These are fastened to two pillars of stone, brick, or iron. Two counterpoises WW are connected with the axis as in the plate, so as to take a large portion of the weight of the axis and telescope from the Y's, and thus to diminish the friction upon these and to render the rotation about VV more easy and regular. In the ordinary use of the transit, the line VV is placed accurately level and also perpendicular to the meridian, or in the east and west line. To effect this "adjustment" there are two sets of adjusting screws, by which the ends of VV in the Y's may be moved either up and down, or north and south. The plate gives the form of transit used in permanent observatories, and shows the observing chair C, the reversing carriage R, and the level L. The arms of the latter have Y's, which can be placed over the pivots VV.

The *line of collimation* of the transit telescope is the line drawn through the centre of the objective perpendicular to the *rotation axis* VV.

The *reticle* is a network of fine spider-lines placed in the focus of the objective.

In Fig. 24 the circle represents the field of view of a transit as seen through the eye-piece. The seven vertical lines, I, II, III, IV, V, VI, VII, are seven fine spider-lines tightly stretched across a hole in a metal plate, and so adjusted as to be perpendicular to the direction of a star's apparent diurnal motion. The horizontal wires, *guide-wires*, *a* and *b*, mark the centre of the field. The field is illuminated at night by a lamp at the end of the axis which shines through the hollow interior of the latter, and causes the field to appear bright. The wires are dark against a bright ground. The *line of sight* is a line joining the centre of the objective and the central one, IV, of the seven vertical wires.

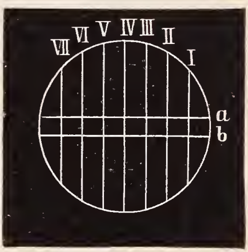

Fig. 24.

The whole transit is in adjustment when, first, the axis VV is horizontal; second, when it lies east and west; and third, when the line of sight and the line of collimation coincide. When these conditions are fulfilled the line of sight intersects the celestial sphere in the meridian of the place, and when TT is rotated about VV the line of sight marks out the celestial meridian of the place on the sphere.

The clock stands near the transit instrument. The times when a star passes the wires I–VII are noted. The average of these is the time when the star was on the middle thread, or, what is the same thing, on the celestial meridian. At that instant its hour-angle is zero. (See page 39.)

The *sidereal time* at that instant is the hour-angle of the vernal equinox (see page 44). This is measured from the meridian towards the west. The right ascension of the star which is observed is the same quantity, measured from the vernal equinox towards the east. As the star is on the meridian, the two are equal. Suppose we know the right ascension of the star and that it is α. Suppose the clock time of transit is T. It should have been α if the clock were correct. The correction of the clock at this instant is thus $\alpha - T$.

This is the use we make of stars of *known* right ascensions. By observing any one of them we can get a value of the clock correction.

Suppose the clock to be correct, and suppose we note that a star whose right ascension is *unknown* is on the wire IV at the time α' by the clock. α' is then the right ascension of that star. In this way the positions of stars, or of the sun and planets (in right ascension only), are determined.

The Meridian Circle.

The meridian circle is a combination of the transit instrument with a graduated circle fastened to its axis and moving with it. A meridian circle is shown in Fig. 25. It has two circles finely divided on their sides. The graduation of each circle is viewed by four microscopes. The microscopes are 90° apart. The cut shows also the hanging level by which the error of level of the axis is found.

The instrument can be used as a transit to determine right ascensions, as before described. It can be also used to measure declinations in the following way: If the telescope is pointed to the nadir, a certain division of

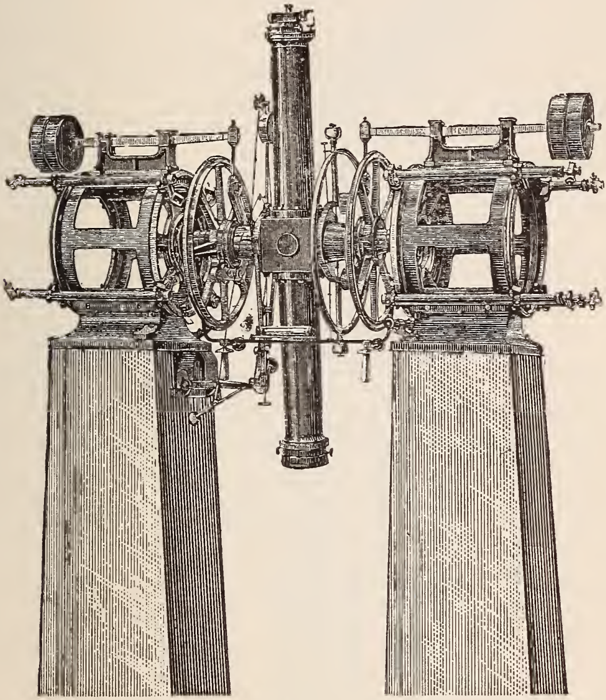

Fig. 25.

the circles, as *N*, is under the first microscope. We can make the *nadir* a visible point by placing a basin of quicksilver below the telescope and looking in it through the telescope. We shall see the wires of the reticle and also their reflected images in the quicksilver. When these coincide, the telescope points to the nadir. If it is then pointed to the pole, the reading will change by the angular distance between the nadir and the pole, or by $90° + \varphi$, φ being the latitude of the place (supposed to be known). The polar reading P of the circle is thus known when the nadir reading N is found. If the telescope is then pointed to various stars of *unknown* polar distances, p', p'', p''', etc., as they successively cross the meridian, and if the circle readings for these stars are P', P'', P''', etc., it follows that $p' = P' - P$; $p'' = P'' - P$; $p''' = P''' - P$; etc.

Thus the meridian circle serves to determine by observation *both* co-ordinates of the apparent position of a body.

The Equatorial.

An *equatorial telescope* is one mounted in such a way that a star may be followed through its diurnal orbit by turning the telescope about one axis only. The equatorial mounting consists essentially of a pair of *axes* at right angles to each other. One of these $S\,N$ (the *polar axis*) is directed toward the elevated pole of the heavens, and it therefore makes an angle with the horizon equal to the latitude of the place (p. 31). This axis can be turned about its own axial line. On one extremity it carries another axis $L\,D$ (the *declination axis*), which is fixed at right angles to it, but which can again be rotated about *its* axial line.

To this last axis a telescope is attached, which may either be a reflector or a refractor. It is plain that such a telescope may be directed to any point of the heavens; for we can rotate the declination axis until the telescope points to any given polar distance or declination. Then, keeping the telescope fixed in respect to the declination axis, we can

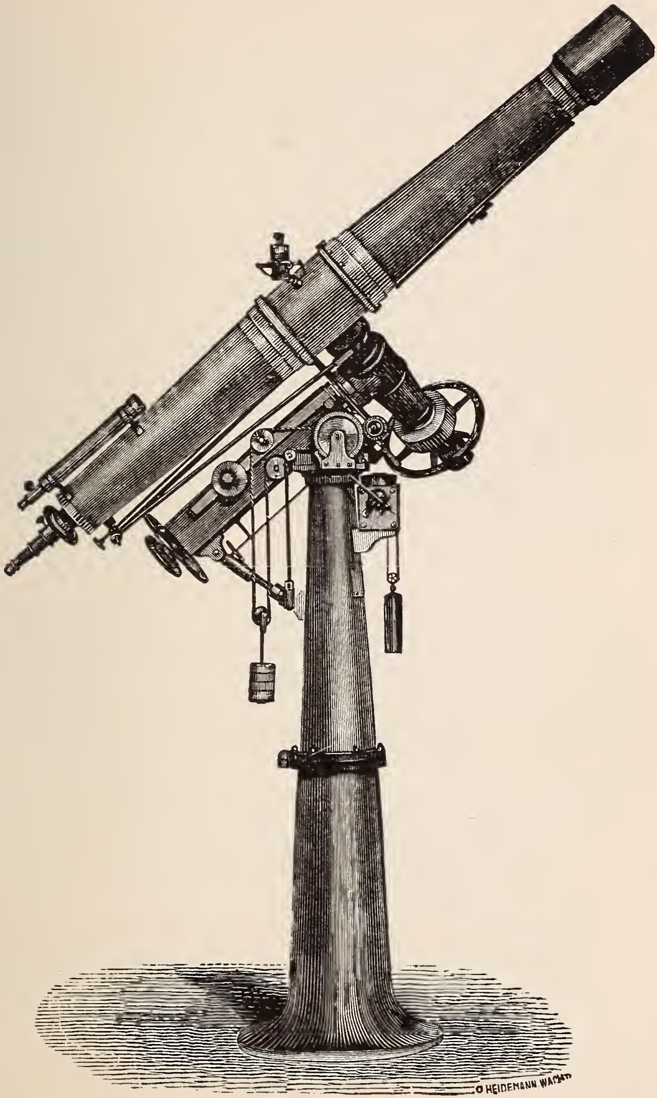

FIG. 26.

rotate the whole instrument as one mass about the polar axis until the telescope points to any portion of the parallel of declination defined by the given right ascension or hour-angle. Fig. 26 is an equatorial of six-inch aperture which can be moved from place to place.

If we point such a telescope to a star when it is rising (doing this by rotating the telescope first about its declination axis and then about the polar axis), and fix the telescope in this position, we can, by simply rotating the whole apparatus on the polar axis, cause the telescope to trace out on the celestial sphere the apparent diurnal path which this star will appear to follow from rising to setting. In such telescopes a driving-clock is so arranged that it can turn the telescope round the polar axis at the same rate at which the earth itself turns about its own axis of rotation, but in a contrary direction. Hence such a telescope once pointed at a star will continue to point at it as long as the driving-clock is in operation, thus enabling the astronomer to make such an examination or observation of it as is required.

The Sextant.

The sextant is a portable instrument by which the *altitudes* of celestial bodies or the *angular distances* between them may be measured. It is used chiefly by navigators for determining the latitude and the local time of the position of the ship. Knowing the local time, and comparing it with a chronometer regulated on Greenwich time, the longitude becomes known and the ship's place is fixed. (See page 52.)

It consists of an arc of a divided circle usually 60° in extent, whence the name. This arc is in fact divided into 120 equal parts, each marked as a degree, and these are again divided into smaller spaces, so that by means of the vernier at the end of the index-arm MS an arc of 10″ (usually) may be read.

The *index-arm* MS carries the *index-glass* M, which is a silvered plane mirror set perpendicular to the plane of the divided arc. The *horizon-glass* m is also a plane mirror fixed perpendicular to the plane of the divided circle.

This last glass is fixed in position, while the first revolves with the index-arm. The horizon-glass is divided into two parts, of which the lower one is silvered, the upper half being transparent. E is a telescope of low power pointed toward the horizon-glass. By it any object to which it is directly pointed can be seen through the *unsilvered* half of the horizon-glass. Any other object in the same plane can be brought into the same field by rotating the index-arm (and the index-glass with it), so that a beam of light from this second object shall strike the index-glass at the proper angle, there to be reflected to the horizon-glass, and again reflected down the telescope *E*. Thus the images of any two objects in the plane of the sextant may be brought together in the telescope by viewing one directly and the other by reflection.

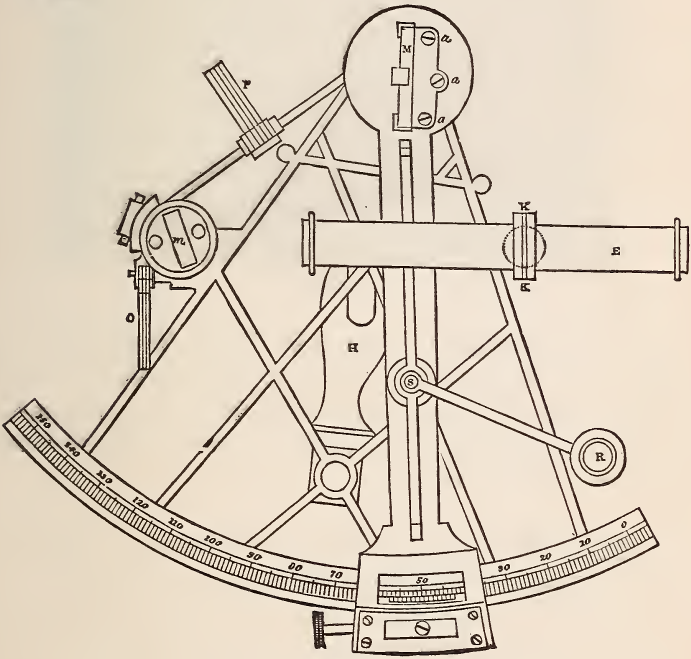

FIG. 27.

This instrument is used daily at sea to determine the ship's position by measuring the altitude of the sun. This is done by pointing the telescope, *EB*, to the sea-horizon, H in the figure, which appears like a line in the field of the telescope, and by moving the index-arm till the image of the sun, S, coincides with the horizon. The arc read from the sextant at this time is the sun's altitude. From the altitude of the sun on the meridian the ship's latitude is known (see page 52). From its altitude at another hour

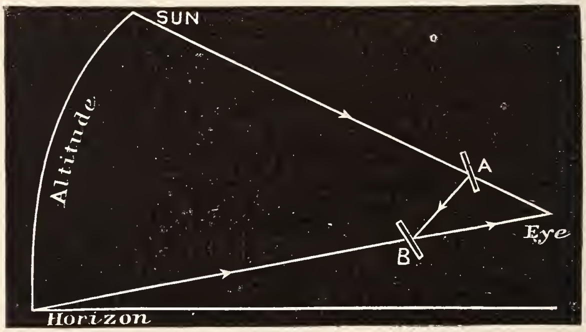

FIG. 28.

the local time can be computed. The difference between the local time and the Greenwich time, as shown by the ship's chronometer, gives the ship's longitude. By means of this simple instrument the place of a vessel can be found within a mile or so.

The above are the instruments of astronomy which best illustrate the principles of astronomical observations.

Practical Astronomy is the *science* which teaches the theory of these instruments and of their application to observation, and it includes the *art* of so combining the observations and so using the appliances as to get the best results.

The Astronomical Ephemeris, or Nautical Almanac.

The *Astronomical Ephemeris*, or, as it is more commonly called, the *Nautical Almanac*, is a work in which celestial phenomena and the positions of the heavenly bodies are computed in advance.

The usefulness of such a work, especially to the navigator, depends upon its regular appearance on a uniform plan and upon the fulness and accuracy of its data; it was therefore necessary that its issue should be taken up as a government work. An astronomical ephemeris or nautical almanac is now published annually by each of the governments of Germany, Spain, Portugal, France, Great Britain, and the United States. They are printed three years or more beforehand, in order that navigators going on long voyages may supply themselves in advance.

The Ephemeris furnishes the fundamental data from which all our household almanacs are calculated.

The principal quantities given in the American Ephemeris for each year are as follows:

The positions (R. A. and δ) of the sun and the principal large planets for Greenwich noon of every day in each year.

The right ascension and declination of the moon's centre for every Greenwich hour in the year.

The distance of the moon from certain bright stars and planets for every third Greenwich hour of the year.

The right ascensions and declinations of upward of two hundred of the brighter fixed stars, corrected for precession, nutation, and aberration, for every ten days.

The positions of the principal planets at every visible transit over the meridian of Washington.

Complete elements of all the eclipses of the sun and moon, with maps showing the passage of the moon's shadow or penumbra over those regions of the earth where the eclipses will be visible, and tables whereby the phases of the eclipses can be accurately computed for any place.

Tables for predicting the occultations of stars by the moon.

Eclipses of *Jupiter's* satellites and miscellaneous phenomena.

Catalogues of Stars.—Of the same general nature with the Ephemeris are catalogues of the fixed stars. The object of such a catalogue is to give the right ascension and declination of a number of stars for some epoch, the beginning of the year 1875 for instance, with the data by which the position of each star can be found at any other epoch.

To give the student a still further idea of the *Ephemeris*, we present a small portion of one of its pages for the year 1882:

FEBRUARY, 1882—AT GREENWICH MEAN NOON.

Day of the week.	Day of the month.	The Sun's Apparent right ascension.	The Sun's Diff. for 1 hour.	The Sun's Apparent declination.	The Sun's Diff. for 1 hour.	Equation of time to be subtracted from mean time.	Diff. for 1 hr.	Sidereal time or right ascension of mean sun.
		H. M. S.	S.	° ′ ″	″	M. S.	S.	H. M. S.
Wed.	1	21 0 13.04	10.175	S 17 2 22.4	+42.82	13 51.34	0.318	20 46 21.70
Thur.	2	21 4 16.84	10.141	16 45 5.4	43.57	13 58.58	0.284	20 50 18.26
Frid.	3	21 8 19.82	10.107	16 27 30.9	44.30	14 5.01	0.250	20 54 14.81
Sat.	4	21 12 21.98	10.073	16 9 39.2	+44.99	14 10.61	0.216	20 58 11.37
Sun.	5	21 16 23.33	10.040	15 51 30.8	45.69	14 15.41	0.183	21 2 7.92
Mon.	6	21 20 23.88	10.007	15 33 6.1	46.36	14 19.40	0.150	21 6 4.48
Tues.	7	21 24 23.63	9.974	15 14 25.4	+47.03	14 22.60	0.117	21 10 1.03
Wed.	8	21 28 22.60	9.941	14 55 29.1	47.66	14 25.01	0.084	21 13 57.59
Thur.	9	21 32 20.79	9.909	14 36 17.7	48.28	14 26.65	0.052	21 17 54.14
Frid.	10	21 36 18.21	9.877	14 16 51.6	48.88	14 27.51	0.020	21 21 50.70
Sat.	11	21 40 14.88	9.846	13 57 11.2	49.47	14 27.63	0.011	21 25 47.25
Sun.	12	21 44 10.80	9.815	13 37 16.9	50.03	14 26.99	0.042	21 29 43.81
Mon.	13	21 48 5.98	9.784	13 17 9.1	+50.59	14 25.63	0.073	21 33 40.35
Tues.	14	21 52 0.43	9.753	12 56 48 3	51.12	14 23.52	0.104	21 37 36.91
Wed.	15	21 55 54.16	9.723	12 36 14.9	51.65	14 20.70	0.134	21 41 33.46
Thur.	16	21 59 47.17	9.693	12 15 29.3	+52.14	14 17.15	0.164	21 45 30.02
Frid.	17	22 3 39.47	9.664	11 54 32.1	52.62	14 12.90	0.193	21 49 26.57
Sat.	18	22 7 31.07	9.635	11 33 23.6	53.07	14 7.94	0.222	21 53 23.13

The third column shows the R. A. of the sun's centre at Greenwich mean noon of each day. The fourth column shows the hourly change of this quantity (9.815 on Feb. 12). At Greenwich 0 hours the sun's R. A. was $21^h\ 44^m\ 10^s.80$. Washington is $5^h\ 8^m$ ($5^h.13$) west of Greenwich. At Washington mean noon, on the 12th, the Greenwich mean time was $5^h.13$. 9.815×5.13 is $50^s.35$. This is to be *added*, since the R. A. is increasing. The sun's R. A. at Washington mean noon is therefore $21^h\ 45^m\ 1^s.15$. A similar process will give the sun's declination for Washington mean noon. In the same manner, the R. A. and Dec. of the sun for *any* place whose longitude is known can be found.

The column "Equation of Time" gives the quantity to be subtracted from the Greenwich mean solar time to obtain the Greenwich apparent solar time (see page 188). Thus, for Feb. 1, the Greenwich mean time of Greenwich mean noon is $0^h\ 0^m\ 0^s$. The true sun crossed the Greenwich meridian (apparent noon) at $23^h\ 46^m\ 08^s.66$ on the preceding day; *i.e.*, Jan. 31.

When it was $0^h\ 0^m\ 0^s$ of Greenwich mean time on Feb. 13, it was also $21^h\ 33^m\ 40^s.35$ of Greenwich local sidereal time (see the last column of the table).

CHAPTER IV.

MOTION OF THE EARTH.

Ancient Ideas of the Planets.

It was observed by the ancients that while the great mass of the stars maintained their positions relatively to each other month after month and year after year, there were visible to them seven heavenly bodies which *changed* their positions relatively to the stars and to each other. These they called planets or wandering stars. It was found that the seven planets performed a very slow revolution around the celestial sphere from west to east, in periods ranging from one month in the case of the moon to thirty years in that of *Saturn.*

The idea of the fixed stars being set in a solid sphere was in perfect accord with their diurnal revolution as observed by the naked eye. But it was not so with the planets. The latter, after continued observation, were found to move sometimes backward and sometimes forward; and it was quite evident that at certain periods they were nearer the earth than at other periods. These motions were entirely inconsistent with the theory that they were fixed in solid spheres.

These planets (which are visible to the naked eye), together with the earth, and a number of other bodies which the telescope has made known to us, form a family or system by themselves, the dimensions of which, although inconceivably greater than any which we have to deal with at the surface of the earth, are quite insignificant when compared with the distance which separates us from the fixed stars. The sun being the great central body of this system, it is called the *Solar System.* There are eight large planets, of which the earth is the third in the order of distance from the sun, and these bodies all perform a regular revolution around the sun. *Mercury,* the nearest, performs its revolution in three months; *Neptune,* the farthest, in 164 years.

Annual Revolution of the Earth.

To an observer on the earth the sun seems to perform an annual revolution among the stars, a fact which has been known from early ages. This motion is due to the annual revolution of the earth round the sun.

In Fig. 29 let S represent the sun, $ABCD$ the orbit of the earth around it, and $EFGH$ the sphere of the fixed stars. This sphere, being supposed infinitely distant, must be considered as infinitely larger than the circle $ABCD$. Suppose now that 1, 2, 3, 4, 5, 6 are a number of consecutive positions of the earth in its orbit. The line $1S$ drawn from the sun to the earth in the first position is called the *radius-vector* of the earth. Suppose this line extended infinitely so as to meet the celestial sphere in the point $1'$. It is evident that to an observer on the earth at 1 the sun will appear projected on the sphere in the direction of $1'$; when the earth reaches 2 it will appear in the direction of $2'$, and so on. In other words, as the earth revolves around the sun, the latter will seem to perform a revolution among the fixed stars, which are immensely more distant than itself. The points $1'$, $2'$, etc., can be fixed by their relations to the various fixed stars, whose places are known.

It is also evident that the point in which the earth would be projected if viewed from the sun is always exactly opposite that in which the sun appears as projected from the earth. Moreover, if the earth moves more rapidly in

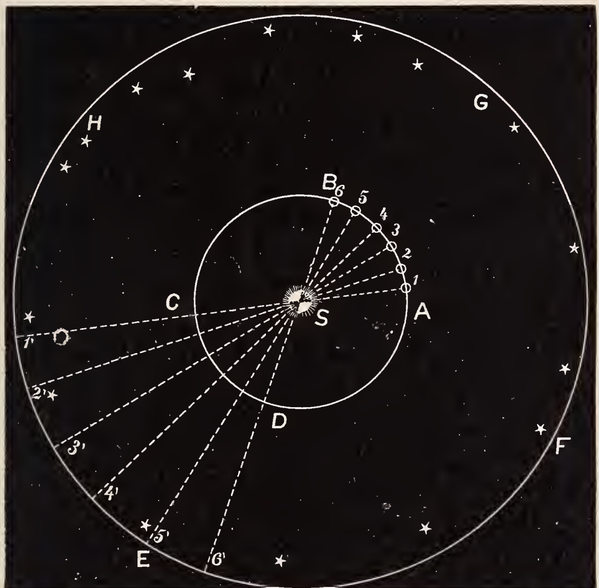

FIG. 29.—REVOLUTION OF THE EARTH.

some points of its orbit than in others, it is evident that the sun will also appear to move more rapidly among the stars, and that the two motions must always accurately correspond to each other.

The radius-vector of the earth in its annual course describes a plane, which in the figure may be represented by that of the paper. This plane continued to infinity in every direction will cut the celestial sphere in a great circle; and it is clear that the sun will always appear to move in this circle. The plane and the circle are indifferently termed *the ecliptic.* The plane of the ecliptic is generally taken as the fundamental one, to which the positions of all the bodies in the solar system are referred. It divides the celestial sphere into two equal parts. In thinking of the celestial motions, it is convenient to conceive of this plane as horizontal. Then if we draw a vertical line through the sun at right angles to this plane (perpendicular to the plane of the paper on which the figure is represented), the point at which this line intersects the celestial sphere will be the pole of the ecliptic.

Let us now study the apparent annual revolution of the sun produced by the real revolution of the earth in its *orbit.*

When the earth is at 1 in the figure the sun will appear to be at 1′, near some star, as drawn. Now by the *diurnal* motion of the earth the sun is made to rise, to culminate, and to set successively for each meridian on the globe. This star being near the sun rises, culminates, and sets with it; it is on the meridian of any place at the local noon of that place (and is therefore not visible except in a telescope). The star on the right-hand side of the figure near the line $CS1$ prolonged is nearly opposite to the sun. When the sun is rising at any place, that star will be setting; when the sun is on the meridian of the place, this star is on the lower meridian; when the sun is setting, this star is rising. It is about 180° from the sun. Now suppose the earth to move to 2. The sun will be seen at 2′, near the star there marked. 2′ is *east* of 1′; the sun appears to move *among the stars* (in consequence of the earth's *annual* motion) from west to east. The star near 2′ will rise, culminate, and set with the sun at every place on the earth. The star near 1′ being *west* of 2′ will rise *before* the sun, culminate before him, and set before he does.

If, for example, the star 1′ is near the equator when the sun is 15° east of it, the star will rise about 1 hour earlier than the sun. When the sun is 30° east of it (at 3′, for example), the star will rise 2 hours before the sun. When the sun is 90° east of 1′, the star will rise 6 hours before the sun, and so on. That is, when the sun is rising at any place, this star will be on the meridian of the place. When the sun appears in the line 1′*CS* 1 prolonged to the right in the figure, the star 1′ will be on the meridian at midnight, and is then said to be *in opposition* to the sun. It is 180° from it. When the sun appears to be near *H*, the star 1′ will be about 45° or 3 hours *east* of the sun. The sun will rise first to any place on the earth, and the star will rise 3 hours later, say at 9 A.M. Finally the sun will come back to the same star again and they will rise, culminate, and set together.

We know that this cycle is about 365 days in length. In this time the sun moves 360°, or about 1° daily. This cycle is perpetually repeated. Its length is *a sidereal year;* that is, the interval of time required for the sun to move in the sky from one star back to the same star again or for the earth to make one revolution in its orbit among the stars.

The ancients were familiar with this phenomenon. They knew most of the brighter stars by name. The *heliacal rising* of a bright star (its rising with *Helios*, the sun) marked the beginning of a cycle. At the end of it, seasons and crops and the periodical floods of the Nile had repeated themselves. It was in this way that the first accurate notions of the year arose.

The apparent position of a body as seen from the earth is called its *geocentric place.* The apparent position of a body as seen from the sun is called its *heliocentric place.*

In the last figure, suppose the sun to be at S, and the earth at 4. $4'$ is the *geocentric* place of the sun, and G is the *heliocentric* place of the earth.

THE SUN'S APPARENT PATH.

It is evident that if the apparent path of the sun lay in the equator, it would, during the entire year, rise exactly in the east and set in the west, and would always cross the meridian at the same altitude. The days would always be twelve hours long, for the same reason that a star in the equator is always twelve hours above the horizon and twelve hours below it. But we know that this is not the case, the sun being sometimes north of the equator and sometimes south of it, and therefore having a motion in declination. To understand this motion, suppose that on March 19th, 1879, the sun had been observed with a meridian circle and a sidereal clock at the moment of transit over the meridian of Washington. Its position would have been found to be this:

Right Ascension, $23^h\ 55^m\ 23^s$; Declination, $0°\ 30'$ south.

Had the observation been repeated on the 20th and following days, the results would have been:

March 20,	R. Ascen.	$23^h\ 59^m\ 2^s$;	Dec.	$0°\ 6'$ South.
21,	"	$0^h\ 2^m\ 40^s$;	"	$0°\ 17'$ North.
22,	"	$0^h\ 6^m\ 19^s$;	"	$0°\ 41'$ North.

If we lay these positions down on a chart, we shall find them to be as in Fig. 30, the centre of the sun being south of the equator in the first two positions, and north of it in the last two. Joining the successive positions by a line, we shall have a representation of a small portion of the apparent path of the sun on the celestial sphere, or of the ecliptic.

It is clear from the observations and the figure that the sun crossed the equator between six and seven o'clock on the afternoon of March 20th, and therefore that the equator and ecliptic intersect at the point where the sun was at that hour. This point is called the *vernal equinox*, the first word indicating the season, while the second expresses

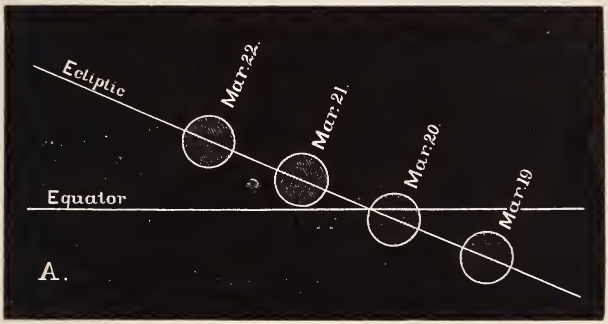

FIG. 30.—THE SUN CROSSING THE EQUATOR.

the equality of the nights and days which occurs when the sun is on the equator. It will be remembered that this equinox is the point from which right ascensions are counted in the heavens, in the same way that we count longitudes on the earth from Greenwich or Washington. A sidereal clock at any place is therefore so set that the hands shall read 0 hours 0 minutes 0 seconds at the moment when the vernal equinox crosses the meridian of the place.

Continuing our observations of the sun's apparent course for six months from March 20th till September 23d, we should find it to be as in Fig. 31. It will be seen that Fig. 30 corresponds to the right-hand end of 31, but is on a much larger scale. The sun, moving along the great circle of the ecliptic, will reach its greatest northern declination about June 21st. This point is indicated on the figure as 90° from the vernal equinox, and is called the *summer solstice.* The sun's right ascension is then six hours, and its declination $23\frac{1}{2}°$ north. The student should complete the figure by drawing the half not given here.

Fig. 31.—The Sun's Apparent Path in Summer.

The course of the sun now inclines toward the south, and it again crosses the equator about September 22d at a point diametrically opposite the vernal equinox. All great circles intersect each other in two opposite points, and the ecliptic and equator intersect at the two opposite equinoxes. The equinox which the sun crosses on September 22d is called the *autumnal equinox.*

During the six months from September to March the sun's course is a counterpart of that from March to September, except that it lies south of the equator. It attains its greatest south declination about December 22d, in right ascension 18 hours and south declination 23° 30′. This point is called the *winter solstice.* It then begins to incline its course toward the north, reaching the vernal equinox again on March 20th, 1880.

The two equinoxes and the two solstices may be regarded as the four cardinal points of the sun's apparent annual circuit around the heavens. Its passage through these points is determined by measuring its altitude or declination from day to day with a meridian circle. Since in our latitude greater altitudes correspond to greater declinations, it follows that the summer solstice occurs on the day when the altitude of the sun is greatest, and the winter solstice on that when it is least. The mean of these altitudes is that of the equator, and may therefore be found by subtracting the latitude of the place from 90°. The time when the sun reaches this altitude going north, marks the vernal equinox, and that when it reaches it going south marks the autumnal equinox.

These passages of the sun through the cardinal points have been the subjects of astronomical observation from the earliest ages on account of their relations to the change of the seasons. An ingenious method of finding the time when the sun reached the equinoxes was used by the astronomers of Alexandria about the beginning of our era. In the great Alexandrian Museum, a large ring or wheel was set up parallel to the plane of the equator; in other words, it was so fixed that a star at the pole would shine perpendicularly on the wheel. Evidently its plane if extended must have passed through the east and west points of the horizon, while its inclination to the vertical was equal to the latitude of the place, which was not far from 30°. When the sun reached the equator going north or south, and shone upon this wheel, its lower edge would be exactly covered by the shadow of the upper edge; whereas in any other position the sun would shine upon the lower inner edge. Thus the time at which the sun reached the equinox could be determined, at least to a fraction of a day. By the more exact methods of modern times it can be determined within less than a minute.

It will be seen that this method of determining the annual apparent course of the sun by its declination or altitude is entirely independent of its relation to the fixed stars; and it could be equally well applied if no stars were ever visible. There are, therefore, two entirely distinct ways of finding when the sun or the earth has completed its apparent circuit around the celestial sphere; the one by the transit instrument and sidereal clock, which show when the sun returns to the *same position among the stars*, the other by the measurement of altitude, which shows when it returns to the *same equinox*. By the former method, already described, we conclude that it has completed an annual circuit when it returns to the same star; by the latter when it returns to the same equinox. These two methods will give slightly different results for the length of the year, for a reason to be hereafter described.

The Zodiac and its Divisions.—The zodiac is a belt in the heavens, commonly considered as extending some 8° on each side of the ecliptic, and therefore about 16° wide. The planets known to the ancients are always seen within this belt. At a very early day the zodiac was mapped out into twelve signs known as the *signs of the zodiac*, the names of which have been handed down to the present time. Each of these signs was supposed to be the seat of a constellation after which it was called. Commencing at the vernal equinox, the first thirty degrees through which the sun passed, or the region among the stars in which it was found during the month following, was called the sign *Aries*. The next thirty degrees was called *Taurus*. The names of all the twelve signs in their proper order, with the approximate time of the sun's entering upon each, are as follows:

Aries, the Ram,	March 20.
Taurus, the Bull,	April 20.
Gemini, the Twins,	May 20.
Cancer, the Crab,	June 21.
Leo, the Lion,	July 22.
Virgo, the Virgin,	August 22.
Libra, the Balance,	September 22.
Scorpius, the Scorpion,	October 23.
Sagittarius, the Archer,	November 23.
Capricornus, the Goat,	December 21.
Aquarius, the Water-bearer,	January 20.
Pisces, the Fishes,	February 19.

Each of these signs coincides roughly with a constellation in the heavens; and thus there are twelve constellations called by the names of these signs, but the signs and the constellations no longer correspond. Although the sun now crosses the equator and enters the *sign* Aries on the 20th of March, he does not reach the *constellation* Aries until nearly a month later. This arises from the precession of the equinoxes, to be explained hereafter.

Obliquity of the Ecliptic.

We have already stated that when the sun is at the summer solstice it is about $23\frac{1}{2}°$ north of the equator, and when at the winter solstice, about $23\frac{1}{2}°$ south. This shows that the ecliptic and equator make an angle of about $23\frac{1}{2}°$ with each other. This angle is called the obliquity of the ecliptic, and its determination is very simple. It is only necessary to find by repeated observation the sun's greatest north declination at the summer solstice, and its greatest south declination at the winter solstice. Either of these declinations, which must be equal if the observations are accurately made, will give the obliquity of the ecliptic. It has been continually diminishing from the earliest ages at a rate of about half a second a year, or, more exactly, about 47″ in a century. This diminution is due to the gravitating forces of the planets, and will continue for several thousand years to come. It will not, however, go on indefinitely, but the obliquity will only oscillate between comparatively narrow limits.

In the preceding paragraphs we have explained the apparent annual circuit of the sun relative to the equator, and shown how the seasons depend upon this circuit. In order that the student may clearly grasp the entire subject, it is necessary to show the relation of these apparent movements to the actual movement of the earth around the sun.

To understand the relation of the equator to the ecliptic, we must remember that the celestial pole and the celestial equator have really no reference whatever to the heavens, but depend solely on the direction of the earth's axis of rotation. The pole of the heavens is nothing more than that point of the celestial sphere toward which the earth's axis happens to point. If the direction of this axis changes, the position of the celestial pole among the stars will change also; though to an observer on the earth, unconscious of the change, it would seem as if the starry sphere moved while the pole remained at rest. Again, the celestial equator being merely the great circle in which the plane of the earth's equator, extended out to infinity in every direction, cuts the celestial sphere, any change in the direction of the pole of the earth would necessarily change the position of the equator among the stars. Now the positions of the celestial pole and the celestial equator among the stars seem to remain unchanged throughout the year. (There is, indeed, a minute change, but it does not affect our present reasoning.) This shows that, as the earth revolves around the sun, its axis is constantly directed toward nearly the same point of the celestial sphere.

The Seasons.

The conclusions to which we are thus led respecting the real revolution of the earth are shown in Fig. 32. Here S represents the sun, with the orbit of the earth surrounding it, but viewed nearly edgeways so as to be much foreshortened. A B C D are the four cardinal positions of the earth which correspond to the cardinal points of the apparent path of the sun already described. In each figure of the earth NS is the axis, N being its north and S its south pole. Since this axis points in the same direction relative to the stars during an entire year, it follows that the different lines NS are all parallel. Again, since the equator does not coincide with the ecliptic, these lines are not perpendicular to the ecliptic, but are inclined from this perpendicular by $23\frac{1}{2}°$.

When the earth is at A the sun's north-polar distance (the angle at the centre of the earth at *A* between the lines to the north pole and to the sun) is $113\frac{1}{2}°$; at *B* it is 90°; at *C* it is $66\frac{1}{2}°$; at *D* it is again 90°, and between $66\frac{1}{2}$ and $113\frac{1}{2}°$ the north-polar distance continually varies. This may be plainer if the student draws the lines *SA*, *SB*, *SC*, *SD*, and prolongs the lines *NS* at each position of the earth.

Now the sun shines on only one half of the earth; *viz.*, that hemisphere turned toward him. This hemisphere is left bright in each of the figures of the earth at *A*, *B*, *C*, *D*.

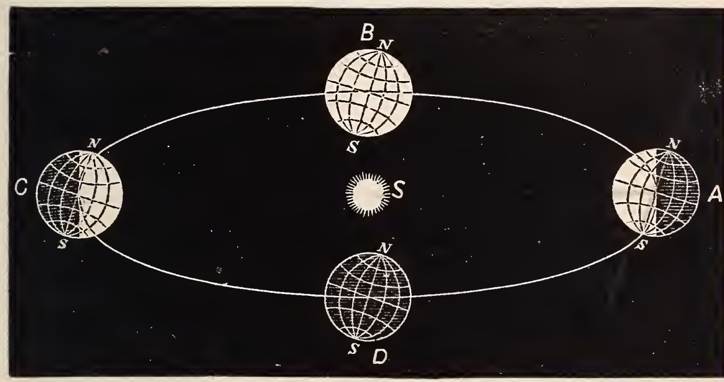

FIG. 32.—CAUSES OF THE SEASONS.

Consider the diagram at *A*, and remember that the earth is turning round so that every observer is carried round his parallel of latitude every 24 hours. The parallels are drawn in the cut, and it is plain that a person near *N* will remain in darkness all the 24 hours; any one in the northern hemisphere is *less* than half the time in the light—that is, the sun is less than half the time above his horizon—and a person in the southern hemisphere is *more* than half the time in the light. At the equator the days and nights are always equal. At the south pole it is perpetual day. The spectator near the south pole is carried round in a parallel of latitude which is perpetually shined upon. This is the *winter* solstice (midwinter in the northern hemisphere, midsummer in the southern).

Next suppose the earth at B: B is 90° from A; that is, 3 months later. The sun's rays just graze the north and south poles; each parallel of latitude is half light and half dark; the days and nights are equal. This is the equinox of spring—the vernal equinox. The sun's north-polar distance is 90°. At C we have the *summer solstice* (summer in the northern hemisphere, winter in the southern). Here is perpetual day at the north pole, perpetual night at the south; long days to all the northern hemisphere, long nights in the southern. Three months later we have the *autumnal equinox* at D.

This change of the seasons depends upon the change of the sun's north-polar distance.

The exact phenomena at each place may be studied by constructing a diagram for the latitude of that place (see page 42) and assuming the sun's north-polar distance as follows:

March 21,	N.P.D.	90°,	Vernal Equinox.
June 20,	N.P.D.	66½,	Summer Solstice.
September 21,	N.P.D.	90,	Autumnal Equinox.
December 21,	N.P.D.	113½,	Winter Solstice.

Two such diagrams are given in the text-book (page 28).

The student should be able to prove that the sun is always in the zenith of some place in the torrid zone.

Celestial Latitude and Longitude.

To describe the positions of the sun and planets in space we need two new co-ordinates.

The *Celestial Latitude* of a star is its angular distance north or south of the *ecliptic.*

The *Celestial Longitude* of a star is its angular distance from the vernal equinox measured on the *ecliptic* from west to east. Having the right ascension and declination of a body (which can be had by observation), we can compute its celestial latitude and longitude. These co-ordinates are no longer *observed* (as they were by the ancients), but deduced from observations of right ascension and declination.

CHAPTER V.

THE PLANETARY MOTIONS.

Apparent and Real Motions of the Planets.

Definitions.—The solar system comprises a number of bodies of various orders of magnitude and distance, subjected to many complex motions. Our attention will be particularly directed to the motions of the great planets. These bodies may, with respect to their apparent motions, be divided into three classes.

Speaking, for the present, of the sun as a planet, the first class comprises the *sun* and *moon*. We have seen that if, upon a star chart, we mark down the positions of the sun day by day, they will all fall into a regular circle which marks out the ecliptic. The monthly course of the moon is found to be of the same nature; and although its motion is by no means uniform in a month, it is always toward the east, and always along or very near a certain great circle.

The second class comprises *Venus* and *Mercury*. The apparent motion of these bodies is an oscillating one on each side of the sun. If we watch for the appearance of one of these planets after sunset from evening to evening, we shall find it to appear above the western horizon. Night after night it will be farther and farther from the sun until it attains a certain maximum distance; then it will appear to return towards the sun again, and for a while to be lost in its rays. A few days later it will reappear to the west of the sun, and thereafter be visible in the eastern horizon before sunrise. In the case of *Mercury* the time required for one complete oscillation back and forth is about four months; and in the case of *Venus* it is more than a year and a half.

The third class comprises *Mars, Jupiter,* and *Saturn,* as well as a great number of planets not visible to the naked eye. The general or average motion of these planets is toward the east, a complete revolution in the celestial sphere being performed in times ranging from two years in the case of *Mars* to 164 years in that of *Neptune.* But, instead of moving uniformly forward, they seem to have a swinging motion; first, they move forward or toward the east through a pretty long arc, then backward or westward through a short one, then forward through a longer one, etc. It is by the excess of the longer arcs over the shorter ones that the circuit of the heavens is made.

The general motion of the sun, moon, and planets among the stars being toward the east, motion in this direction is called *direct;* motions toward the west are called *retrograde.* During the periods between direct and retrograde motion the planets will for a short time appear stationary.

The planets *Venus* and *Mercury* are said to be at greatest *elongation* when at their greatest angular distance from the sun. The elongation which occurs with the planet east of the sun, and therefore visible in the western horizon after sunset, is called the eastern elongation, the other the western one.

A planet is said to be in *conjunction* with the sun when it is in the same direction as seen from the earth, or when, as it seems to pass by the sun, it approaches nearest to it.

It is said to be in *opposition* to the sun when exactly in the opposite direction—rising when the sun sets, and *vice versa.** If, when a planet is in conjunction, it is between the earth and the sun, the conjunction is said to be an *inferior* one; if beyond the sun, it is said to be *superior.*

FIG. 33.—ORBITS OF THE PLANETS.

Arrangements and Motions of the Planets.—The sun is the real centre of the solar system, and the planets proper revolve around it as the centre of motion. The order of the five innermost large planets, or the relative position of

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* A planet is in conjunction with the sun when it has the same geocentric longitude; in opposition when the longitudes differ 180°.

their orbits, is shown in Fig. 33. These orbits are all nearly, but not exactly, in the same plane. The planets *Mercury* and *Venus* which, as seen from the earth, never appear to recede very far from the sun, are in reality those which revolve inside the orbit of the earth. The planets of the third class, which perform their circuits at all distances from the sun, are what we call the superior planets, and are more distant from the sun than the earth is. Of these the orbits of *Mars, Jupiter,* and a swarm of telescopic planets are shown in the figure; next outside of *Jupiter* comes *Saturn,* the farthest planet readily visible to the naked eye, and then *Uranus* and *Neptune,* telescopic planets. On the scale of Fig. 33 the orbit of *Neptune* would be more than two feet in diameter. Finally, the moon is a small planet revolving around the earth as its centre, and carried with the latter as it moves around the sun.

Inferior planets are those whose orbits lie inside that of the earth, as *Mercury* and *Venus.*

Superior planets are those whose orbits lie outside that of the earth, as *Mars, Jupiter, Saturn,* etc.

The farther a planet is situated from the sun the slower is its orbital motion. Therefore, as we go from the sun, the periods of revolution are longer, for the double reason that the planet has a larger orbit to describe and moves more slowly in its orbit. It is to this slower motion of the outer planets that the occasional apparent retrograde motion of the planets is due, as may be seen by studying Fig. 34. The apparent position of a planet, as seen from the earth, is determined by the line joining the earth and planet. Supposing this line to be continued so as to intersect the celestial sphere, the apparent motion of the planet will be defined by the motion of the point in which the line intersects the sphere. If this motion is toward the east, it is direct; if toward the west, retrograde.

The Apparent Motion of a Superior Planet.—In the figure let *S* be the sun, *ABCDEF* the orbit of the earth, and *HIKLMN* the orbit of a superior planet, as *Mars*. When the earth is at *A* suppose *Mars* to be at *H*, and let *B* and *I*, *C* and *K*, *D* and *L*, *E* and *M*, *F* and *N* be corresponding positions. As the earth moves faster than *Mars*

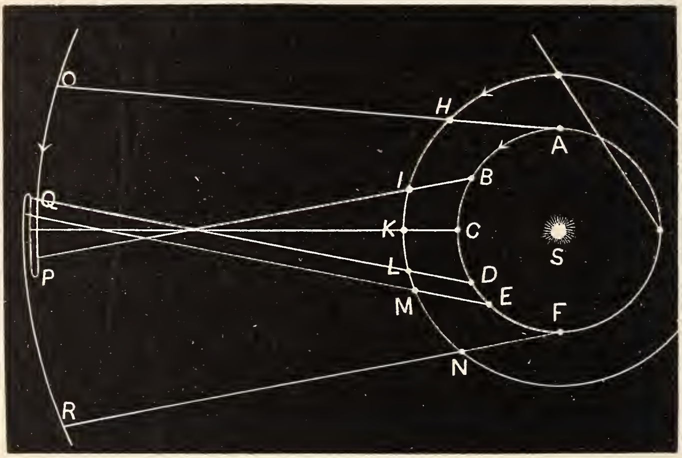

FIG. 34.

the arcs *AB*, *BC*, etc., correspond to greater angles at the centre than *H I*, *I K*, etc.

When the earth is at *A*, *Mars* will be seen on the celestial sphere at the apparent position *O*. When the earth is at *B*, *Mars* will be seen at *P*. As the earth describes *AB*, *Mars* will appear to describe *OP* moving in the same direction as the earth's orbital motion; *i.e.*, *direct*. When the earth is at *C*, *Mars* is at *K* (in opposition to the sun), and its motion is *retrograde* along the small arc beyond *QP* in the figure. When the earth reaches D the planet has finished its retrograde arc. As the earth moves from D to E the planet moves from L to M, and the lines joining earth and planet are parallel and correspond to a fixed position on the celestial sphere. The planet is at *a station*. As the earth moves from E to F the apparent motion of *Mars* is direct from Q to R; and in the same way the apparent motion of any outer planet can be determined by drawing its orbit outside of the earth's orbit $ABCDEF$ and laying off on this orbit positions which correspond to the points $ABCDEF$ and joining the corresponding positions. It will be found that all outer planets have a retrograde motion at opposition, etc.

The Apparent Motion of an Inferior Planet.—To determine the corresponding phenomena for an inferior planet the same figure may be used. Suppose $HIKLM$ to be the orbit of the *earth*, and $ABCDEF$ the orbit of *Mercury*, and suppose H and A, I and B, etc., to be corresponding positions. Suppose HA to be tangent to *Mercury's* orbit. The angle AHS is the elongation of *Mercury*, and it is the greatest elongation it can ever have.

Let the student construct the apparent positions of *Mercury* as seen from the earth from the data given in the figure. From the apparent positions he can determine the apparent motions. As *Mercury* moves from AB its apparent motion is direct. On both sides of the inferior conjunction C its motion is retrograde. From D to E it is stationary. Also let him construct the apparent positions of the sun at different times by drawing the lines HS, IS, KS, etc., towards the right. The angles between the apparent positions of *Mercury* and the sun will be the elongations of *Mercury* at various times.

Theory of Epicycles.—Complicated as the apparent motions of the planets were, it was seen by the ancient astronomers that they could be represented by a combination of two motions. First, a small circle or epicycle was supposed to move *around the earth* (not the sun) with a regular, though not uniform, forward motion, and then the planet was supposed to move around the circumference of this circle. The relation of this theory to the true one was this: The regular forward motion of the epicycle represents the real motion of the planet around the sun, while the motion of the planet around the circumference of the epicycle is an apparent one arising from the revolution of the earth around the sun. To explain this we must understand some of the laws of relative motion.

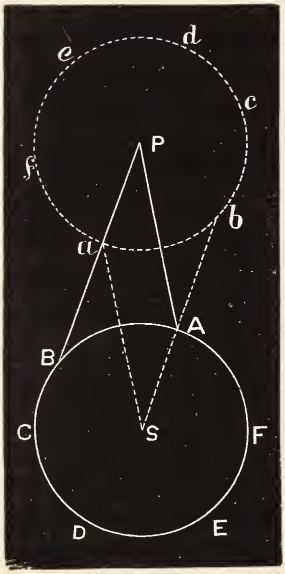

Fig. 35.

It is familiarly known that if an observer in unconscious motion looks upon an object at rest, the object will appear to him to move in a direction opposite that in which he moves. As a result of this law, if the observer is unconsciously describing a circle, an object at rest will appear to him to describe a circle of equal size. This is shown by the following figure. Let S represent the sun, and $A\,B\,C\,D\,E\,F$ the orbit of the earth. Let us suppose the observer on the earth carried around in this orbit, but imagining himself at rest at S, the centre of motion. Suppose he keeps observing the direction and distance of the planet P, which for the present we suppose to be at rest, since it is only the relative motion that we shall have to consider. When the observer is at A he really sees the planet in a direction and distance $A\,P$, but imagining himself at S he thinks he see the planet at the point a determined by drawing a line $S\,a$ parallel and equal to $A\,P$. As he passes from A to B the planet will seem to him to move in the opposite direction from a to b, the point b being determined by drawing $S\,b$ equal and parallel to $B\,P$. As he recedes from the planet through the arc $B\,C\,D$, the planet seems to recede from him through $b\,c\,d$; and while he moves from left to right through DE the planet seems to move from right to left through *de*. Finally, as he approaches the planet through the arc *efa* the planet seems to approach him through EFA, and when he returns to A the planet will appear at A, as in the beginning. Thus the planet, though really at rest, would seem to him to move over the circle *abcdef* corresponding to that in which the observer himself was carried around the sun.

The planet being really in motion, it is evident that the combined effect of the real motion of the planet and the apparent motion around the circle *abcdef* will be represented by carrying the centre of this circle P along the true orbit of the planet. The motion of the earth being more rapid than that of an outer planet, it follows that the apparent motion of the planet through *ab* is more rapid than the real motion of P along the orbit. Hence in this part of the orbit the movement of the planet will be retrograde. In every other part it will be direct, because the progressive motion of P will at least overcome, sometimes be added to, the apparent motion around the circle.

In the ancient astronomy the apparent small circle *abcdef* was called the *epicycle.*

In the case of the inner planets *Mercury* and *Venus* the relation of the epicycle to the true orbit is reversed. Here the epicyclic motion is that of the planet round its real orbit; that is, the true orbit of the planet around the sun was itself taken for the epicycle, while the forward motion was really due to the apparent revolution of the sun produced by the annual motion of the earth.

By constructing a figure for this case the student can readily see how this comes about.

Although the observations of two thousand years ago could be tolerably well explained by these epicycles, yet with every increase of accuracy in observation new complications had to be introduced, until at the time of COPERNICUS (1542) the confusion was very great.

The Copernican System of the World.—COPERNICUS revived a belief taught by some of the ancients that the sun was the centre of the system, and that the earth and planets moved about him in circular orbits. While this was a step, and a great step, forward, purely *circular* orbits for the planets would not explain all the facts.

From the time of COPERNICUS (1542) till that of KEPLER and GALILEO (1600 to 1630) the whole question of the true system of the universe was in debate. The circular orbits introduced by COPERNICUS also required a complex system of epicycles to account for some of the observed motions of the planets, and with every increase in accuracy of observation new devices had to be introduced into the system to account for the new phenomena observed. In short, the system of COPERNICUS accounted for so many facts (as the stations and retrogradations of the planets) that it could not be rejected, and had so many difficulties that without modification it could not be accepted.

KEPLER'S LAWS OF PLANETARY MOTION.

Kepler and Galileo.—KEPLER (born 1571, d. 1630) was a genius of the first order. He had a thorough acquaintance with the old systems of astronomy and a thorough belief in the essential accuracy of the Copernican system, whose fundamental theorem was that the sun and not the earth was the centre of our system. He lived at the same time with GALILEO, who was the first person to observe the heavenly bodies with a telescope of his own invention, and he had the benefit of accurate observations of the planets made by TYCHO BRAHE. The opportunity for determining the true laws of the motions of the planets existed then as it never had before; and fortunately he was able, through labors of which it is difficult to form an idea to-day, to reach a true solution.

The Periodic Time of a Planet.—The time of revolution of a planet in its orbit round the sun (its *periodic time*) can be learned by continuous observations of the planet's course among the stars.

From ancient times the geocentric positions of the planets had been observed. These positions were referred to the places of the brightest fixed stars, and the relative places of these stars had been fixed with a tolerable accuracy. The time required for a planet to move from one star to the same star again was the time of revolution of the planet referred to the earth.

The real motion of the earth was known from observations of the apparent motion of the sun. By calculation it was possible to refer the motions *as observed* (*i.e.*, with reference to the earth) to the real motions (*i.e.*, those about the sun).

It was thus found that the periodic times of the known planets were:

For *Mercury*	about	88	days.
Venus	"	225	"
Earth	"	365	"
Mars	"	687	"
Jupiter	"	4333	"
Saturn	"	10,759	"

These values were known to the predecessors of Copernicus. He also showed (what is evident when we examine Fig. 34) that to an observer on the sun the motions of the planets would be always direct, and that no *stations* or *retrogradations* of the planets would be seen from the sun.

In Fig. 36 let S be the sun, E the earth, and M a planet. Suppose the lines SE and SM drawn. They will meet the celestial sphere at points whose positions with reference to the fixed stars could be ascertained by observation. The relative positions of these fixed stars were also known by previous observations. The angle $E'SE''$ was thus known since it was determined by the angular distance of the stars supposed to be at E' and E''. The angle MES was known, since it could be directly measured (the *elongation* of M from the sun). Hence the other angle of the triangle MSE was known, since it was 180° less the sum of $E'SE''$ and SEM. Therefore a triangle could be *constructed* which should have the same shape as MES. In such a triangle SM would represent the distance of the

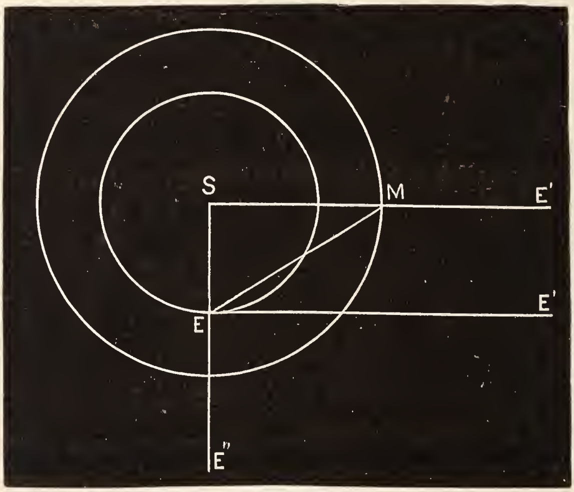

FIG. 36.

planet from the sun, and SE the distance of the earth. The ratio $\frac{SM}{SE}$ could then be determined. Nothing was known, from this calculation, of the *absolute value* of SE or SM in miles, but observations of this sort on all the planets gave the value of their distances from the sun in terms of the distance of the earth from the sun. It is often convenient to call the distance SE unity; and if SE be taken as the *astronomical unit*, it has been found that

For *Mercury*	a_1	$= 0.3871$
Venus	a_2	$= 0.7233$
Earth	a_3	$= 1.0000$
Mars	a_4	$= 1.5237$
Jupiter	a_5	$= 5.2028$
Saturn	a_6	$= 9.5388$

The calculation which we have described could be made for every position of each planet, and thus its distances from the sun at every point of its orbit could be determined.

The radius-vector of a planet is the line which joins it to the sun.

The relative lengths of the radii-vectores of each planet at any time were thus found by observation, in terms of the earth's radius-vector = 1.

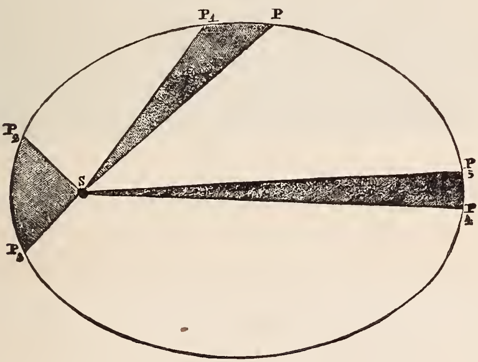

FIG. 37.

Suppose S to be the sun, and draw lines SP, SP_1, SP_2, SP_3, etc., to the heliocentric positions of a planet at different times. On these lines lay off distances SP, SP_1, SP_2, etc., proportional to the lengths of the planet's radii-vectores determined as above. Join the points P, P_1, P_2, P_3, etc. The line joining these is a visible representation of the shape of the planet's orbit, drawn to scale. This shape is not that of a circle, but it is *an ellipse,* and the sun, S, is not at the centre but at *a focus* of the ellipse.

An ellipse is a curve such that the sum of the distances of every point of the curve from two fixed points (the foci) is a constant quantity.

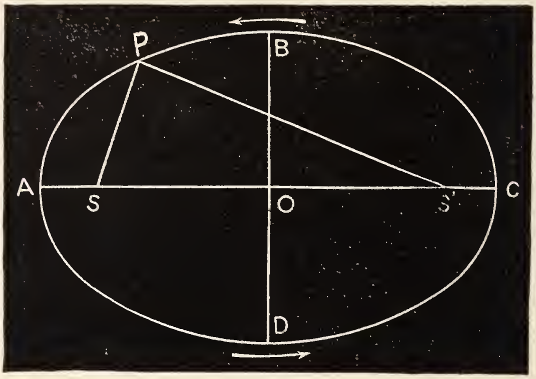

FIG. 38.

The Ellipse.—$ADCP$ is an ellipse; S and S' are the foci. By the definition of an ellipse $SP + PS' = AC$, and this is true for every point. S is the focus occupied by the sun, "the filled focus." AS is the *least distance* of the planet from the sun, its *perihelion distance;* and A is the *perihelion,* that point nearest the sun. C is the *aphelion,* the point farthest from the sun. SA, SD, SC, SB, SP are radii-vectores at different parts of the orbit. AC is the major axis of the orbit $= 2a$. This major axis of the orbit is twice the *mean distance* of the planet from the sun, a. BD is the minor axis, $2b$. The ratio of OS to OA is the *eccentricity* of the ellipse. By the definition of the ellipse, again, $BS + BS' = AC$; and $BS = BS' = a$. $\overline{BS}^2 = \overline{BO}^2 + \overline{OS}^2$, or $OS = \sqrt{a^2 - b^2}$ and the eccentricity of the ellipse is $\frac{OS}{OA} = \frac{\sqrt{a^2 - b^2}}{a}$.

Kepler's Laws.—By computations based on the observations of *Mars* made by TYCHO BRAHE, KEPLER deduced his first two laws of motion in the solar system. The first law of KEPLER is—

I. Each planet moves around the sun in an ellipse, having the sun at one of its foci. To understand Law II:

Suppose the planet to be at the points P, P_1, P_2, P_3, P_4, etc., at the times T, T_1, T_2, T_3, T_4, etc. (Fig. 37).

Suppose the *times* $T_1 - T$, $T_3 - T_2$, $T_5 - T_4$ to be equal. KEPLER computed the areas of the surfaces $P\,S\,P_1$, $P_2\,S\,P_3$, $P_4\,S\,P_5$ and found that these areas were equal also, and that this was true for each planet. The second law of KEPLER is—

II. The radius-vector of each planet describes equal areas in equal times.

These two laws are true for each planet moving in its own ellipse about the sun.

For a long time KEPLER sought for some law which should connect the motion of one planet in *its* ellipse with the motion of another planet in *its* ellipse. Finally he found such a relation between the mean distances of the different planets (see table on page 107) and their periodic times (see table on p. 105).

His third law is:

III. The squares of the periodic times of the planets are proportional to the cubes of their mean distances from the sun.

That is, if T_1, T_2, T_3, etc., are the periodic times of the different planets whose mean distances are a_1, a_2, a_3, etc., then

$$T_1^2 : T_2^2 = a_1^3 : a_2^3;$$
$$T_2^2 : T_3^2 = a_2^3 : a_3^3;$$
$$\text{etc.} \qquad \text{etc.}$$

If T_3 and a_3 are the periodic time and the mean distance of the earth, and if T_3 (= 1 year) is taken as the unit of time and a_3 as the unit of distance, then we shall have

$$T_1^2 : 1 = a_1^3 : 1 \text{ or } \frac{T_1^2}{a_1^3} = 1 \text{ or } \frac{T_1}{a_1^{\frac{3}{2}}} = 1;$$

$$T_2^2 : 1 = a_2^3 : 1 \text{ or } \frac{T_2^2}{a_2^3} = 1 \text{ or } \frac{T_2}{a_2^{\frac{3}{2}}} = 1;$$

and so on.

The data which KEPLER had were not quite so accurate as those which we have given, and the table below shows the very figures on which KEPLER'S conclusion was based:

PLANET.	$a^{\frac{3}{2}}$	T	$T \div a^{\frac{3}{2}}$
Mercury..............	0.2378	0.2408 years	1.013
Venus................	0.6104	0.6151	1.008
Earth................	1.0000	1.0000	1.000
Mars.................	1.8740	1.8810	1.004
Jupiter..............	11.914	11.8764	0.996
Saturn...............	28.058	29.4605	1.050

Although the numbers in the third column were not strictly the same, their differences were no greater than might easily have been produced by the errors of the observations which KEPLER used; and on the evidence here given he advanced his third law. The order of discovery of the true theory of the solar system was, then—

I. To prove that the earth moved in space;

II. To prove that the centre of this motion was the sun;

III. To establish the three laws of KEPLER, which gave the circumstances of this motion.

By means of the first two laws of KEPLER the motions of each planet in its own ellipse became known; that is, the position of the planet at any future time could be predicted. For example, if the planet was at P at a time T, and the question was as to its place at a subsequent time T', this could be solved by computing, first, how large an *area* would be described by the radius-vector in the interval $T' - T$; and second, what the angle at S of the sector having this area would be. Then drawing a line through S making this angle with the line SP (say $SP_{\prime\prime}$), and laying off the length of the radius-vector $SP_{\prime\prime}$, the position of the planet became known.

From the third law the *relative* values of the mean distances a_1, a_2, a_4, a_5, etc., could be determined with great and increasing accuracy.

From the equation $\frac{T}{a^2} = 1$, a could be determined so soon as T was known. With each revolution of the planet T became known more accurately, as did also a.

These laws are the foundations of our present theory of the solar system. They were based on observation pure and simple. We may anticipate a little to say that these laws have been compared with the most precise observations we can make at the present time, and discussed in all their consequences by processes unknown to KEPLER, and that they are strictly true if we make the following modifications.

If there were only one planet revolving about the sun, then it would revolve in a perfect ellipse, and obey the second law exactly. In a system composed of the sun and more than one planet each planet disturbs the motion of every other slightly, by attracting it from the orbit which it would otherwise follow.

Thus neither the first nor the second law can be precisely true of any planet, although they are very nearly so. In the same way the relation between the orbits of any two planets as expressed in the third law is not *precise*, although it is a very close approximation.

Elements of a Planet's Orbit.—When we know a and b for any orbit, the shape and size of the orbit is known.

Knowing a we also know T, the periodic time; in fact a is found from T by KEPLER'S law III.

If we know the planet's celestial longitude (L) at a given epoch, say December 31st, 1850, we have all the *elements* necessary for finding the place of the planet *in its orbit* at any time, as has been explained (page 110).

The orbit lies in a certain plane; this plane intersects the plane of the ecliptic at a certain angle, which we call the *inclination* i. Knowing i, the plane of the planet's orbit is fixed. The plane of the orbit intersects the plane of the ecliptic in a line, the *line of the nodes.* Half of the planet's orbit lies below (south of) the plane of the ecliptic and half above. As the planet moves in its orbit it must pass through the plane of the ecliptic twice for every revolution.

The point where it passes through the ecliptic going from the south half to the north half of its orbit is the *ascending node;* the point where it passes through the ecliptic going from north to south is the *descending node* of the planet's orbit. If we have only the *inclination* given, the orbit of the planet may lie anywhere in the plane whose angle with the ecliptic is i. If we fix the place of the nodes, or of one of them, the orbit is thus fixed in its plane. This we do by giving the (celestial) longitude of the ascending node Ω.

Now everything is known except the relation of the planet's orbit to the sun. This is fixed by the *longitude of the perihelion*, or P.

Thus the *elements* of a planet's orbit are:

i, the *inclination* to the ecliptic, which fixes the plane of the planet's orbit;

Ω, the *longitude of the node*, which fixes the position of the line of intersection of the orbit and the ecliptic;

P, the *longitude of the perihelion*, which fixes the position of the major axis of the planet's orbit with relation to the sun, and hence in space;

a and e, the *mean distance* and *eccentricity* of the orbit, which fix the shape and size of the orbit;

T and M, the *periodic time* and the *longitude at epoch*, which enable the place of the planet in its orbit, and hence in space, to be fixed at any future or past time.

The elements of the older planets of the solar system are now known with great accuracy, and their positions for two or three centuries past or future can be *predicted* with a close approximation to the accuracy with which these positions can be observed.

CHAPTER VI.

UNIVERSAL GRAVITATION.

NEWTON'S LAWS OF MOTION

THE establishment of the theory of universal gravitation furnishes one of the best examples of scientific method which is to be found. We shall describe its leading features, less for the purpose of making known to the reader the technical nature of the process than for illustrating the true theory of scientific investigation, and showing that such investigation has for its object the discovery of what we may call generalized facts. The real test of progress is found in our constantly increased ability to foresee either the course of nature or the effects of any accidental or artificial combination of causes. So long as prediction is not possible, the desires of the investigator remain unsatisfied. When certainty of prediction is once attained, and the laws on which the prediction is founded are stated in their simplest form, the work of science is complete.

To the pre-Newtonian astronomers the phenomena of the geometrical laws of planetary motion, which we have just described, formed a group of facts having no connection with anything on the earth's surface. The epicycles of HIPPARCHUS and PTOLEMY were a truly scientific conception, in that they explained the seemingly erratic motions of the planets by a single simple law. In the heliocentric theory of COPERNICUS this law was still further simplified by dispensing in great part with the epicycle, and replacing the latter by a motion of the earth around the sun, of the same nature with the motions of the planets. But COPERNICUS had no way of accounting for, or even of describing with rigorous accuracy, the small deviations in the motions of the planets around the sun. In this respect he made no real advance upon the ideas of the ancients.

KEPLER, in his discoveries, made a great advance in representing the motions of all the planets by a single set of simple and easily understood geometrical laws. Had the planets followed his laws exactly, the theory of planetary motion would have been substantially complete. Still, further progress was desired for two reasons. In the first place, the laws of KEPLER did not perfectly represent all the planetary motions. When observations of the greatest accuracy were made, it was found that the planets deviated by small amounts from the ellipse of KEPLER. Some small emendations to the motions computed on the elliptic theory were therefore necessary. Had this requirement been fulfilled, still another step would have been desirable; namely, that of connecting the motions of the planets with motions upon the earth, and reducing them to the same laws.

Notwithstanding the great step which KEPLER made in describing the celestial motions, he unveiled none of the great mystery in which they were enshrouded. When KEPLER said that observation showed the law of planetary motion to be that around the circumference of an ellipse, as asserted in his law, he said all that it seemed possible to learn, supposing the statement perfectly exact. And it was all that could be learned from the mere study of the planetary motions. In order to connect these motions with those on the earth, the next step was to study the laws of force and motion here around us. Singular though it may appear, the ideas of the ancients on this subject were far more erroneous than their conceptions of the motions of the planets. We might almost say that before the time of GALILEO scarcely a single correct idea of the laws of motion was generally entertained by men of learning. Among those who, before the time of NEWTON, prepared the way for the theory in question, GALILEO, HUYGHENS, and HOOKE are entitled to especial mention. The general laws of motion laid down by NEWTON were three in number.

Law First: *Every body preserves its state of rest or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.*

It was formerly supposed that a body acted on by no force tended to come to rest. Here lay one of the greatest difficulties which the predecessors of NEWTON found, in accounting for the motion of the planets. The idea that the sun in some way caused these motions was entertained from the earliest times. Even PTOLEMY had a vague idea of a force which was always directed toward the centre of the earth, or, which was to him the same thing, toward the centre of the universe, and which not only caused heavy bodies to fall, but bound the whole universe together. KEPLER, again, distinctly affirms the existence of a gravitating force by which the sun acts on the planets; but he supposed that the sun must also exercise an impulsive forward force to keep the planets in motion. The reason of this incorrect idea was, of course, that all bodies in motion on the surface of the earth had practically come to rest. But what was not clearly seen before the time of NEWTON, or at least before GALILEO, was that this arose from the inevitable resisting forces which act upon all moving bodies upon the earth.

Law Second: *The alteration of motion is ever proportional to the moving force impressed, and is made in the direction of the right line in which that force acts.*

The first law might be considered as a particular case of this second one which arises when the force is supposed to vanish. The accuracy of both laws can be proved only by very carefully conducted experiments. They are now considered as conclusively proved.

Law Third: *To every action there is always opposed an equal reaction; or the mutual actions of two bodies upon each other are always equal, and in opposite directions.*

That is, if a body A acts in any way upon a body B, B will exert a force exactly equal on A in the opposite direction.

These laws once established, it became possible to *calculate* the motion of any body or system of bodies when once the forces which act on them were known, and, *vice versa*, to define what forces were requisite to produce any given motion. The question which presented itself to the mind of NEWTON and his contemporaries was this: *Under what law of force will planets move round the sun in accordance with* KEPLER'S *laws?*

Supposing a body to move around in a circle, and putting R the radius of the circle, T the period of revolution, HUYGHENS had shown that the centrifugal force of the body, or, which is the same thing, the attractive force toward the centre which would keep it in the circle, was proportional to $\frac{R}{T^2}$. But by KEPLER'S third law T^2 is proportional to R^3. Therefore this centripetal force is proportional to $\frac{R}{R^3}$; that is, to $\frac{1}{R^2}$. Thus it followed immediately from KEPLER'S third law that the central force which would keep the planets in their orbits was inversely as the square of the distance from the sun, supposing each orbit to be circular. The first law of motion once completely understood, it was evident that the planet needed no force impelling it forward to keep up its motion, but that, once started, it would keep on forever.

The next step was to solve the problem, What law of force will make a planet describe an ellipse around the sun, having the latter in one of its foci? Or, supposing a planet to move round the sun, the latter attracting it with a force inversely as the square of the distance; what will be the form of the orbit of the planet if it is not circular? A solution of either of these problems was beyond the power of mathematicians before the time of NEWTON; and it thus remained uncertain whether the planets moving under the influence of the sun's gravitation would or would not describe ellipses. Unable, at first, to reach a satisfactory solution, NEWTON attacked the problem in another direction, starting from the gravitation, not of the sun, but of the earth, as explained in the following section.

GRAVITATION IN THE HEAVENS.

The reader is probably familiar with the story of NEWTON and the falling apple. Although it has no authoritative foundation, it is strikingly illustrative of the method by which NEWTON must have reached a solution of the problem. The course of reasoning by which he ascended from gravitation on the earth to the celestial motions was as follows: We see that there is a force acting all over the earth by which all bodies are drawn toward its centre. This force is called gravitation. It extends without sensible diminution to the tops not only of the highest buildings, but of the highest mountains. How much higher does it extend? Why should it not extend to the moon? If it does, the moon would tend to drop toward the earth, just as a stone thrown from the hand drops. As the moon moves round the earth in her monthly course, there must be some force drawing her toward the earth; else, by the first law of motion, she would fly entirely away in a straight line. Why should not the force which makes the apple fall be the same force which keeps her in her orbit? To answer this question, it was not only necessary to calculate the intensity of the force which would keep the moon herself in her orbit, but to compare it with the intensity of gravity at the earth's surface. It had long been known that the distance of the moon was about sixty radii of the earth, from measures of her parallax (see page 57). If this force diminished as the inverse square of the distance, then at the moon it would be only $\frac{1}{3600}$ as great as at the surface of the earth. On the earth a body falls sixteen feet in a second. If, then, the theory of gravitation were correct, the moon ought to fall towards the earth $\frac{1}{3600}$ of this amount, or about $\frac{1}{19}$ of an inch in a second. The moon being in motion, if we imagine it moving in a straight line at the beginning of any second, it ought to be drawn away from that line $\frac{1}{19}$ of an inch at the end of the second. When the calculation was made it was found to agree exactly with this result of theory. Thus it was shown that the force which holds the moon in her orbit is the same force that makes the stone fall, diminished as the inverse square of the distance from the centre of the earth.

It thus appeared that central forces, both toward the sun and toward the earth, varied inversely as the squares of the distances. KEPLER'S second law showed that the line drawn from the planet to the sun would describe equal areas in equal times. NEWTON showed that this could not be true unless the force which held the planet was directed toward the sun. We have already stated that the third law showed that the force was inversely as the square of the distance, and thus agreed exactly with the theory of gravitation. It only remained to consider the results of the first law, that of the elliptic motion. After long and laborious efforts, NEWTON was enabled to demonstrate rigorously that this law also resulted from the law of the inverse square, and could result from no other. Thus all mystery disappeared from the celestial motions; and planets were shown to be simply heavy bodies moving according to the same laws that were acting here around us, only under very different circumstances. *All three of* KEPLER'S *laws were embraced in the single law of gravitatian toward the sun.* The sun attracts the planets as the earth attracts bodies here around us,

Mutual Action of the Planets.—By NEWTON's third law of motion, each planet must attract the sun with a force equal to that which the sun exerts upon the planet. The moon also must attract the earth as much as the earth attracts the moon. Such being the case, it must be highly probable that the planets attract each other. If so, KEPLER's laws can only be an approximation to the truth. The sun, being immensely more massive than any of the planets, overpowers their attraction upon each other, and makes the law of elliptic motion very nearly true. But still the comparatively small attraction of the planets must cause some deviations. Now, deviations from the pure elliptic motion were known to exist in the case of several of the planets, notably in that of the moon, which, if gravitation were universal, must move under the influence of the combined attraction of the earth and of the sun. NEWTON, therefore, attacked the complicated problem of the determination of the motion of the moon under the combined action of these two forces. He showed in a general way that its deviations would be of the same nature as those shown by observation. But the complete solution of the problem, which required the answer to be expressed in numbers, was beyond his power.

Gravitation Resides in each Particle of Matter.—Still another question arose. Were these mutually attractive forces resident in the centres of the several bodies attracted, or in each particle of the matter composing them? NEWTON showed that the latter must be the case, because the smallest bodies, as well as the largest, tended to fall toward the earth, thus showing an equal gravitation in every separate part. It was also shown by NEWTON that if a planet were on the surface of the earth or outside of it, it would be attracted with the same force as if the whole mass of the earth were concentrated in its centre. Putting together the various results thus arrived at, NEWTON was able to formulate his great law of universal gravitation in these comprehensive words: "*Every particle of matter in the universe attracts every other particle with a force directly as the masses of the two particles, and* *inversely as the square of the distance which separates them."*

To show the nature of the attractive forces among these various particles, let us represent by m and m' the masses of two attracting bodies. We may conceive the body m to be composed of m particles, and the other body to be composed of m' particles. Let us conceive that each particle of one body attracts each particle of the other with a force $\frac{1}{r^2}$. Then every particle of m will be attracted by each of the m' particles of the other, and therefore the total attractive force on each of the m particles will be $\frac{m'}{r^2}$. Each of the m particles being equally subject to this attraction, the total attractive force between the two bodies will be $\frac{m\,m'}{r^2}$. When a given force acts upon a body, it will produce less motion the larger the body is, the *accelerating* force being proportional to the total attracting force divided by the mass of the body moved. Therefore the accelerating force which acts on the body m', and which determines the amount of motion, will be $\frac{m}{r^2}$; and conversely the accelerating force acting on the body m will be represented by the fraction $\frac{m'}{r^2}$.

Remarks on the Theory of Gravitation.

The real nature of the great discovery of Newton is so frequently misunderstood that a little attention may be given to its elucidation. Gravitation is frequently spoken of as if it were a theory of Newton's, and very generally received by astronomers, but still liable to be ultimately rejected as a great many other theories have been. Not infrequently people of greater or less intelligence are found making great efforts to prove it erroneous. Newton did not discover any new force, but only showed that the motions of the heavens could be accounted for by a force which we all know to exist. Gravitation (Latin *gravitas*—

weight, heaviness) is the force which makes all bodies here at the surface of the earth tend to fall downward; and if any one wishes to subvert the theory of gravitation, he must begin by proving that this force does not exist. This no one would think of doing. What NEWTON did was to show that this force, which, before his time, had been recognized only as acting on the surface of the earth, really extended to the heavens, and that it resided not only in the earth itself, but in the heavenly bodies also, and in each particle of matter, however situated. To put the matter in a terse form, what NEWTON discovered was not *gravitation*, but the *universality* of gravitation.

It may be inquired, is the induction which supposes gravitation universal so complete as to be entirely beyond doubt? We reply that within the solar system it certainly is. The laws of motion as established by observation and experiment at the surface of the earth must be considered as mathematically certain. It is an observed fact that the planets in their motions deviate from straight lines in a certain way. By the first law of motion, such deviation can be produced only by a force; and the direction and intensity of this force admit of being calculated once that the motion is determined. When thus calculated, it is found to be exactly represented by one great force constantly directed toward the sun, and smaller subsidiary forces directed toward the several planets. Therefore no fact in nature is more firmly established than that of universal gravitation, as laid down by NEWTON, at least within the solar system.

We shall find, in describing double stars, that gravitation is also found to act between the components of a great number of such stars. It is certain, therefore, that at least some stars gravitate toward each other, as the bodies of the solar system do; but the distance which separates most of the stars from each other and from our sun is so immense that no evidence of gravitation between individual stars and the sun has yet been given by observation. Still, that they do gravitate according to NEWTON'S law can hardly be seriously doubted by any one who understands the subject.

The student may now be supposed to see the absurdity of supposing that the theory of gravitation can ever be subverted. It is not, however, absurd to suppose that it may yet be shown to be the result of some more general law. Attempts to do this are made from time to time by men of a philosophic spirit; but thus far no theory of the subject having much probability in its favor has been propounded.

CHAPTER VII.

THE MOTIONS AND ATTRACTION OF THE MOON.

EACH of the planets, except *Mercury* and *Venus,* is attended by one or more satellites, or *moons* as they are sometimes familiarly called. These objects revolve around their several planets in nearly circular orbits, accompanying them in their revolutions around the sun. Their distances from their planets are very small compared with the distances of the latter from each other and from the sun. Their magnitudes also are very small compared with those of the planets around which they revolve. Considering each system by itself, the satellites revolve around their central planets, or "primaries," in nearly circular orbits, and in each system KEPLER'S laws govern the motion of the satellites about the primary. Each system is carried around the sun without any derangement of the motion of its several bodies among themselves.

Our earth has a single satellite accompanying it in this way, the moon. It revolves around the earth in a little less than a month. The nature, causes, and consequences of this motion form the subject of the present chapter.

The Moon's Motions and Phases.

That the moon performs a monthly circuit in the heavens is a fact with which we are all familiar from childhood. At certain times we see her newly emerged from the sun's rays in the western twilight, and then we call her the new moon. On each succeeding evening we see her further to the east, so that in two weeks she is opposite the sun, rising in the east as he sets in the west. Continuing her course two weeks more, she has approached the sun on the other side, or from the west, and is once more lost in his rays. At the end of twenty-nine or thirty days, we see her again emerging as new moon, and her circuit is complete. The sun has been apparently moving toward the east among the stars during the whole month, so that during the interval from one new moon to the next the moon has to make a complete circuit relatively to the stars, and to move forward some 30° further to overtake the sun, which has also been moving toward the east at the rate of 1° daily. The revolution of the moon among the stars is performed in about $27\frac{1}{3}$ days,* so that if we observe when the moon is very near some star, we shall find her in the same position relative to the star at the end of this interval.

The motion of the moon in this circuit differs from the apparent motions of the planets in being always forward. We have seen that the planets, though, on the whole, moving toward the east, are effected with an apparent retrograde motion at certain intervals, owing to the motion of the earth around the sun. But the earth is the real centre of the moon's motion, and carries the moon along with it in its annual revolution around the sun. To form a correct idea of the real motion of these three bodies, we must imagine the earth performing its circuit around the sun in one year, and carrying with it the moon, which makes a revolution around it in 27 days, at a distance only about $\frac{1}{400}$ that of the sun.

Phases of the Moon.—The moon, being a non-luminous body, shines only by reflecting the light falling on her from some other body. The principal source of light is the sun. Since the moon is spherical in shape, the sun can illuminate one half her surface. The appearance of the moon varies according to the amount of her illuminated hemisphere which is turned toward the earth, as can be seen by studying Fig. 39. Here the central globe is the earth; the circle around it represents the orbit of the moon. The rays of the sun fall on both earth and moon from the right, the distance of the sun being, on the scale of the

* More exactly, 27.32166^d.

figure, some 30 feet. Eight positions of the moon are shown around the orbit at *A, E, C,* etc., and the right-hand hemisphere of the moon is illuminated in each position. Outside these eight positions are eight others showing how the moon looks as seen from the earth in each position.

At *A* it is "new moon," the moon being nearly between

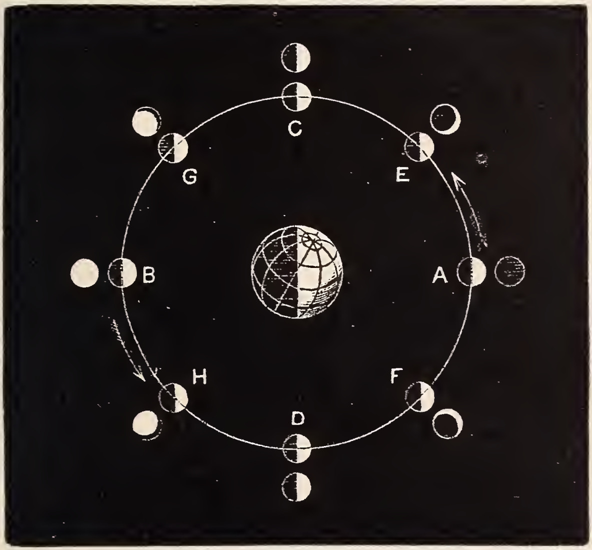

FIG. 39.

the earth and the sun. Its dark hemisphere is then turned toward the earth, so that it is entirely invisible. The sun and moon then rise and set together.

At *E* the observer on the earth sees about a fourth of the illuminated hemisphere, which looks like a crescent, as shown in the outside figure. In this position a great deal of light is reflected from the earth to the moon, rendering the dark part of the latter visible by a gray light. This appearance is sometimes called the "old moon in the new moon's arms." At C the moon is said to be in her "first quarter," and one half her illuminated hemisphere is visible. The moon is on the meridian at 6 P.M. At G three fourths of the illuminated hemisphere is visible, and at B the whole of it. The latter position, when the moon is opposite the sun, is called "full moon." The moon rises at sunset. After this, at H, D, F, the same appearances are repeated in the reversed order, the position D being called the "last quarter."

The Tides.

It is not possible in an elementary treatise to give a complete account of the theory of the tides of the ocean due to the effect of the sun and moon. A general account may be presented which will be sufficient to show the nature of the effects produced and of their causes.

Let us consider the earth to be composed of a solid centre surrounded by an ocean of uniform (and not very great) depth. The moon exercises an attraction upon every particle of the earth's mass, solid and fluid alike. The attraction of the whole moon (M) upon a particle m is $\frac{Mm}{\rho^2}$, where ρ is the distance from the centre of the moon to m. If m is one of the solid particles of the earth, it cannot move towards M in obedience to the attraction unless all the other solid particles move, since the earth proper is rigid.

If m is a fluid particle, it is free to move in obedience to the forces impressed upon it. The attraction of M is proportional to $\frac{1}{\rho^2}$; that is, the particles nearest M are most attracted, and, on the whole, the water on the part of the earth nearest the moon will be raised toward M.

The moon also attracts the solid parts of the earth more than she attracts the water most distant from her, and this produces exactly the same *effect* as if there was another moon M exactly opposite to M. The elevation of the water under M' will not be quite as great as that under M, on account of the increased distance from M.

Thus the moon's action tends to elevate the whole mass of water on the line joining her centre with the centre of the earth, and this is so not only on the part of this line nearest the moon, but also on that farthest from her.

This elevation of the waters of the ocean above their mean level is called *the tide.* The tidal effect of the moon produces a distortion of the spherical shell of water which we have supposed to surround the earth, and elongates this shell into the shape of an ellipsoid, the longer axis of which is always directed to the moon. Now as the moon moves around the earth once in 24^h 54^m, this ellipsoidal shape must also move with her. The crest of the wave directly under M would come back to the same meridian every 24^h 54^m. The outer crest (under M') would come 12^h 27^m after the first, so there would be two *high tides* at any one meridian every (lunar) day. The first (and largest) high tide would be at the time of the moon's visible transit over the meridian. The second high tide would be 12^h 27^m later, when the moon was on the lower meridian of the place.

The high tides occur when there is more water than the mean depth, and between these high tides we should have low tides, two in each lunar day. Similarly there would be two high tides daily at each meridian, due to the attractive force of the sun. These would have a period of 24 hours and could not always agree with the lunar high tides. When the solar and lunar high tides coincided (at new and full moon), then we should have the highest high tides and the lowest low tides. (These are the Spring tides, so called.) When the moon and the sun were 90° apart (moon at first and third quarter), then we should have the lowest high tides and the highest low tides. (Neap tides, so called.)

The tide-producing force of the moon is to that of the sun as 800 is to 355. The great mass of the sun compensates in some degree for his relatively great distance.

At spring tides sun and moon work together; at neap tides they oppose each other. The relative heights are as $800 + 355 : 800 - 355$, or as 13 to 5 approximately.

The explanation above relates to an earth covered by an ocean of uniform depth. To fit it to the facts as they are, a thousand circumstances must be taken into account, which depend upon the modifying effects of continents and islands, of deep and shallow seas, of currents and winds. Practically, the high tide at any station is predicted by adding to the time of the moon's transit over its meridian a quantity determined from observation and not from theory

Effects of the Tides upon the Earth's Rotation.—As the tide-wave moves it meets with resistance due to friction. The amount of this resistance is subtracted daily from the earth's energy of rotation. The tides act on the earth, in a way, as if they were a light friction-brake applied to an enormously heavy wheel turning rapidly. The wheel has been set to turning, and, so far as we know, it will never have any more rotative energy given to it. Every subtraction of energy, however small, is a positive and irretrievable loss.

The lunar tides are gradually, though very slowly, lengthening the day. Since accurate astronomical observations began there has been no *observational* proof of any appreciable change in the length of the day, but the change has been going on nevertheless.

CHAPTER VIII.

ECLIPSES OF THE SUN AND MOON.

ECLIPSES are phenomena arising from the shadow of one body being cast upon another, or from a dark body passing over a bright one. In an eclipse of the sun, the shadow of the moon sweeps over the earth, and the sun is wholly or partially obscured to observers on that part of the earth where the shadow falls. In an eclipse of the moon, the latter enters the shadow of the earth, and is wholly or partially obscured in consequence of being deprived of some or all of its borrowed light. The satellites of other planets are from time to time eclipsed in the same way by entering the shadows of their primaries; among these the satellites of *Jupiter* are objects whose eclipses may be observed with great regularity.

THE EARTH'S SHADOW AND PENUMBRA.

In Fig. 40 let S represent the sun, and E the earth. Draw straight lines, DBV and $D'B'V$, each tangent to the sun and the earth. The two bodies being supposed spherical, these lines will be the intersections of a cone with the plane of the paper, and may be taken to represent that cone. It is evident that the cone BVB' will be the outline of the shadow of the earth, and that within this cone no direct sunlight can penetrate. It is therefore called the earth's *shadow-cone.*

Let us also draw the lines $D'BP$ and $DB'P'$ to represent the other cone tangent to the sun and earth. It is then evident that within the region VBP and $VB'P'$ the light of the sun will be partially but not entirely cut off.

Dimensions of Shadow.—Let us investigate the distance EV from the centre of the earth to the vertex of the shadow. The triangles VEB and VSD are similar, having a right angle at B and at D. Hence

$$VE : EB = VS : SD = ES : (SD - EB).$$

So if we put

$l = VE$, the length of the shadow measured from the centre of the earth,
$r = ES$, the radius-vector of the earth,
$R = SD$, the radius of the sun,
$\rho = EB$, the radius of the earth,

we have

$$l = VE = \frac{ES \times EB}{SD - EB} = \frac{r\rho}{R - \rho}.$$

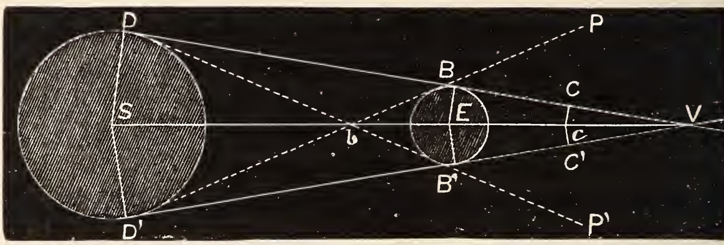

FIG. 40.—FORM OF SHADOW.

That is, l is expressed in terms of known quantities, and thus is known.

The radius of the shadow diminishes uniformly with the distance as we go outward from the earth. At any distance z from the earth's centre it will be equal to $\left(1 - \frac{z}{l}\right)\rho$, for this formula gives the radius ρ when $z = 0$, and the diameter zero when $z = l$ as it should.*

* It will be noted that this expression is not, rigorously speaking, the semi-diameter of the shadow, but the shortest distance from a point on its central line to its conical surface. This distance is measured in a direction EB perpendicular to DB, whereas the diameter would be perpendicular to the axis SE, and its half-length would be a little greater than EB.

Eclipses of the Moon.

The mean distance of the moon from the earth is about 60 radii of the latter, and the length $E\,V$ of the earth's shadow is 217 radii of the earth. Hence when the moon passes through the shadow she does so at a point less than three tenths of the way from E to V. The radius of the shadow here will be $\frac{217-60}{217}$ of the radius $E\,B$ of the earth, a quantity which we readily find to be about 4600 kilometres. The radius of the moon being 1736 kilometres, it will be entirely enveloped by the shadow when it passes through it within 2864 kilometres of the axis $E\,V$ of the shadow. If its least distance from the axis exceed this amount, a portion of the lunar globe will be outside the limits $B\,V$ of the shadow-cone, and will therefore receive a portion of the direct light of the sun. If the least distance of the centre of the moon from the axis of the shadow is greater than the sum of the radii of the moon and the shadow—that is, greater than 6336 kilometres—the moon will not enter the shadow at all, and there will be no eclipse proper, though the brilliancy of the moon is diminished wherever she is within the penumbral region.

When an eclipse of the moon occurs, the phases are laid down in the almanac. (See Fig. 40.) Supposing the moon to be moving around the earth from below upward, its advancing edge first meets the boundary $B'P'$ of the penumbra. The time of this occurrence is given in the almanac as that of "moon entering penumbra." A small portion of the sunlight is then cut off from the advancing edge of the moon, and this amount constantly increases until the edge reaches the boundary $B'\,V$ of the shadow. It is curious, however, that the eye can scarcely detect any diminution in the brilliancy of the moon until she has almost touched the boundary of the shadow. The observer must not, therefore, expect to detect the coming eclipse until very nearly the time given in the almanac as that of "moon entering shadow." As this happens, the advancing portion of the lunar disk will be entirely lost to view, as if it were cut off by a rather ill-defined line. It takes the moon about an hour to move over a distance equal to her own diameter, so that if the eclipse is nearly central the whole moon will be immersed in the shadow about an hour after she first strikes it. This is the time of beginning of total eclipse. So long as only a moderate portion of the moon's disk is in the shadow, that portion will be entirely invisible, but if the eclipse becomes total the whole disk of the moon will nearly always be plainly visible, shining with a red coppery light. This is owing to the refraction of the sun's rays by the lower strata of the earth's atmosphere. We shall see hereafter that if a ray of light $D B$ passes from the sun to the earth, so as just to graze the latter, it is bent by refraction more than a degree out of its course, so that at the distance of the moon the whole shadow of the earth is filled with this refracted light. An observer on the moon would, during a total eclipse of the latter, see the earth surrounded by a ring of light, and this ring would appear red, owing to the absorption of the blue and green rays by the earth's atmosphere, just as the sun seems red when setting.

The moon may remain enveloped in the shadow of the earth during a period ranging from a few minutes to nearly two hours, according to the distance at which she passes from the axis of the shadow and the velocity of her angular motion. When she leaves the shadow, the phases which we have described occur in reverse order.

It very often happens that the moon passes through the penumbra of the earth without touching the shadow at all. The diminution of light in such cases is scarcely perceptible unless the moon at least grazes the edge of the shadow.

Eclipses of the Sun.

In Fig. 40 we may suppose $B E B'$ to represent the moon. The geometrical theory of the shadow will remain the same, though the actual length of the shadow in miles will be much less. The mean length of the moon's shadow cast by the sun is 377,000 kilometres. This is nearly equal to the distance of the moon from the earth when she is in conjunction with the sun. We therefore conclude that when the moon passes between the earth and the sun, the former will be very near the vertex V of the shadow. As a matter of fact, an observer on the earth's surface will sometimes pass through the region $C\,V\,C'$, and sometimes on the other side of V.

Now, in Fig. 40, still supposing BEB' to be the moon, and SDD' to be the sun, let us draw the lines $DB'P'$ and $D'BP$ tangent to both moon and sun, but crossing each other between these bodies at b. It is evident that an observer outside the space $PBB'P'$ will see the whole sun, no part of the moon being projected upon it; while within this space the sun will be more or less obscured. The whole obscured space may be divided into three regions, in each of which the character of the phenomenon is different.

First, we have the region BVB' forming the shadow-cone proper. Here the sunlight is entirely cut off by the moon, and darkness is therefore complete, except so far as light may enter by refraction or reflection. To an observer at V the moon would exactly cover the sun, the two bodies being apparently tangent to each other all around.

Secondly, we have the conical region to the right of V between the lines $B\,V$ and $B'\,V$ continued. In this region the moon is seen wholly projected upon the sun, the visible portion of the latter presenting the form of a ring of light around the moon. This ring of light will be wider in proportion to the apparent diameter of the sun, the farther out we go, because the moon will appear smaller than the sun, and its angular diameter will diminish in a more rapid ratio than that of the sun. This region is that of *annular eclipse*, because the sun will present the appearance of an annulus or ring of light around the moon.

Thirdly, we have the region $P\,B\,V$ and $P'B'\,V$, which we notice is continuous, extending around the interior cone. An observer here would see the moon partly projected upon the sun, and therefore a certain part of the sun's light would be cut off. Along the inner boundary $B\,V$ and $B'\,V'$ the obscuration of the sun will be complete, but the amount of sunlight will gradually increase out to the outer boundary $B\,P\,B'\,P'$, where the whole sun is visible. This region of partial obscuration is called the *penumbra*.

To show more clearly the phenomena of solar eclipses, we present another figure representing the penumbra of the moon thrown upon the earth.* The outer of the two circles S represents the limb of the sun. The exterior tangents which mark the boundary of the shadow cross each other at V before reaching the earth. The earth (E) being a little beyond the vertex of the shadow, there can be no total eclipse. In this case an observer in the penumbral region, CO or DO, will see the moon partly projected on the sun, while if he chance to be situated at O he will see an annular eclipse. To show how this is, we draw dotted lines from O tangent to the moon. The angle between these lines represents the apparent diameter of the moon as seen from the earth. Continuing them to the sun, they show the apparent diameter of the moon as projected upon the sun. It will be seen that, in the case supposed, when the vertex of the shadow is between the earth and moon the latter will necessarily appear

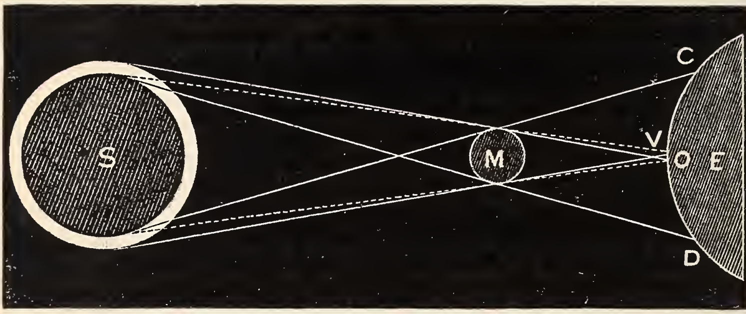

FIG. 41.—FIGURE OF SHADOW FOR ANNULAR ECLIPSE.

smaller than the sun, and the observer will see a portion of the solar disk on all sides of the moon, as shown in Fig. 42.

If the moon were a little nearer the earth than it is represented in Fig. 41, its shadow would reach the earth in the neighborhood of O. We should then have a total eclipse at each point of the earth on which it fell. It will be seen, however, that a total or annular eclipse of the sun is visible only on a very small portion of the earth's surface, because the distance of the moon changes so little that the earth can never be far from the vertex V of the shadow. As the

* It will be noted that all the figures of eclipses are necessarily drawn very much out of proportion. Really the sun is 400 times the distance of the moon, which again is 60 times the radius of the earth. But it would be entirely impossible to draw a figure of this proportion; we are therefore obliged to represent the earth in Fig. 40 as larger than the sun, and the moon as nearly half way between the earth and sun.

moon moves around the earth from west to east, its shadow, whether the eclipse be total or annular, moves in the same direction. The diameter of the shadow at the surface of the earth ranges from zero to 150 miles. It therefore sweeps along a belt of the earth's surface of that breadth, in the same direction in which the earth is rotating. The velocity of the moon relative to the earth being 3400 kilometres per hour, the shadow would pass along with this velocity if the earth did not rotate, but owing to the earth's rotation the velocity relative to points on its surface may range from 2000 to 3400 kilometres (1200 to 2100 miles).

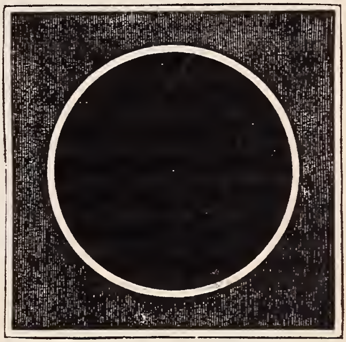

Fig. 42.—Dark Body of Moon projected on Sun during an Annular Eclipse.

The reader will readily understand that in order to see a total eclipse an observer must station himself beforehand at some point of the earth's surface over which the shadow is to pass. These points are generally calculated some years in advance, in the astronomical ephemerides.

It will be seen that a partial eclipse of the sun may be visible from a much larger portion of the earth's surface than a total or annular one. The space CD (Fig. 41) over which the penumbra extends is generally of about one half the diameter of the earth. Roughly speaking, a partial eclipse of the sun may sweep over a portion of the earth's surface ranging from zero to perhaps one fifth or one sixth of the whole.

There are really more eclipses of the sun than of the moon. A year never passes without at least two of the former, and sometimes five or six, while there are rarely more than two eclipses of the moon, and in many years none at all. But at any one place more eclipses of the moon will be seen than of the sun. The reason of this is that an eclipse of the moon is visible over the entire hemisphere of the earth on which the moon is shining, and as it lasts several hours, observers who are not in this hemisphere at the beginning of the eclipse may, by the earth's rotation, be brought into it before it ends. Thus the eclipse will be seen over more than half the earth's surface. But, as we have just seen, each eclipse of the sun can be seen over only so small a fraction of the earth's surface as to more than compensate for the greater absolute frequency of solar eclipses.

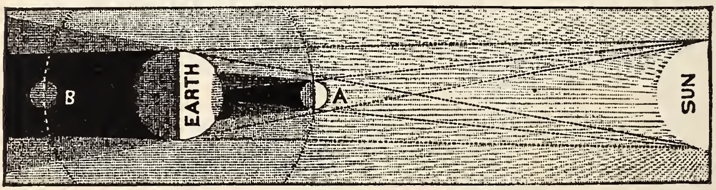

FIG. 43.—COMPARISON OF SHADOW AND PENUMBRA OF EARTH AND MOON. *A* IS THE POSITION OF THE MOON DURING A SOLAR, *B* DURING A LUNAR, ECLIPSE.

It will be seen that, in order to have either a total or annular eclipse visible upon the earth, the line joining the centres of the sun and moon, being continued, must strike the earth. To an observer on this line the centres of the two bodies will seem to coincide. An eclipse in which this occurs is called a *central* one, whether it be total or annular. Fig. 43 will perhaps aid in giving a clear idea of the phenomena of eclipses of both sun and moon.

THE RECURRENCE OF ECLIPSES.

If the orbit of the moon around the earth were in or near the plane of the ecliptic there would be an eclipse of the sun at every new moon, and an eclipse of the moon at every full moon. But, owing to the inclination of the moon's orbit, the shadow and penumbra of the moon commonly pass above or below the earth at the time of new moon, while the moon, at her full, commonly passes above or below the shadow of the earth. It is only when the moon is near its node at the moment of new or full moon that an eclipse can occur.

The question now arises, how near must the moon be to its node in order that an eclipse may occur? It is found that if, at the moment of new moon, the moon is more than 18°·6 from its node no eclipse of the sun is possible, while if it is less than 13°·7 an eclipse is certain. Between these limits an eclipse may occur or fail according to the respective distances of the sun and moon from the earth. Half way between these limits, or say 16° from the node, it

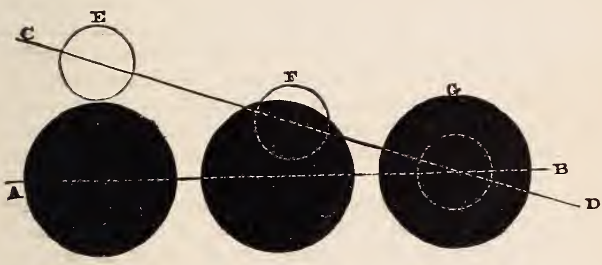

Fig. 44.—Illustrating lunar eclipse at different distances from the node. The dark circles are the earth's shadow, the centre of which is always in the ecliptic *A B*. The moon's orbit is represented by *C D*. At *G* the eclipse is central and total, at *F* it is partial, and at *E* there is barely an eclipse.

is an even chance that an eclipse will occur; toward the lower limit (13°·7) the chances increase to certainty; toward the upper one (18°·6) they diminish to zero. The corresponding limits for an eclipse of the moon are 9° and 12½°; that is, if at the moment of full moon the distance of the moon from her node is greater than 12½° no eclipse can occur, while if the distance is less than 9° an eclipse is certain. We may put the mean limit at 11°. Since, in the long-run, new and full moon will occur equally at all distances from the node, there will be, on the average, sixteen eclipses of the sun to eleven of the moon, or nearly fifty per cent more.

If, at the moment of new moon, the distance of the moon from the node is less than 10½° there will be a central eclipse of the sun, and if greater than this there will not be such an eclipse. The eclipse limit may range half a degree or more on each side of this mean value, owing to the varying distance of the moon from the earth. Inside of 10° a central eclipse may be regarded as certain, and outside of 11° as impossible.

If the direction of the moon's nodes from the centre of the earth were invariable, eclipses could occur only at the two opposite months of the year when the sun had nearly the same longitude as one node. For instance, if the longitudes of the two opposite nodes were respectively 54° and 234°, then, since the sun must be within 12° of the node to allow of an eclipse of the moon, its longitude would have to be either between 42° and 66°, or between 222° and 246°. But the sun is within the first of these regions only in the month of May, and within the second only during the month of November. Hence lunar eclipses could then occur only during the months of May and November, and the same would hold true of central eclipses of the sun. Small partial eclipses of the latter might be seen occasionally a day or two from the beginnings or ends of the above months, but they would be very small and quite rare. Now, the nodes of the moon's orbit were actually in the above directions in the year 1873. Hence during that year eclipses occurred only in May and November. We may call these months the seasons of eclipses for 1873.

There is a retrograde motion of the moon's nodes amounting to 19½° in a year. The nodes thus move back to meet the sun in its annual revolution, and this meeting occurs about 20 days earlier every year than it did the year before. The result is that the season of eclipses is constantly shifting, so that each season ranges throughout the whole year in 18·6 years. For instance, the season corresponding to that of November, 1873, had moved back to July and August in 1878, and will occur in May, 1882, while that of May, 1873, will be shifting back to November in 1882.

It may be interesting to illustrate this by giving the days in which the sun is in conjunction with the nodes of the moon's orbit during several years.

Ascending Node.	Descending Node.
1879. January 24.	1879. July 17.
1880. January 6.	1880. June 27.
1880. December 18.	1881. June 8.
1881. November 30.	1882. May 20.
1882. November 12.	1883. May 1.
1883. October 25.	1884. April 12.
1884. October 8.	1885. March 25.

During these years, eclipses of the moon can occur only within 11 or 12 days of these dates, and eclipses of the sun only within 15 or 16 days.

In consequence of the motion of the moon's node, three varying angles come into play in considering the occurrence of an eclipse: the longitude of the node, that of the sun, and that of the moon. One revolution of the moon relatively to the node is accomplished, on the average, in 27·21222 days. If we calculate the time required for the sun to return to the node, we shall find it to be 346·6201 days.

Now, let us suppose the sun and moon to start out together from a node. At the end of 346·6201 days the sun, having apparently performed nearly an entire revolution around the celestial sphere, will again be at the same node, which has moved back to meet it. But the moon will not be there. It will, during the interval, have passed the node 12 times, and the 13th passage will not occur for a week. The same thing will be true for 18 successive returns of the sun to the node; we shall not find the moon there at the same time with the sun; she will always have passed a little sooner or a little later. But at the 19th return of the sun and the 242d of the moon, the two bodies will be in conjunction within half a degree of the node. We find from the preceding periods that

242	returns of the moon to the node require	6585.357	days.
19	" " sun " " "	6585.780	"

The two bodies will therefore pass the node within 10 hours of each other. This conjunction of the sun and moon will be the 223d new moon after that from which we started. Now, one lunation (that is, the interval between two consecutive new moons) is, in the mean, 29.530588 days; 223 lunations therefore require 6585.32 days. The new moon, therefore, occurs a little before the bodies reach the node, the distance from the latter being that over which the moon moves in $0^d.036$, or the sun in $0^d.459$. This distance is 28′ of arc, somewhat less than the apparent semidiameter of either body. This would be the smallest distance from either node at which any new moon would occur during the whole period. The next nearest approaches would have occurred at the 35th and 47th lunations respectively. The 35th new moon would have occurred about 6° before the two bodies arrived at the node from which we started, and the 47th about 1½° past the opposite node. No other new moon would occur so near a node before the 223d one, which, as we have just seen, would occur 0° 28′ west of the node. This period of 223 new moons, or 18 years 11 days, was called the *Saros* by the ancient astronomers, and by means of it they predicted eclipses.

The possibility of a total eclipse of the sun arises from the occasional very slight excess of the apparent angular diameter of the moon over that of the sun. This excess is so slight that such an eclipse can never last more than a few minutes. It may be of interest to point out the circumstances which favor a long duration of totality. These are:

(1) That the moon should be as near as possible to the earth, or, technically speaking, in perigee, because its angular diameter as seen from the earth will then be greatest.

(2) That the sun should be near its greatest distance from the earth, or in apogee, because then its angular diameter will be the least. It is now in this position about the end of June; hence the most favorable time for a total eclipse of very long duration is in the summer months. Since the moon must be in perigee and also between the earth and sun, it follows that the longitude of the perigee must be nearly that of the sun. The longitude of the sun at the end of June being 100°, this is the most favorable longitude of the moon's perigee.

(3) The moon must be very near the node in order that the centre of the shadow may fall near the equator. The reason of this condition is that the duration of a total eclipse may be considerably increased by the rotation of the earth on its axis. We have seen that the shadow sweeps over the earth from west toward east with a velocity of about 3400 kilometres per hour. Since the earth rotates in the same direction, the velocity relative to the observer on the earth's surface will be diminished by a quantity depending on this velocity of rotation, and therefore greater the greater the velocity. The velocity of rotation is greatest at the earth's equator, where it amounts to 1660 kilometres per hour, or nearly half the velocity of the moon's shadow. Hence the duration of a total eclipse may, within the tropics, be nearly doubled by the earth's rotation. When all the favorable circumstances combine in the way we have just described, the duration of a total eclipse within the tropics will be about seven minutes and a half. In our latitude the maximum duration will be somewhat less, or not far from six minutes, but it is only on very rare occasions, hardly once in many centuries, that all these favorable conditions can be expected to concur.

Occultation of Stars by the Moon.—A phenomenon which, geometrically considered, is analogous to an eclipse of the sun is the occultation of a star by the moon. Since all the bodies of the solar system are nearer than the fixed stars, it is evident that they must from time to time pass between us and the stars. The planets are, however, so small that such a passage is of very rare occurrence, and when it does happen the star is generally so faint that it is rendered invisible by the superior light of the planet before the latter touches it. But the moon is so large and her angular motion so rapid that she passes over some star visible to the naked eye every few days. Such phenomena are termed *occultations of stars by the moon.* It must not, however, be supposed that they can be observed by the naked eye. In general, the moon is so bright that only stars of the first magnitude can be seen in actual contact with her limb, and even then the contact must be with the unilluminated limb.

CHAPTER IX.

THE EARTH.

Our object in the present chapter is to trace the effects of terrestrial gravitation and to study the changes to which it is subject in various places. Since every part of the earth attracts every other part as well as every object upon its surface, it follows that the earth and all the objects that we consider terrestrial form a sort of system by themselves, the parts of which are firmly bound together by their mutual attraction. This attraction is so strong that it is found impossible to project any object from the surface of the earth into the celestial spaces. Every particle of matter now belonging to the earth must, so far as we can see, remain upon it forever.

Mass and Density of the Earth.

The *mass* of a body may be defined as *the quantity of matter which it contains.*

There are two ways to measure this quantity of matter: (1) By the attraction or weight of the body—this weight being, in fact, the mutual force of attraction between the body and the earth; (2) By the inertia of the body, or the amount of force which we must apply to it in order to make it move with a definite velocity. Mathematically, there is no reason why these two methods should give the same result, but by experiment it is found that the attraction of all bodies is proportional to their inertia. In other words, all bodies, whatever their chemical constitution, fall exactly the same number of feet in one second under the influence of gravity, supposing them in a vacuum and at the same place on the earth's surface. Although the mass of a body is most conveniently measured by its weight, yet mass and weight must not be confounded.

The weight of a body is the apparent force with which it is attracted toward the centre of the earth.

This force is not the same in all parts of the earth, nor at different heights above the earth's surface. It is therefore a variable quantity, depending upon the position of the body, while the mass of the body is something inherent in it, which remains constant wherever the body may be taken, even if it is carried through the celestial spaces, where its *weight* would be reduced to almost nothing.

The unit of mass which we may adopt is arbitrary. Generally the most convenient unit is the weight of a body at some fixed place on the earth's surface—the city of Washington, for example. Suppose we take such a portion of the earth as will weigh one kilogramme in Washington; we may then consider the mass of that particular lot of earth or rock as the unit of mass, no matter to what part of the universe we take it. Suppose, also, that we could bring all the matter composing the earth to the city of Washington, one unit of mass at a time, for the purpose of weighing it, returning each unit of mass to its place in the earth immediately after weighing, so that there should be no disturbance of the earth itself. The sum-total of the weights thus found would be the mass of the earth, and would be a perfectly definite quantity, admitting of being expressed in kilogrammes or pounds. We can readily calculate the mass of a volume of water equal to that of the earth because we know the magnitude of the earth in litres, and the mass of one litre of water. Dividing this into the mass of the earth, supposing ourselves able to determine this mass, and we shall have the specific gravity, or what is more properly called the *density*, of the earth.

What we have supposed for the earth we may imagine for any heavenly body; namely, that it is brought to the city of Washington in small pieces, and there weighed one piece at a time. Thus the total mass of the earth or any heavenly body is a perfectly defined and determinate quantity.

It may be remarked in this connection that our units of weight, the pound, the kilogramme, etc., are practically units of mass rather than of weight. If we should weigh out a pound of tea in the latitude of Washington, and then take it to the equator, it would really be less heavy at the equator than in Washington; but if we take a pound weight with us, that also would be lighter at the equator, so that the two would still balance each other, and the tea would be still considered as weighing one pound. Since things are actually weighed in this way by weights which weigh one unit at some definite place, say Washington, and which are carried all over the world without being changed, it follows that a body which has any given weight in one place will, as measured in this way, have the same apparent weight in any other place, although its real weight will vary. But if a spring-balance or any other instrument for determining absolute weights were adopted, then we should find that the weight of the same body varied as we took it from one part of the earth to another. Since, however, we do not use this sort of an instrument in weighing, but pieces of metal which are carried about without change, it follows that what we call units of weight are properly units of mass.

Density of the Earth.—We see that all bodies around us tend to fall toward the centre of the earth. According to the law of gravitation, this tendency is not simply a single force directed toward the centre of the earth, but is the resultant of an infinity of separate forces arising from the attractions of all the separate parts which compose the earth. The question may arise, how do we know that each particle of the earth attracts a stone which falls, and that the whole attraction does not reside in the centre? The proofs of this are numerous, and consist rather in the exactitude with which the theory represents a great mass of disconnected phenomena than in any one principle admitting of demonstration. Perhaps, however, the most conclusive proof is found in the hbserved fact that masses of matter at the surface of the earth do really attract each other as required by the law of NEWTON. It is found, for example, that isolated mountains attract a plumb-line in their neighborhood.

It is noteworthy that though astronomy affords us the means of determining with great precision the *relative* masses of the earth, the moon, and all the planets, it does not enable us to determine the absolute mass of any heavenly body in units of the weights we use on the earth. The sun has about 328,000 times the mass of the earth, and the moon only $\frac{1}{80}$ of this mass, but to know the absolute mass of either of them we must know how many kilogrammes of matter the earth contains. To determine this we must know the mean density of the earth, and this is something about which direct observation can give us no information, because we cannot penetrate more than an insignificant distance into the earth's interior. The only way to determine the density of the earth is to find how much matter it must contain in order to attract bodies on its surface with a force equal to their observed weight; that is, with such intensity that at the equator a body shall fall nearly five metres in a second. To find this we must know the relation between the mass of a body and its attractive force. This relation can only be found by measuring the attraction of a body of known mass.

An attempt to do this was made toward the close of the last century, the attracting body selected being Mount Schehallien in Scotland. The volume, V, of the mountain was known by careful topographical surveys. The specific gravity or density, D, of the rocks composing the mountain was determined by experiment. The mass, M, of the mountain was $V \times D$; that is, a known quantity.

A plumb-line set up at the south end of the mountain was attracted away from the true vertical toward the mountain; that is, toward the north. A plumb-line at the north end of the mountain was attracted toward the south. The amounts of these deviations were measured, and they were due to the mass of the mountain. Hence a measure of its attractive force was obtained.

The actual process of determining the deviations of the plumb-lines N and S was this: The *latitudes* of the stations S and N were determined. These were nothing but the declinations of the *zeniths* of N and S, the zeniths being determined by the directions of plumb-lines at each station. The difference of latitudes of N and S by astronomical observations was known in arc and therefore in feet. If the mountain had no attraction on the plumb-lines, this difference in feet would be the same as the distance apart of the two stations determined by the topographical survey. But it was different, and the amount of the difference was a measure of the attraction of this particular mass. This is the general principle according to which the relation of mass and attraction is determined. As the mass of the mountain and its attraction was known, the density of the whole earth could be determined. The earth's mass (M') was equal to its volume (V') times its density (D'). Its volume was known, its mass was known, because it must be such as to attract bodies with forces measured by their weights, and hence its density was determined from this experiment. The actual result was that the earth was 4·7 times as dense as water. Other researches give about 5·6 for the density of the earth; this is more than double the average specific gravity of the rocks which compose the surface of the globe: whence it follows that the inner portions of the earth are much more dense than the outer parts.

Laws of Terrestrial Gravitation.

The earth being very nearly spherical, certain theorems respecting the attraction of spheres may be applied to it. The demonstration of these theorems requires the use of the Integral Calculus, and will be omitted here, only the conditions and the results being stated. Let us imagine a hollow shell of matter, of which the internal and external surfaces are both spheres, attracting any other mass of matter, a small particle we may suppose. This particle will be attracted by every particle of the shell with a force inversely as the square of its distance from it. The total attraction of the shell will be the resultant of this infinity of separate attractive forces.

Theorem I.—*If the particle be outside the shell, it will be attracted as if the whole mass of the shell were concentrated in its centre.*

Theorem II.—*If the particle be inside the shell, the opposite attractions in every direction will neutralize each other, no matter whereabouts in the interior the particle may be, and the resultant attraction of the shell will therefore be zero.*

To apply this to the attraction of a solid sphere, let us first suppose a body either outside the sphere or on its surface. If we conceive the sphere as made up of a great number of spherical shells, the attracted point will be external to all of them. Since each shell attracts as if its whole mass were in the centre, it follows that the whole sphere attracts a body upon the outside of its surface as if its entire mass were concentrated at its centre.

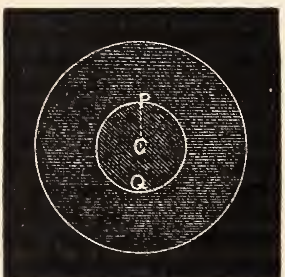

Fig. 45.

Let us now suppose the attracted particle inside the sphere, as at P, Fig. 45, and imagine a spherical surface PQ concentric with the sphere and passing through the attracted particle. All that portion of the sphere lying outside this spherical surface will be a spherical shell having the particle inside of it, and will therefore exert no attraction whatever on the particle. That portion inside the surface will constitute a sphere with the particle on its surface, and will therefore attract as if all this portion were concentrated in the centre. To find what this attraction will be, let us first suppose the whole sphere of equal density. Let us put

a, the radius of the entire sphere.
r, the distance PC of the particle from the centre.

The total volume of matter inside the sphere PQ will then be, by geometry, $\frac{4}{3}\pi r^3$. Dividing by the square of the distance r, we see that the attraction will be represented by

$$\frac{4}{3}\pi r;$$

that is, inside the sphere the attraction will be directly as the distance of the particle from the centre. If the particle is at the surface we have $r = a$, and the attraction is $\frac{4}{3}\pi a$. Outside the surface the whole volume of the sphere $\frac{4}{3}\pi a^3$ will attract the particle, and the attraction will be $\frac{4}{3}\pi \frac{a^3}{r^2}$. If we put $r = a$ in this formula, we shall have the same result as before for the surface attraction.

Let us next suppose that the density of the sphere varies from its centre to its surface, so as to be equal at equal distances from the centre. We may then conceive of it as formed of an infinity of concentric spherical shells, each homogeneous in density, but not of the same density as the others. Theorems I. and II. will then still apply, but their result will not be the same as in the case of a homogeneous sphere for a particle inside the sphere. Referring to Fig. 45, let us put

D, the mean density of the shell outside the particle P.
D', the mean density of the portion PQ inside of P.

We shall then have:

Volume of the shell, $\frac{4}{3}\pi (a^3 - r^3)$. Volume of the inner sphere, $\frac{4}{3}\pi r^3$. Mass of the shell $=$ vol. $\times D = \frac{4}{3}\pi D (a^3 - r^3)$. Mass of the inner sphere = vol. $\times D' = \frac{4}{3}\pi D'r^3$. Mass of the whole sphere = sum of masses of shell and inner sphere $= \frac{4}{3}\pi\left(Da^3 + (D' - D)r^3\right)$:

Attraction of the whole sphere upon a point at its surface $= \frac{\text{Mass}}{a^2} = \frac{4}{3}\pi\left(Da + (D' - D)\frac{r^3}{a^2}\right)$.

Attraction of the inner sphere (the same as that of the whole shell) upon a point at $P = \frac{\text{Mass}}{r^2} = \frac{4}{3}\pi D'r$.

If, as in the case of the earth, the density continually increases toward the centre, the value of D' will increase also, as r diminishes, so that gravity will diminish less rapidly than in the case of a homogeneous sphere, and may, in fact, actually increase as we descend. To show this, let us subtract the attraction at P from that at the surface. The difference will give :

$$\text{Diminution at } P = \frac{4}{3}\pi\left(Da + (D' - D)\frac{r^3}{a^2} - D'r\right)$$

Now let us suppose r a very little less than a, and put $r = a - d$; d will then be the depth of the particle below the surface.

Cubing this value of r, neglecting the higher powers of d, and dividing by a^2, we find $\frac{r^3}{a^2} = a - 3d$. Substituting in the above equation, the diminution of gravity at P becomes $\frac{4}{3}\pi(3D - 2D')d$.

We see that if $3D < 2D'$—that is, if the density at the surface is less than $\frac{2}{3}$ of the mean density of the whole inner mass—this quantity will become negative, showing that the force of gravity will be less at the surface than at a small depth in the interior. But it must ultimately diminish, because it is necessarily zero at the centre. It was on this principle that Professor AIRY determined the density of the earth by comparing the vibrations of a pendulum at the bottom of the Harton Colliery, and at the surface of the earth in the neighborhood. At the bottom of the mine the pendulum gained about $2^s \cdot 5$ per day, showing the force of gravity to be greater there than at the surface.

FIGURE AND MAGNITUDE OF THE EARTH.

If the earth were fluid and did not rotate on its axis, it would assume the form of a perfect sphere. The opinion is entertained that the earth was once in a molten state, and that this is the origin of its present nearly spherical form. If we give such a sphere a rotation upon its axis, the centrifugal force at the equator acts in a direction opposed to gravity, and thus tends to enlarge the circle of the equator. It is found by mathematical analysis that the form of such a revolving fluid sphere, supposing it to be perfectly homogeneous, will be an oblate ellipsoid ; that is, all the meridians will be equal and similar ellipses, having their major axes in the equator of the sphere and their minor axes coincident with the axis of rotation. Our earth, however, is not wholly fluid, and the solidity of its continents prevents its assuming the form it would take if the ocean covered its entire surface. By the figure of the earth we mean, hereafter, not the outline of the solid and liquid portions respectively, but the figure which it would assume if its entire surface were an ocean. Let us imagine canals dug down to the ocean level in every direction through the continents, and the water of the ocean to be admitted into them. Then the curved surface touching the water in all these canals, and coincident with the surface of the ocean, is that of the ideal earth considered by astronomers. By the figure of the earth is meant the figure of this liquid surface, without reference to the inequalities of the solid surface.

We cannot say that this ideal earth is a perfect ellipsoid, because we know that the interior is not homogeneous, but all the geodetic measures heretofore made are so nearly represented by the hypothesis of an ellipsoid that the latter is a very close approximation to the true figure. The deviations hitherto noticed are of so irregular a character that they have not yet been reduced to any certain law.

The largest which have been observed seem to be due to the attraction of mountains, or to inequalities in the density of the rocks beneath the surface.

Method of Triangulation.—Since it is practically impossible to measure around or through the earth, the magnitude as well as the form of our planet has to be found by combining measurements on its surface with astronomical observations. Even a measurement on the earth's surface made in the usual way of surveyors would be impracticable, owing to the intervention of mountains, rivers, forests, and other natural obstacles. The method of triangulation is therefore universally adopted for measurements extending over large areas.

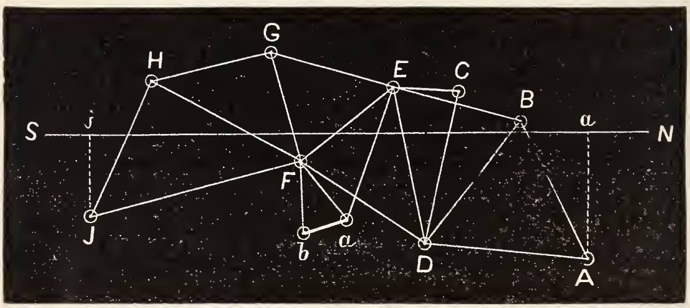

Fig. 46.—A Part of the French Triangulation near Paris.

Triangulation is executed in the following way: Two points, *a* and *b*, a few miles apart, are selected as the extremities of a base-line. They must be so chosen that their distance apart can be accurately measured by rods; the intervening ground should therefore be as level and free from obstruction as possible. One or more elevated points, *E F*, etc., must be visible from one or both ends of the base-line. By means of a theodolite and by observation of the pole-star, the directions of these points relative to the meridian are accurately observed from each end of the base, as is also the direction *a b* of the base-line itself. Suppose *F* to be a point visible from each end of the base, then in the triangle *a b F* we have the length *a b* determined by actual measurement, and the angles at a and b determined by observations. With these data the lengths of the sides $a\,F$ and $b\,F$ are determined by a simple computation.

The observer then transports his instruments to F, and determines in succession the direction of the elevated points or hills $D\,E\,G\,H\,J$, etc. He next goes in succession to each of these hills, and determines the direction of all the others which are visible from it. Thus a network of triangles is formed, of which all the angles are observed with the theodolite, while the sides are successively calculated from the first base. For instance, we have just shown how the side $a\,F$ is calculated; this forms a base for the triangle $E\,F\,a$, the two remaining sides of which are computed. The side $E\,F$ forms the base of the triangle $G\,E\,F$, the sides of which are calculated, etc. In this operation more angles are observed than are theoretically necessary to calculate the triangles. This surplus of data serves to insure the detection of any errors in the measures, and to test their accuracy by the agreement of their results. Accumulating errors are further guarded against by measuring additional sides from time to time as opportunity offers.

Chains of triangles have thus been measured in Russia and Sweden from the Danube to the Arctic Ocean, in England and France from the Hebrides to Algiers, in this country down nearly our entire Atlantic coast and along the great lakes, and through shorter distances in many other countries. An east and west line is now being run by the Coast Survey from the Atlantic to the Pacific Ocean. Indeed it may be expected that a network of triangles will be gradually extended over the surface of every civilized country, in order to construct perfect maps of it.

Suppose that we take two stations, a and j, Fig. 46, situated north and south of each other, determine the latitude of each, and calculate the distance between them by means of triangles, as in the figure. It is evident that by dividing the distance in kilometres by the difference of latitude in degrees we shall have the length of one degree of latitude. Then if the earth were a sphere, we should at once have its circumference by multiplying the length of one degree by 360. It is thus found that the length of a degree is a little more than 111 kilometres, or between 69 and 70 English statute miles. Its circumference is therefore about 40,000 kilometres, and its diameter between 12,000 and 13,000.*

* When the metric system was originally designed by the French, it was intended that the kilometre should be $\frac{1}{10000}$ of the distance from the pole of the earth to the equator. This would make a degree of the meridian equal, on the average, to $111\frac{1}{9}$ kilometres. But the metre actually adopted is nearly $\frac{1}{100}$ of an inch too short.

Owing to the ellipticity of the earth, the length of one degree varies with the latitude and the direction in which it is measured. The next step in the order of accuracy is to find the magnitude and the form of the earth from measures of long arcs of latitude (and sometimes of longitude) made in different regions, especially near the equator and in high latitudes. But we shall still find that different combinations of measures give slightly different results, both for the magnitude and the ellipticity, owing to the irregularities in the direction of attraction which we have already described. The problem is therefore to find what ellipsoid will satisfy the measures with the least sum-total of error. New and more accurate solutions will be reached from time to time as geodetic measures are extended over a wider area. The following are among the most recent results:

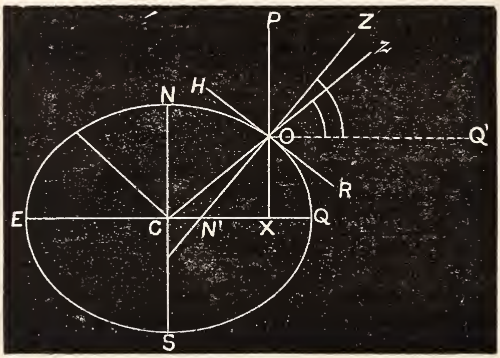

FIG. 47.

the earth's polar semidiameter, 6355·270 kilometres; earth's equatorial semidiameter, 6377·377 kilometres ; earth's compression, $\frac{1}{288.5}$ of the equatorial diameter ; earth's eccentricity of meridian, 0·08319. Another result is that of Captain CLARKE of England, who found: polar semidiameter, 6356·456* kilometres; equatorial semidiameter, 6378·191 kilometres.

Geographic and Geocentric Latitudes.—An obvious result of the ellipticity of the earth is that the plumb-line does not point toward the earth's centre. Let Fig. 47 represent a meridional section of the earth, NS being the axis of rotation, EQ the plane of the equator, and O the position of the observer. The line HR, tangent to the

* Captain CLARKE's results are given in feet. the polar radius being 20,854,895 feet, the equatorial 20,926,202. These numbers are in the proportion 292 : 293.

earth at O, will then represent the horizon of the observer, while the line $Z N'$, perpendicular to $H R$, and therefore normal to the earth at O, will be the vertical as determined by the plumb-line. The angle $O N' Q$, or $Z O Q'$, which the observer's zenith makes with the equator will then be his astronomical or geographical latitude. This is the latitude which in practice we always have to use, because we are obliged to determine latitude by astronomical observation, and not by measurement from the equator. We cannot determine the direction of the true centre C of the earth by direct observation of any kind, but only the direction of the plumb-line, or of the perpendicular to a fluid surface. $Z O Q'$ is the astronomical latitude. If, however, we conceive the line $C O z$ drawn from the centre of the earth through O, z will be the observer's *geocentric zenith*, while the angle $O C Q$ will be his *geocentric latitude*. It will be observed that it is the geocentric and not the geographic latitude which gives the true position of the observer relative to the earth's centre. The difference between the two latitudes is the angle $C O N'$ or $Z O z$; this is called the *angle of the vertical*. It is zero at the poles and at the equator, because here the normals pass through the centre of the ellipse, and it attains its maximum of 11′ 30″ at latitude 45°. It will be seen that the geocentric latitude is always less than the geographic. In north latitudes the geocentric zenith is south of the apparent zenith, and in southern latitudes north of it; being nearer the equator in each case.

Motion of the Earth's Axis, or Precession of the Equinoxes.

Sidereal and Equinoctial Year.—In describing the apparent motion of the sun, two ways of finding the time of its apparent revolution around the sphere were described; in other words, of fixing the length of a year. One of these methods consists in finding the interval between successive passages of the sun through the equinoxes, or, which is the same thing, across the plane of the equator, and the other by finding when it returns to the same position among the stars. Two thousand years ago Hipparchus found, by comparing his own observations with those made two centuries before by Timocharis, that these two methods of fixing the length of the year did not give the same result. It had previously been considered that the length of a year was about 365¼ days, and in attempting to correct this period by comparing his observed times of the sun's passing the equinox with those of TIMOCHARIS, HIPPARCHUS found that the length required a diminution of seven or eight minutes. He therefore concluded that the true length of the equinoctial year was 365 days 5 hours and about 53 minutes. When, however, he considered the return of the sun not to the equinox, but to the same position relative to the bright star *Spica Virginis,* he found that it took some minutes more than 365¼ days to complete the revolution. Thus there are two years to be distinguished, the *tropical* or *equinoctial* year and the *sidereal* year. The first is measured by the time of the sun's return to the equinox; the second by its return to the same position relative to the stars. Although the sidereal year is the correct astronomical period of one revolution of the earth around the sun, yet the equinoctial year is the one to be used in civil life, because the change of seasons depends upon that year. Modern determinations show the respective lengths of the two years to be:

Sidereal year,	$365^d\ 6^h\ 9^m\ 9^s = 365^d.25636.$
Equinoctial year,	$365^d\ 5^h\ 48^m\ 46^s = 365^d.24220.$

It is evident from this difference between the two years that the position of the equinox among the stars must be changing, and that it must move toward the west, because the equinoctial year is the shorter. This motion is called the *precession of the equinoxes,* and amounts to about 50″ per year. The equinox being simply the point in which the equator and the ecliptic intersect, it is evident that it can change only through a change in one or both of these circles. HIPPARCHUS found that the change was in the equator and not in the ecliptic, because the declinations of the stars changed, while their latitudes did not. Since the equator is defined as a circle everywhere 90° distant from the pole, and since it is moving among the stars, it follows that the pole must also be moving among the stars. But the pole is nothing more than the point in which the earth's axis of rotation intersects the celestial sphere: the position of this pole in the celestial sphere depends solely upon the *direction* of the earth's axis, and is not changed by the motion of the earth around the sun. Hence precession shows that the direction of the earth's axis is continually changing. Careful observations from the time of HIPPARCHUS until now show that the change in question consists in a slow revolution of the pole of the earth around the pole of the ecliptic as projected on the celestial sphere. The rate of motion is such that the revolution will be completed in between 25,000 and 26,000 years. At the end of this period the equinox and solstices will have made a complete revolution in the heavens.

The nature of this motion will be seen more clearly by referring to Fig. 32, p. 93. We have there represented the earth in four positions during its annual revolution. We have represented the axis as inclining to the right in each of these positions, and have described it as remaining parallel to itself during an entire revolution. The phenomena of precession show that this is not absolutely true, but that, in reality, the direction of the axis is slowly changing. This change is such that, after the lapse of some 6400 years, the north pole of the earth, as represented in the figure, will not incline to the right, but toward the observer, the amount of the inclination remaining nearly the same. The result will evidently be a shifting of the seasons. At D we shall have the winter solstice, because the north pole will be inclined toward the observer and therefore from the sun, while at A we shall have the vernal equinox instead of the winter solstice, and so on.

In 6400 years more the north pole will be inclined toward the left, and the seasons will be reversed. Another interval of the same length, and the north pole will be inclined from the observer, the seasons being shifted through another quadrant. Finally, at the end of about 25,800 years, the axis will have resumed its original direction.

Precession thus arises from a motion of the earth alone and not of the heavenly bodies. Although the direction of the earth's axis changes, yet the position of this axis relative to the crust of the earth remains invariable. Some have supposed that precession would result in a change in the position of the north pole on the surface of

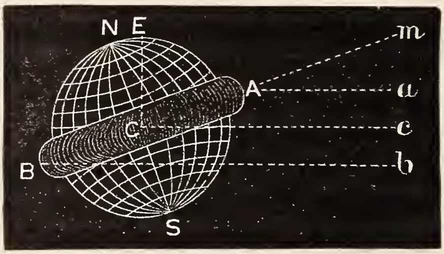

FIG. 48.

the earth, so that the northern regions would be covered by the ocean as a result of the different direction in which the ocean would be carried by the centrifugal force of the earth's rotation. This, however, is a mistake. It has been shown that the position of the poles, and therefore of the equator, on the surface of the earth, cannot change except from some variation in the arrangement of the earth's interior. Scientific investigation has yet shown nothing to indicate any probability of such a change.

The motion of precession is not uniform, but is subject to several small inequalities which are called *nutation*.

THE CAUSE OF PRECESSION.

The cause of precession, etc., is illustrated in the figure, which shows a spherical earth surrounded by a ring of matter at the equator. If the earth were really spherical there would be no precession. It is, however, ellipsoidal with a protuberance at the equator. The effect of this protuberance is to be examined. Consider the action between the sun and earth alone. If the ring of matter were absent, the earth would revolve about the sun as is shown in Fig. 32, p. 93 (Seasons).

We remember that the sun's N. P. D. is 90° at the equinoxes, and $66\frac{1}{2}°$ and $113\frac{1}{2}°$ at the solstices. At the equinoxes the sun is in the direction Cm; that is, NCm is 90°. At the winter solstice the sun is in the direction Cc; $NCc = 113\frac{1}{2}°$. It is clear that in the latter case the effect of the sun on the ring of matter will be to pull it down from the direction Cm towards the direction Cc. An opposite effect will be produced by the sun when its polar distance is $66\frac{1}{2}°$.

The moon also revolves round the earth in an orbit inclined to the equator, and in every position of the moon it has a different action on the ring of matter. The earth is all the time rotating on its axis, and these varying attractions of sun and moon are equalized and distributed since different parts of the earth are successively presented to the attracting body. The result of all the complex motions we have described is a conical motion of the earth's axis NC about the line CE.

The earth's shape is not that given in the figure, but it is an ellipsoid of revolution. The ring of matter is not confined to the equator, but extends away from it in both directions. The effects of the forces acting on the earth as it is are however, similar to the effects we have described.

CHAPTER X.

CELESTIAL MEASUREMENTS OF MASS AND DISTANCE.

The Celestial Scale of Measurement.

The units of length and mass employed by astronomers are necessarily different from those used in daily life. The distances and magnitudes of the heavenly bodies are never reckoned in miles or other terrestrial measures for astronomical purposes; when so expressed it is only for the purpose of making the subject clearer to the general reader. The units of weight or mass are also, of necessity, astronomical and not terrestrial. The mass of a body may be expressed in terms of that of the sun or of the earth, but never in kilogrammes or tons, unless in popular language. There are two reasons for this course. One is that in most cases celestial distances have first to be determined in terms of some celestial unit—the earth's distance from the sun, for instance—and it is more convenient to retain this unit than to adopt a new one. The other is that the values of celestial distances in terms of ordinary terrestrial units are for the most part uncertain, while the corresponding values in astronomical units are known with great accuracy.

An extreme instance of this is afforded by the dimensions of the solar system. By a series of astronomical observations, investigated by means of Kepler's laws and the theory of gravitation, it is possible to determine the forms of the planetary orbits, their positions, and their dimensions in terms of the earth's mean distance from the sun as the unit of measure, with great precision. KEPLER'S third law enables us to determine the mean distance of a planet from the sun when we know its period of revolution. All the major planets, as far out as *Saturn,* have been observed through so many revolutions that their *periodic times* can be determined with great exactness—in fact within a fraction of a millionth part of their whole amount. The more recently discovered planets, *Uranus* and *Neptune,* will, in the course of time, have their periods determined with equal precision. Then, if we square the periods expressed in years and decimals of a year, and extract the cube root of this square, we have the *mean distance* of the planet with the same order of precision. This distance is to be corrected slightly in consequence of the attractions of the planets on each other, but these corrections also are known with great exactness. Again, the *eccentricities* of the orbits are exactly determined by careful observations of the positions of the planets during successive revolutions. Thus we could make a map of the planetary orbits so exact that the error would entirely elude the most careful scrutiny, though the map itself might be many yards in extent.

On the scale of this same map we could lay down the magnitudes of the planets with as much precision as our instruments can measure their angular semidiameters. Thus we know that the mean diameter of the sun, as seen from the earth, is 32′; hence we deduce from formulæ already given on pages 5 and 57 that the diameter of the sun is .0093083 of the distance of the sun from the earth. We can therefore, on our supposed map of the solar system, lay down the sun in its true size, according to the scale of the map, from data given directly by observation. In the same way we can do this for each of the planets, the earth and moon excepted. There is no immediate and direct way of finding how large the earth or moon would look from a planet; whence the exception.

But without further special research into this subject, we shall know nothing about the *scale* of our map. That is, we have no means of knowing how many miles or kilometres correspond in space to an inch or a foot on the map. It is clear that in order to fix the distances or the magnitudes of the planets according to any terrestrial standard, we must know this scale. Of course if we can learn either the distance or magnitude of any one of the planets laid down on the map, in miles or in semidiameters of the earth, we shall be able at once to find the scale. But this process is so difficult that the general custom of astronomers is not to attempt to use a scale of miles, but to employ the mean distance of the sun from the earth as the unit in celestial measurements. Thus, in astronomical language, we say that the distance of *Mercury* from the sun is 0.387, that of *Venus* 0.723, that of *Mars* 1.523, that of *Saturn* 9.539, and so on. But this gives us no information respecting the distances and magnitudes in terms of terrestrial measures. The unknown quantities of our map are the magnitude of the earth and its distance from the sun in terrestrial units of length. Could we only take up a point of observation on the sun or a planet, and determine exactly the angular magnitude of the earth as seen from that point, we should be able to lay down the earth of our map in its correct size. Then, since we already know the size of the earth in terrestrial units from geodetic surveys we, should be able to find the scale of our map, and thence the dimensions of the whole system in terms of those units.

It will be seen that what the astronomer really wants is not so much the dimensions of the solar system in miles as to express the size of the earth in celestial measures. This, however, amounts to the same thing, because having one, the other can be readily deduced from the known magnitude of the earth in terrestrial measures.

The magnitude of the earth is not the only unknown quantity on our map. From KEPLER's laws we can determine nothing respecting the distance of the moon from the earth, because unless a change is made in the units of time and space, they apply only to bodies moving around the sun. We must therefore determine the distance of the moon as well as that of the sun to be able to complete our map on a known scale of measurement.

MEASURES OF THE SOLAR AND LUNAR PARALLAX.

The problem of distances in the solar system is reduced by the preceding considerations to measuring the distances of the sun and moon in terms of the earth's radius. The most direct method of doing this is by determining their respective parallaxes, which we have shown to be the same as the earth's angular semidiameter as seen from them. In the case of the sun, the required parallax can be determined as readily by measuring the parallaxes of any of the planets as by measuring that of the sun, because any one measured distance on the map will give us the scale of our map. Now, the planets *Venus* and *Mars* occasionally come much nearer the earth than the sun ever does, and their parallaxes also admit of more exact measurement.

The parallax of the sun is therefore determined not by observations on the sun itself, but on these two planets.

The general principles of the method of determining the parallax of a planet by simultaneous observations at distant stations will be seen by referring to the figure. If two observers, situated at S' and S'', make a simultaneous observation of the direction of the body P, it is evident that the solution of a plane triangle will give the distance of P from each station. In practice, however, it would

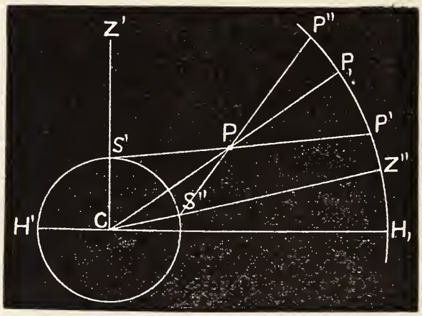

FIG. 49.

be impracticable to make simultaneous observations at distant stations; and as the planet is continually in motion, the problem is a much more complex one than that of simply solving a triangle.

This is the method of determining the parallax of the moon. Knowing the actual figure of the earth, observations of the moon made at stations widely separated in latitude, as Paris and the Cape of Good Hope, can be combined so as to give the parallax of the moon and thus its distance. On precisely the same principles the parallaxes of *Venus* or *Mars* have been determined.

Solar Parallax from Transits of Venus.—When *Venus* is at her inferior conjunctions she is between the sun and the earth. If the orbit of *Venus* lay in the ecliptic, she would be projected on the sun's disk at every inferior conjunction. The inclination of her orbit is, however, about $3\frac{1}{2}°$, and thus the *transits* of *Venus* occur only when *Venus* happens to be near the node of her orbit at the time of inferior conjunction. When this occurs she is seen to pass across the sun's disk. In the last figure, if P is the place of *Venus* at such a time, and if the disk of the sun is $P'P''$, then an observer at S'' will see *Venus* at P'' and one at S' will see her at P'. The distance $P'P''$ can be measured directly, or it can be calculated by observing the time required for *Venus* to pass across the chord of the sun's disk at P'' and across the chord at P'. It is obvious that these chords are of different length.

The *parallax* of *Venus* (π') is the angle subtended by the earth's radius at P; the parallax of the sun (π) is the angle subtended by the earth's radius at P_1.

If a is the distance of the earth from *Venus*, and if b is the distance of the earth from the sun, we know that the earth's radius c will subtend an angle at *Venus* of $\frac{c}{a} = \pi'$, and at the sun of $\frac{c}{b} = \pi$ (see page 5). That is, $c = a\,\pi' = b\,\pi$ and $\pi' = \frac{b}{a} \cdot \pi$. b is $1 \cdot 00$; and a is about 0.26 at the time of a transit. Hence $\pi' = 3.8\pi$.

What we really measure is the difference of the parallaxes π' and π, and thus, by employing the transit of *Venus* to measure the sun's parallax ($8''.8$), we are enabled to use an angle 2.8 times as large, or about $25''$. Even this is a very difficult matter: it is hardly possible by any one set of measures of the solar parallax to determine the latter without an uncertainty of $\frac{1}{200}$ of its whole amount. In the distance of the sun this corresponds to an uncertainty of nearly half a million of miles. Astronomers have therefore sought for other methods of determining the sun's distance. Although some of these may be a little more certain than measures of parallax, there is none by which the distance of the sun in miles can be determined with any approximation to the accuracy which characterizes other celestial measures.

Other Methods of Determining Solar Parallax.—A very interesting and probably the most accurate method of measuring the sun's distance depends upon a knowledge of the velocity of light. We shall hereafter see that the time required for light to pass from the sun to the earth is known with considerable exactness, being very nearly 498 seconds. This time can be determined still more accurately. If then we can determine experimentally how many miles or kilometres light moves in a second, we shall at once have the distance of the sun by multiplying that quantity by 498. The velocity of light is about 300,000 kilometres per second. This distance would reach about eight times around the earth. It is seldom possible to see two points on the earth's surface more than a hundred kilometres apart, and distinct vision at distances of more than twenty kilometres is rare. Hence to determine experimentally the time required for light to pass between two terrestrial stations requires the measurement of an interval of time which, even under the most favorable cases, can be only a fraction of a thousandth of a second. Methods of doing it, however, have been devised, and the velocity of light would seem to be about 299,900 kilometres per second. Multiplying this by 498, we obtain 149,350,000 kilometres (a little less than 93,000,000 miles) for the distance of the sun. The time required for light to pass from the sun to the earth is still uncertain by nearly a second, but this value of the sun's distance is probably the best yet obtained. The corresponding value of the sun's parallax is 8″.81.

Yet other methods of determining the sun's distance are given by the theory of gravitation. It is found by mathematical investigation that the motion of the moon is subject to several inequalities, having the sun's horizontal parallax as a factor. If the position of the moon could be determined by observation with the same exactness that the position of a star or planet can (which it cannot be), this would probably afford the most accurate method of determining the solar parallax.

Brief History of Determinations of the Solar Parallax.—The determination of the distance of the sun must at all times have been one of the most interesting scientific problems presented to the human mind. The first known attempt to effect a solution of the problem was made by ARISTARCHUS, who flourished in the third century before CHRIST. It was founded on the principle that the time of the moon's first quarter will vary with the ratio between the distance of the moon and sun, which may be shown as follows. In Fig. 50 let E represent the earth, M the moon, and S the sun. Since the sun always illuminates one half of the lunar globe, it is evident that when one

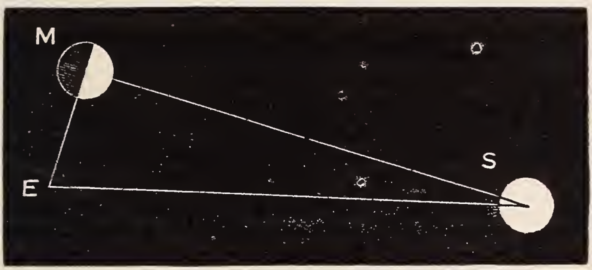

FIG. 50.

half of the moon's disk appears illuminated the triangle EMS must be right-angled at M. The angle MES can be determined by measurement, being equal to the angular distance between the sun and the moon. Having two of the angles, the third can be determined, because the sum of the three must make two right angles. Thence we shall have the ratio between EM, the distance of the moon, and ES, the distance of the sun, by a trigonometrical computation. Then knowing the distance of the moon, which can be determined with comparative ease (see page 162), we have the distance of the sun by multiplying by this ratio. ARISTARCHUS concluded, from his supposed measures, that the angle MES was three degrees less than a right angle. We should then have $\frac{EM}{ES} = \frac{1}{19}$ very nearly, since 3° is $\frac{1}{19}$ of 57° and $ES = 57°$ (see page 5). It would follow from this that the sun was 19 times the distance of the moon. We now know that this result is entirely wrong, and that it is so because it is impossible to determine the time when the moon is exactly half illuminated with any approach to the accuracy necessary in the solution of the problem. In fact, the greatest angular distance of the earth and moon, as seen from the sun—that is, the angle ESM—is only about one quarter the angular diameter of the moon as seen from the earth.

The second attempt to determine the distance of the sun is mentioned by PTOLEMY, though HIPPARCHUS may be the real inventor of it. It is founded on a somewhat complex geometrical construction of a total eclipse of the moon. It is only necessary to state the result, which was that the sun was situated at the distance of 1210 radii of the earth. This result, like the former, was due only to errors of observation. So far as all the methods known at the time could show, the real distance of the sun appeared to be infinite; nevertheless PTOLEMY'S result was received without question for fourteen centuries.

The first really successful measure of the parallax of a planet was made upon *Mars* during the opposition of 1672, by the first of the two methods already described. An expedition was sent to the colony of Cayenne to observe the declination of the planet from night to night, while corresponding observations were made at the Paris Observatory. From a discussion of these observations, CASSINI obtained a solar parallax of 9″.5, which is within a second of the truth. The next steps forward were made by the transits of *Venus* in 1761 and 1769. The leading civilized nations caused observations on these transits to be made at various points on the globe. The method used was very simple, consisting in the determination of the times at which *Venus* entered upon the sun's disk and left it again. The absolute times of ingress and egress, as seen from different points of the globe, might differ by 20 minutes or more on account of parallax. The results, however, were found to be discordant. It was not until more than half a century had elapsed that the observations were systematically calculated by ENCKE of Germany, who concluded that the parallax of the sun was 8″.578, and the distance 95 millions of miles.

In 1854 it began to be suspected that ENCKE'S value of the parallax was much too small. HANSEN, from the theory of the moon, found the parallax of the sun to be 8″.916. This result seemed to be confirmed by other observations, especially those of *Mars* during 1862. It was therefore concluded that the sun's parallax was probably between 8″.90 and 9″.00. Subsequent researches have, however, been diminishing this value. In 1867, from a discussion of all the data which were considered of value, it was concluded by one of the writers that the most probable parallax was $8''.848$. The measures of the velocity of light reduce this value to $8''.81$, and it is now doubtful whether the true value is any larger than this.

All we can say at present is that the solar parallax is probably between $8''.79$ and $8''.83$, or, if outside these limits, that it can be very little outside.

Relative Masses of the Sun and Planets.

In estimating celestial masses as well as distances, it is necessary to use what we may call celestial units; that is, to take the mass of some celestial body as a unit, instead of any multiple of the pound or kilogram. The reason of this is that the *ratios* between the masses of the planetary system, or, which is the same thing, the mass of each body in terms of that of some one body as the unit, can be determined independently of the mass of any one of them. To express a mass in kilogrammes or other terrestrial units, it is necessary to find the mass of the earth in such units, as already explained. This, however, is not necessary for astronomical purposes, where only the relative masses of the several planets are required. In estimating the masses of the individual planets, that of the sun is generally taken as a unit. The planetary masses will then all be very small fractions.

The mass of	the sun	being	1.00,	the mass of	*Mercury*	is	$\frac{1}{5000000}$;
"	"	"	"	"	*Venus*	is	$\frac{1}{425000}$;
"	"	"	"	"	*Earth*	is	$\frac{1}{326800}$;
"	"	"	"	"	*Mars*	is	$\frac{1}{3093500}$;
"	"	"	"	"	*Jupiter*	is	$\frac{1}{1048}$;
"	"	"	"	"	*Saturn*	is	$\frac{1}{3502}$;
"	"	"	"	"	*Uranus*	is	$\frac{1}{22600}$;
"	"	"	"	"	*Neptune*	is	$\frac{1}{19380}$.

Masses of the Earth and Sun.—The mass of the earth is connected by a very curious relation with the parallax of the sun. Knowing the latter, we can determine the mass of the sun relative to the earth, which is the same thing as determining the astronomical mass of the earth, that of the sun being unity. This may be clearly seen by reflecting that when we know the radius of the earth's orbit we can determine how far the earth moves aside from a straight line in one second in consequence of the attraction of the sun. This motion measures the attractive force of the sun at the distance of the earth.

Comparing it with the attractive force of the earth, and making allowance for the difference of distances from centres of the two bodies, we determine the ratio between their masses.

The following table shows, for different values of the solar parallax, the corresponding ratio of the masses, and distance of the sun in terrestrial measures:

Solar Parallax. P''	$\frac{M}{m}$	Distance of the Sun		
		In equatorial radii of the earth.	In millions of miles.	In millions of kilometres.
8″.77	335684	23519	93.208	150.001
8″.78	334538	23492	93.102	149.830
8″.79	333398	23466	92.996	149.660
8″.80	332262	23439	92.890	148.490
8″.81	331132	23413	92.785	149.320
8″.82	330007	23386	92.680	149.151
8″.83	328887	23360	92.575	148.982

We have said that the solar parallax is probably contained between the limits 8″.79 and 8″.83. It is certainly hardly more than one or two hundredths of a second without them. So, if we wish to express the constants relating to the sun in round numbers, we may say that—

Its *mass* is 330,000 times that of the earth.

Its *distance* in miles is 93 millions, or perhaps a little less.

Its distance in kilometres is probably between 149 and 150 millions.

CHAPTER XI.

THE REFRACTION AND ABERRATION OF LIGHT AND TWILIGHT.

Atmospheric Refraction.

When we speak of the *place* of a planet or star, we usually mean its *true* place; *i.e.*, its direction from an observer situated at the centre of the earth. We have shown in the section on parallax how observations which are necessarily taken at the surface of the earth are reduced to what they would have been if the observer were situated at the earth's centre. We have supposed the star to be projected on the celestial sphere in the prolongation of the line joining the observer and the star. The ray from the star was considered to suffer no deflection in passing through the stellar spaces and through the earth's atmosphere. But from the principles of physics, we know that such a luminous ray passing from an empty space (as the stellar spaces probably are), and through an atmosphere, must suffer a refraction, as every ray of light is known to do in passing from a rare into a denser medium. As we see the star in the direction in which its light enters the eye—that is, as we project the star on the celestial sphere by prolonging this light-beam backward into space—there must be an apparent displacement of the star from refraction.

We may recall a few definitions from physics. The ray which leaves the star and impinges on the outer surface of the earth's atmosphere is called the *incident ray;* after its deflection by the atmosphere it is called the *refracted ray.* The difference between these directions is called the *astronomical refraction.* If a normal is drawn (perpendicular) to the surface of the refracting medium at the point where the incident ray meets it, the acute angle between the incident ray and the normal is called the *angle of incidence,* and the acute angle between the normal and the refracted ray is called the *angle of refraction.* The refraction itself is the difference of these angles. The normal and both incident and refracted rays are in the same vertical plane. In Fig. 51, SA is the ray incident upon the surface BA of the refracting medium $B'BAN$, AC is the refracted ray, MN the normal, SAM and CAN the angles of incidence and refraction respectively. Produce CA backward in the direction AS': SAS' is the refraction. An observer at C will see the star S as if it were at S'. AS' is the apparent direction of the ray coming from the star S, and S' is the *apparent place* of the star as affected by refraction.

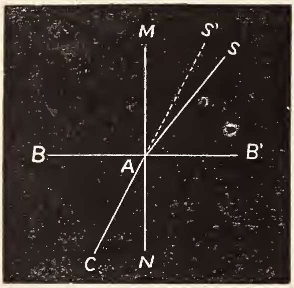

Fig. 51.—Refraction.

This explanation supposes the space above BB' in the figure to be entirely empty, and the earth's atmosphere, equally dense throughout, to fill the space below BB'. In fact, however, the earth's atmosphere is most dense at the surface of the earth, and gradually diminishes in density to its exterior boundary. Therefore we must suppose the atmosphere to be divided into a great number of parallel layers of air, and by assuming an infinite number of these we may also assume that throughout each one of them the air is equally dense. Hence the preceding figure will only represent the refraction at a single one of these layers. The path of a ray of light through the atmosphere is not a straight line like AC, but a curve. We may suppose this curve to be represented in Fig. 52, where the number of layers has been taken very small to avoid confusing the drawing.

Let C be the centre and A a point of the surface of the earth; let S be a star, and $S e$ a ray from the star which is refracted at the various layers into which we suppose the atmosphere to be divided, and which finally enters the eye of an observer at A in the apparent direction $S' A$. He

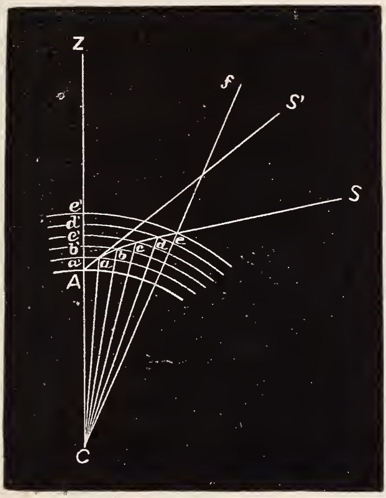

FIG. 52.—REFRACTION OF LAYERS OF AIR.

will then see the star in the direction S' instead of that of S, and $S A S'$, the refraction, will throw the star nearer to his zenith Z.

The angle $S' A Z$ is the apparent zenith distance of S; the true zenith distance of S is $Z A S$, and $S A$ may be assumed to coincide with $S e$, as for all heavenly bodies except the moon it practically does. The line $S e$ prolonged will meet the line $A\ Z$ in a point above A, suppose at b'.

Quantity and Effects of Refraction.—At the zenith the refraction is 0, at 45° zenith distance the refraction is about 1′, and at 90° it is 34′ 30″; that is, bodies at the zenith distances of 45° and 90° appear elevated above their true places by 1′ and 34½′ respectively. If the sun has just risen—that is, if its lower limb is just in apparent contact with the horizon—it is in fact entirely below the true horizon, for the refraction (35′) has elevated its centre by more than its whole apparent diameter (32′).

The moon is full when it is exactly opposite the sun, and therefore, were there no atmosphere, moon-rise of a full moon and sunset would be simultaneous. In fact, both bodies being elevated by refraction, we see the full moon risen before the sun has set. On April 20th, 1837, the full moon rose eclipsed before the sun had set.

Twilight.

It is plain that one effect of refraction is to lengthen the duration of daylight by causing the sun to appear above the horizon before the time of his geometrical rising and after the time of true sunset.

Daylight is also prolonged by the *reflection* of the sun's rays (after sunset and before sunrise) from the small particles of matter suspended in the atmosphere. This produces a general though faint illumination of the atmosphere, just as the light scattered from the floating particles of dust illuminated by a sunbeam let in through a crack in a shutter may brighten the whole of a darkened room.

The sun's direct rays do not reach an observer on the earth after the instant of sunset, since the solid body of the earth intercepts them. But the sun's direct rays illuminate the clouds and the suspended particles of the upper air, and are reflected downwards so as to produce a general illumination of the atmosphere.

In the figure let $A\ B\ C\ D$ be the earth and A an observer on its surface, to whom the sun S is just setting. $A\ a$ is the horizon of A; $B b$ of B; $C c$ of C; $D d$ of D. Let the

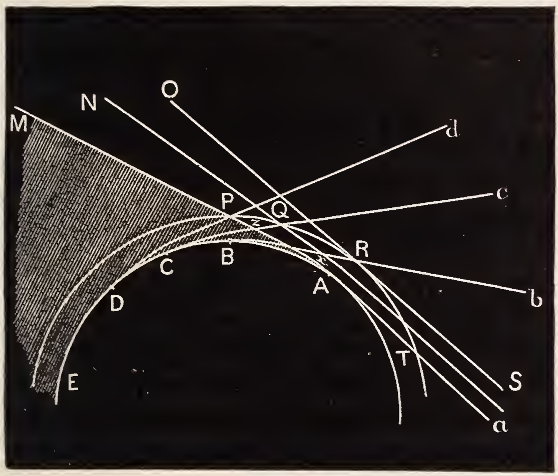

Fig. 53.

circle $P\ Q\ R$ represent the upper layer of the atmosphere. Between $A\ B\ C\ D$ and $P Q R$ the air is filled with suspended particles which will reflect light. The lowest ray of the sun, $S\ A\ M$, just grazes the earth at A; the higher rays $S\ N$ and $S\ O$ strike the atmosphere above A and leave it at the points Q and R. Each of the lines $S\ A\ P\ M$, $S\ Q\ N$, is bent from a straight course by refraction, but $S\ R\ O$ is not bent since it just touches the upper limits of the atmosphere. The space $MABCDE$ is the earth's shadow. An observer at A receives the (last) direct rays from the sun, and also has his sky illuminated by the reflection from all the particles lying in the space $PQRT$ which is all above his horizon Aa.

An observer at B receives no direct rays from the sun. It is after sunset. Nor does he receive any light from all that portion of the atmosphere below APM; but the portion PRx, which lies above his horizon Bb, is lighted by the sun's rays, and reflects to B a portion of the incident rays.

This *twilight* is strongest at R, and fades away gradually toward P.

To an observer at C the twilight is derived from the illumination of the portion PQz which lies above his horizon Cc.

To an observer at D it is night. All of the illuminated atmosphere is below his horizon Dd.

The student should notice for himself the twilight arch which appears in the west after sunset. It is more marked in summer than in winter; in high latitudes than in low ones. There is no true night in England in midsummer, for example, the morning twilight beginning before the evening twilight has ended; and in the torrid zone there is no perceptible twilight.

Aberration and the Motion of Light.

Besides refraction, there is another cause which prevents our seeing the celestial bodies exactly in the true direction in which they lie from us; namely, the progressive motion of light. We see objects only by the light which emanates from them and reaches our eyes, and we know that this light requires time to pass over the space which separates us from the luminous object. After the ray of light once leaves the object, the latter may move away, or even be blotted out of existence, but the ray of light will continue on its course. Consequently when we look at a star, we do not see the star that now is, but the star that was several years ago. If it should be annihilated, we should still see it during the years which would be required for the last ray of light emitted by it to reach us. The velocity of light is so great that in all observations of terrestrial objects our vision may be regarded as instantaneous. But in celestial observations the time required for the light to reach us is quite appreciable and measurable.

The discovery of the propagation of light is among the most remarkable of those made by modern science. The fact that light requires time to travel was first learned by the observations of the satellites of *Jupiter*. Owing to the great magnitude of this planet, it casts a much longer and larger shadow than our earth does, and its inner satellite passes through this shadow and is eclipsed, at every revolution. These eclipses can be observed from the earth, the satellite vanishing from view as it enters the shadow, and reappearing when it leaves it again. The astronomers of the seventeenth century made a careful study of the motions of these bodies. It was, however, necessary to construct tables by which the times of the eclipses could be predicted. It was found by ROEMER that these times depended on the distance of *Jupiter* from the earth. If he made his tables agree with observations when the earth was nearest *Jupiter*, it was found that as the earth receded from *Jupiter* in its annual course around the sun, the eclipses were constantly seen later, until, when at its greatest distance, the times appeared to be 22 minutes late. ROEMER saw that it was in the highest degree improbable that the actual motions of the satellites should be affected with any such inequality; he therefore propounded the bold theory that it took *time* for light to come from *Jupiter* to the earth. The extreme differences in the times of the eclipse being 22 minutes, he assigned this as the time required for light to cross the orbit of the earth, and so concluded that it came from the sun to the earth in 11 minutes. This estimate was too great; the true time for this passage being about 8 minutes and 18 seconds.

Discovery of Aberration.—This theory of ROEMER was not fully accepted by his contemporaries. But in the year 1729 the celebrated BRADLEY, afterward Astronomer Royal of England, discovered a phenomenon of an entirely different character, which confirmed the theory. He was then engaged in making observations on the star γ *Draconis* in order to determine its parallax. The effect of parallax would have been to make the declination of the star greatest in June and least in December, while in March and September the star would occupy an intermediate or mean position. But the result was entirely different. The declinations of June and December were the same, showing no effect of parallax; but instead of remaining constant the rest of the year, the declination was some 40 seconds greater in September than in March, when the effect of parallax would be the same. This showed that the direction of the star appeared different, not according to the position of the earth in its orbit, but according to the direction of the earth's motion around the sun, the star being apparently displaced in this direction.

To show how this is, let AB be the optical axis of a telescope, and S a star from which emanates a ray moving in the true direction SAB'. Perhaps the student will have a clearer conception of the subject if he imagines AB to be a rod which an observer at B seeks to point at the star S. It is evident that he will point this rod in such a way that the ray of light shall run accurately along its length. Suppose now that the observer is moving from B toward B' with such a velocity that he moves

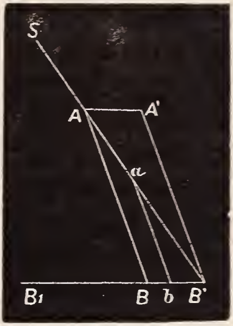

FIG. 54.

from B to B' during the time required for a ray of light to move from A to B'. Suppose, also, that the ray of light SA reaches A at the same time that the end of his rod does. Then it is clear that while the rod is moving from the position AB to the position $A'B'$, the ray of light will move from A to B', and will therefore run accurately along the length of the rod. For instance, if b is one third of the way from B to B', then the light, at the instant of the rod taking the position $b\,a$, will be one third of the way from A to B', and will therefore be accurately on the rod. Consequently, to the observer, the rod will appear to be pointed at the star. In reality, however, the pointing will not be in the true direction of the star, but will deviate from it by a certain angle depending upon the ratio of the velocity with which the observer is carried along to the velocity of light. This presupposes that the motion of the observer is at right angles to that of a ray of light. If this is not his direction, we must resolve his velocity into two components, one at right angles to the ray and one parallel to it. The latter will not affect the apparent direction of the star, which will therefore depend entirely upon the former.

Effects of Aberration.—The apparent displacement of the heavenly bodies thus produced is called the *aberration of light*. Its effect is to cause each of the fixed stars to ascribe an apparent annual oscillation in a very small orbit. The nature of the displacement may be conceived of in the following way: Suppose the earth at any moment, in the course of its annual revolution, to be moving toward a point of the celestial sphere, which we may call P. Then a star lying in the direction P or in the opposite direction will suffer no displacement whatever. A star lying in any other direction will be displaced in the direction of the point P by an angle depending upon its angular distance from P. At 90° from P the displacement will be a maximum.

Now, if the star lies near the pole of the ecliptic, its direction will always be nearly at right angles to the direction in which the earth is moving. A little consideration will show that it will seem to describe a circle in consequence of aberration. If, however, it lies in the plane of the earth's orbit, then the various points toward which the earth moves in the course of the year all lying in the ecliptic, and the star being in this same plane, the apparent motion will be an oscillation back and forth in this plane, and in all other positions the apparent motion will be in an ellipse more and more flattened as we approach the ecliptic. The maximum displacement of a star by aberration is 20″.44.

The connection between the velocity of light and the distance of the sun is such that knowing one we can infer the other. Let us assume, for instance, that the time required for light to reach us from the sun is 498 seconds, which is probably accurate within a single second. Then knowing the distance of the sun, we may obtain the velocity of light by dividing it by 498. But, on the other hand, if we can determine how many miles light moves in a second, we can thence infer the distance of the sun by multiplying it by the same factor. During the last century the distance of the sun was found to be certainly between 90 and 100 millions of miles. It was therefore correctly concluded that the velocity of light was something less than 200,000 miles per second, and probably between 180,000 and 200,000. This velocity has since been determined more exactly by the direct measurements at the surface of the earth already mentioned.

CHAPTER XII.

CHRONOLOGY.

Astronomical Measures of Time.

The intimate relation of astronomy to the daily life of mankind has arisen from its affording the only reliable and accurate measure of intervals of time. The fundamental units of time in all ages have been the day, the month, and the year, the first being measured by the revolution of the earth on its axis, the second, primitively, by that of the moon around the earth, and the third by that of the earth round the sun.

Of the three units of time just mentioned, the most natural and striking is the shortest; namely, the day. It is so nearly uniform in length that the most refined astronomical observations of modern times have never certainly indicated any change. This uniformity, and its entire freedom from all ambiguity of meaning, have always made the day a common fundamental unit of astronomers. Except for the inconvenience of keeping count of the great number of days between remote epochs, no greater unit would ever have been necessary, and we might all date our letters by the number of days after Christ, or after any other fixed date.

The difficulty of remembering great numbers is such that a longer unit is absolutely necessary, even in keeping the reckoning of time for a single generation. Such a unit is the year. The regular changes of seasons in all extra-tropical latitudes renders this unit second only to the day in the prominence with which it must have struck the minds of primitive man. These changes are, however, so slow and ill-marked in their progress that it would have been scarcely possible to make an accurate determination of the length of the year from the observation of the seasons. Here astronomical observations came to the aid of our progenitors, and, before the beginnings of history, it was known that the alternation of seasons was due to the varying declination of the sun, as the latter seemed to perform its annual course among the stars in the "oblique circle" or ecliptic. The seasons were also marked by the position of certain bright stars relatively to the sun; that is, by those stars rising or setting in the morning or evening twilight. Thus arose two methods of measuring the length of the year—the one by the time when the sun crossed the equinoxes or solstices, the other when it seemed to pass a certain point among the stars. As we have already explained, these years were slightly different, owing to the precession of the equinoxes, the first or equinoctial year being a little less and the second or sidereal year a little greater than 365¼ days.

The number of days in a year is too great to admit of their being easily remembered without any break; an intermediate period is therefore necessary. Such a period is measured by the revolution of the moon around the earth, or, more exactly, by the recurrence of new moon, which takes place, on the average, at the end of nearly 29½ days. The nearest round number to this is 30 days, and 12 periods of 30 days each only lack 5¼ days of being a year. It has therefore been common to consider a year as made up of 12 months, the lack of exact correspondence being filled by various alterations of the length of the month or of the year, or by adding surplus days to each year.

The true lengths of the day, the month, and the year having no common divisor, a difficulty arises in attempting to make months or days into years, or days into months, owing to the fractions which will always be left over. At the same time, some rule bearing on the subject is necessary in order that people may be able to remember the year, month, and day. Such rules are found by choosing some *cycle* or period which is very nearly an exact number of two units, of months and of days for example, and by dividing this cycle up as evenly as possible.

Formation of Calendars.

The months now or heretofore in use among the peoples of the globe may for the most part be divided into two classes:

(1) The lunar month pure and simple, or the mean interval between successive new moons.

(2) An approximation to the twelfth part of a year, without respect to the motion of the moon.

The Lunar Month.—The mean interval between consecutive new moons being nearly $29\frac{1}{2}$ days, it was common in the use of the pure lunar month to have months of 29 and 30 days alternately. This supposed period, however, will fall short by a day in about $2\frac{1}{2}$ years. This defect was remedied by introducing cycles containing rather more months of 30 than of 29 days, the small excess of long months being spread uniformly through the cycle. Thus the Greeks had a cycle of 235 months, of which 125 were full or long months, and 110 were short or deficient ones. We see that the length of this cycle was 6940 days ($125 \times 30 + 110 \times 29$), whereas the length of 235 true lunar months is $235 \times 29.53088 = 6939.688$ days. The cycle was therefore too long by less than one third of a day, and the error of count would amount to only one day in more than 70 years. The Mohammedans, again, took a cycle of 360 months, which they divided into 169 short and 191 long ones. The length of this cycle was 10631 days, while the true length of 360 lunar months is 10631.012 days. The count would therefore not be a day in error until the end of about 80 cycles, or nearly 23 centuries. This month therefore follows the moon closely enough for all practical purposes.

Months other than Lunar.—The complications of the system just described, and the consequent difficulty of making the calendar month represent the course of the moon, are so great that the pure lunar month was generally abandoned, except among people whose religion required important ceremonies at the time of new moon. In such cases the year has been usually divided into 12 months of slightly different lengths. The ancient Egyptians, however, had 12 months of 30 days each, to which they added 5 supplementary days at the close of each year.

Kinds of Year.—As we find two different systems of months to have been used, so we may divide the calendar years into three classes, namely:

(1) The lunar year, of 12 lunar months.

(2) The solar year.

(3) The combined luni-solar year.

The Lunar Year.—We have already called attention to the fact that the time of recurrence of the year is not well marked except by astronomical phenomena which the casual observer would hardly remark. But the time of new moon, or of beginning of the month, is always well marked. Consequently it was very natural for people to begin by considering the year as made up of twelve lunations, the error of eleven days being unnoticeable in a single year unless careful astronomical observations were made. Even when this error was fully recognized, it might be considered better to use the regular year of 12 lunar months than to use one of an irregular or varying number of months. The Mohammedans use such a year to this day.

The Solar Year.—In forming this year, the attempt to measure the year by revolutions of the moon is entirely abandoned, and its length is made to depend entirely on the change of the seasons. The solar year thus indicated is that most used in both ancient and modern times. Its length has been known to be nearly 365¼ days from the times of the earliest astronomers, and the system adopted in our calendar of having three years of 365 days each, followed by one of 366 days, has been employed in China from the remotest historic times. This year of 365¼ days is now called by us the *Julian Year*, after JULIUS CÆSAR, from whom we obtained it.

The Metonic Cycle.—These considerations will enable us to understand the origin of our own calendar. We begin with the Metonic Cycle of the ancient Greeks, which still regulates some religious festivals, although it has disappeared from our civil reckoning of time. The necessity of employing lunar months caused the Greeks great difficulty in regulating their calendar so as to accord with their rules for religious feasts, until a solution of the problem was found by METON, about 433 B.C. The discovery of METON was that a period or cycle of 6940 days could be divided up into 235 lunar months, and also into 19 solar years. Of these months, 125 were to be of 30 days each and 110 of 29 days each, which would, in all, make up the required 6940 days. To see how nearly this rule represents the actual motions of the sun and moon, we remark that:

	Days.	Hours.	Min.
235 lunations require................	6939	16	31
19 Julian years require............	6939	18	0
19 true solar years require..........	6939	14	27

We see that though the cycle of 6940 days is a few hours too long, yet if we take 235 true lunar months, we find their whole duration to be a little less than 19 Julian years of 365¼ days each, and a little more than 19 true solar years.

The problem was to take these 235 months and divide them up into 19 years, of which 12 should have 12 months each and 7 should have 13 months each. The long years, or those of 13 months, were probably those corresponding to the numbers 3, 5, 8, 11, 13, 16, and 19, while the first, second, fourth, sixth, etc., were short years. In general, the months had 29 and 30 days alternately, but it was necessary to substitute a long month for a short one every two or three years, so that in the cycle there should be 125 long and 110 short months.

Golden Number.—This is simply the number of the year in the Metonic Cycle, and is said to owe its appellation to the enthusiasm of the Greeks over METON's discovery, the authorities having ordered the division and numbering of the years in the new calendar to be inscribed on public monuments in letters of gold. The rule for finding the golden number is to divide the number of the year by 19 and add 1 to the remainder. From 1881 to 1899 it may be found by simply subtracting 1880 from the year. It is employed in our church calendar for finding the time of Easter Sunday.

The Julian Calendar.—The civil calendar now in use throughout Christendom had its origin among the Romans, and its foundation was laid by JULIUS CÆSAR. Before his time, Rome can hardly be said to have had a chronological system, the length of the year not being prescribed by any invariable rule, and being therefore changed from time to time to suit the caprice or to compass the ends of the rulers. Instances of this tampering disposition are familiar to the historical student. It is said, for instance, that the Gauls having to pay a certain monthly tribute to the Romans, one of the governors ordered the year to be divided into 14 months, in order that the pay-days might recur more rapidly. A year was fixed at 365 days, with the addition of one day to every fourth year. The old Roman months were afterward adjusted to the Julian year in such a way as to give rise to the somewhat irregular arrangement of months which we now have.

Old and New Styles.—The mean length of the Julian year is 365¼ days, about 11¼ minutes greater than that of the true equinoctial year, which measures the recurrence of the seasons. This difference is of little practical importance, as it only amounts to a week in a thousand years, and a change of this amount in that period is productive of no inconvenience. But, desirous to have the year as correct as possible, two changes were introduced into the calendar by Pope Gregory XIII. with this object. They were as follows:

(1) The day following October 4, 1582, was called the 15th instead of the 5th, thus advancing the count 10 days.

(2) The closing year of each century, 1600, 1700, etc., instead of being always a leap-year, as in the Julian calendar, is such only when the number of the century is divisible by 4. Thus while 1600 remained a leap-year, as before, 1700, 1800, and 1900 were to be common years.

This change in the calendar was speedily adopted by all Catholic countries, and more slowly by Protestant ones, England holding out until 1752. In Russia it has never been adopted at all, the Julian calendar being still continued without change. The Russian reckoning is therefore 12 days behind ours, the ten days dropped in 1582 being increased by the days dropped from the years 1700 and 1800 in the new reckoning. This modified calendar is called the *Gregorian Calendar*, or *New Style*, while the old system is called the *Julian Calendar*, or *Old Style*.

It is to be remarked that the practice of commencing the year on January 1st was not universal until comparatively recent times. The most common times of commencing were, perhaps, March 1st and March 22d, the latter being the time of the vernal equinox. But January 1st gradually made its way, and became universal after its adoption by England in 1752.

Solar Cycle and Dominical Letter.—In our church calendars January 1st is marked by the letter A, January 2d by B, and so on to G, when the seven letters begin over again, and are repeated through the year in the same order. Each letter there indicates the same day of the week throughout each separate year, A indicating the day on which January 1st falls, B the day following, and so on. An exception occurs in leap years, when February 29th and March 1st are marked by the same letter, so that a change occurs at the beginning of March. The letter corresponding to Sunday on this scheme is called the *Dominical* or Sunday letter, and when we once know what letter it is, all the Sundays of the year are indicated by that letter, and hence all the other days of the week by their letters. In leap-years there will be two Dominical letters, that for the last ten months of the year being the one next preceding the letter for January and February. In the Julian calendar the Dominical letter must always recur at the end of 28 years (besides three recurrences at unequal intervals in the mean time). This period is called the *solar cycle*, and determines the days of the week on which the days of the month fall during each year.

Since any day of any year occurs one day later in the week than it did the year before, cr two days later when a 29th of February has intervened, the Dominical letters recur in the order G, F, E, D, C, B, A, G, etc. This may also be expressed by saying that any day of a past year occurred one day earlier in the week for every year that has elapsed, and, in addition, one day earlier for every 29th of February that has intervened. This fact will make it easy to calculate the day of the week on which any historical event happened from the day corresponding in any past or future year. Let us take the following example:

On what day of the week was WASHINGTON born, the date being 1732, February 22d, knowing that February 22d, 1879, fell on Saturday? The interval is 147 years: dividing by 4 we have a quotient of 36 and a remainder of 3, showing that, had every fourth year in the interval been a leap-year, there were either 36 or 37 leap-years. As a February 29th followed only a week after the date, the number must be 37;* but as 1800 was dropped from the list of leap-years, the number was really only 36. Then $147 + 36 = 183$ days advanced in the week. Dividing by 7, because the same day of the week recurs after seven days, we find a remainder of 1. So February 22d, 1879, is one day further advanced than was February 22d, 1732; so the former being Saturday, WASHINGTON was born on Friday.

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* Perhaps the most convenient way of deciding whether the remainder does or does not indicate an additional leap-year is to subtract it from the last date, and see whether a February 29th then intervenes. Subtracting 3 years from February 22d, 1879, we have February 22d 1876, and a 29th occurs between the two dates, only a week after the first.

DIVISION OF THE DAY.

The division of the day into hours was, in ancient and mediæval times, effected in a way very different from that which we practise. Artificial time-keepers not being in general use, the two fundamental moments were sunrise and sunset, which marked the day as distinct from the night. The first subdivision of this interval was marked by the instant of noon, when the sun was on the meridian. The day was thus subdivided into two parts. The night was similarly divided by the times of rising and culmination of the various constellations. EURIPIDES (480–407 B.C.) makes the chorus in *Rhesus* ask:

"CHORUS.—Whose is the guard? Who takes my turn? *The first signs are setting, and the seven Pleiades are in the sky, and the Eagle glides midway through heaven.* Awake! Why do you delay? Awake from your beds to watch! See ye not the brilliancy of the moon? Morn, morn indeed is approaching, and *hither is one of the forerunning stars.*"

The interval between sunrise and sunset was divided into twelve equal parts called hours, and as this interval varied with the season, the length of the hour varied also. The night, whether long or short, was divided into hours of the same character, only when the night hours were long those of the day were short, and *vice versa.* These variable hours were called *temporary hours.* At the time of the equinoxes both the day and the night hours were of the same length with those we use; namely, the twenty-fourth part of the day; these were therefore called *equinoctial hours.*

Instead of commencing the civil day at midnight, as we do, it was customary to commence it at sunset. The Jewish Sabbath, for instance, commenced as soon as the sun set on Friday, and ended when it set on Saturday. This made a more distinctive division of the astronomical day than that which we employ, and led naturally to considering the *day* and the *night* as two distinct periods, each to be divided into 12 hours.

So long as temporary hours were used, the beginning of the day and the beginning of the night, or, as we should call it, six o'clock in the morning and six o'clock in the evening, were marked by the rising and setting of the sun; but when equinoctial hours were introduced, neither sunrise nor sunset could be taken to count from, because both varied too much in the course of the year. It therefore became customary to count from noon, or the time at which the sun passed the meridian. The old habit of dividing the day and the night each into 12 parts was continued, the first 12 being reckoned from midnight to noon, and the second from noon to midnight. The day was made to commence at midnight rather than at noon for obvious reasons of convenience, although noon was of course the point at which the time had to be determined.

Equation of Time.—To any one who studied the annual motion of the sun, it must have been quite evident that the intervals between its successive passages over the meridian, or between one noon and the next, could not be the same throughout the year, because the apparent motion of the sun in right ascension is not constant. It will be remembered that the apparent revolution of the starry sphere, or, which is the same thing, the diurnal revolution of the earth upon its axis, may be regarded as absolutely constant for all practical purposes. This revolution is measured around in right ascension as explained in the opening chapter of this work. If the sun increased its right ascension by the same amount every day, it would pass the meridian $3^m\ 56^s$ later every day, as measured by sidereal time, and hence the intervals between successive passages would be equal. But the motion of the sun in right ascension is unequal from two causes: (1) the unequal motion of the earth in its annual revolution around it, arising from the eccentricity of the earth's orbit, and (2) the obliquity of the ecliptic. How the first cause produces an inequality is obvious. The mean motion is $3^m\ 56^s$; the actual motion varies from $3^m\ 48^s$ to $4^m\ 4^s$.

The effect of the obliquity of the ecliptic is still greater. When the sun is near the equinox, the direction of its motion along the ecliptic makes an angle of $23\frac{1}{2}°$ with the parallels of declination. Since its motion in right ascension is measured along the parallel of declination, we see that it is less than the motion in longitude. The days are then 20 seconds shorter than they would be were there no obliquity. At the solstices the opposite effect is produced. Here the different meridians of right ascension are nearer together than they are at the equator; when the sun moves through one degree along the ecliptic, it changes its right ascension by $1°\cdot08$; here, therefore, the days are about 19 seconds longer than they would be if the obliquity of the ecliptic were zero.

We thus have to recognize two slightly different kinds of days: *solar* days and *mean* days. A solar day is the interval of time between two successive transits of the sun over the same meridian, while a mean day is the mean of all the solar days in a year. If we had two clocks, one going with perfect uniformity, but regulated so as to keep as near the sun as possible, and the other changing its rate so as to always follow the sun, the latter would gain or lose on the former by amounts sometimes rising to 22 seconds in a day. The accumulation of these variations through a period of several months would lead to such deviations that the sun-clock would be 14 minutes slower than the other during the first half of February, and 16 minutes faster during the first week in November. The time-keepers formerly used were so imperfect that these inequalities in the solar day were nearly lost in the necessary irregularities of the rate of the clock. All clocks were therefore set by the sun as often as was found necessary or convenient. But during the last century it was found by astronomers that the use of units of time varying in this way led to much inconvenience; they therefore substituted *mean* time for solar or *apparent* time.

Mean time is so measured that the hours and days shall always be of the same length, and shall, on the average, be as much behind the sun as ahead of it. We may imagine a fictitious or mean sun moving along the equator at the rate of $3^m\ 56^s$ in right ascension every day. Mean time will then be measured by the passage of this fictitious sun across the meridian. Apparent time was used in ordinary life after it was given up by astronomers, because it was very easy to set a clock from time to time as the sun passed a noon-mark. But when the clock was so far improved that it kept much better time than the sun did, it was found troublesome to keep putting it backward and forward so as to agree with the sun. Thus mean time was gradually introduced for all the purposes of ordinary life.

The common household almanac should give the equation of time, or the mean time at which the sun passes the meridian, on each day of the year. Then, if any one wishes to set his clock, he knows the moment when the sun passes the meridian, or when it is at some noon-mark, and sets his time-piece accordingly. For all purposes where accurate time is required, recourse must be had to astronomical observation. It is now customary to send time-signals every day at noon, or some other hour agreed upon, from observatories along the principal lines of telegraph. Thus at the present time the moment of Washington noon is signalled to New York, and over the principal lines of railway to the South and West. Each person within reach of a telegraph-office can then determine his local time by correcting these signals for the difference of longitude.

PART II.

THE SOLAR SYSTEM IN DETAIL.

CHAPTER I.

STRUCTURE OF THE SOLAR SYSTEM.

THE solar system consists of the sun as a central body, around which revolve the major and minor planets, with their satellites, a few periodic comets, and an unknown number of meteor swarms. These are permanent members of the system. At times other comets appear, and move usually in parabolas through the system, around the sun, and away from it into space again, thus visiting the system without being permanent members of it.

The bodies of the system may be classified as follows :

1. The central body—the Sun.
2. The four inner planets—*Mercury, Venus*, the *Earth, Mars.*
3. A group of small planets, sometimes called *Asteroids,* revolving outside of the orbit of *Mars.*
4. A group of four outer planets—*Jupiter, Saturn, Uranus,* and *Neptune.*
5. The satellites, or secondary bodies, revolving about the planets, their primaries.
6. A number of comets and meteor swarms revolving in very eccentric orbits about the sun.

The eight planets of Groups 2 and 4 are sometimes classed together as the *major planets,* to distinguish them from the two hundred or more *minor planets* of Group 3. The formal definitions of the various classes, laid down by Sir WILLIAM HERSCHEL in 1802, are worthy of repetition :

Planets are celestial bodies of a certain very considerable size. They move in not very eccentric ellipses about the sun. The planes of their orbits do not deviate many degrees from the plane of the earth's orbit. Their motion about the sun is direct (from west to east). They may have satellites or rings. They have atmospheres of

Fig. 55.—Relative Surfaces of the Planets.

considerable extent, which, however, bear hardly any sensible proportion to their diameters. Their orbits are at certain considerable distances from each other.

Asteroids, now more generally known as *small* or *minor planets,* are celestial bodies which move about the sun in orbits, either of little or of considerable eccentricity, the planes of which orbits may be inclined to the ecliptic at any angle whatsoever. They may or may not have considerable atmospheres.

Comets are celestial bodies, generally of a very small mass, though how far this may be limited is yet unknown. They move in very

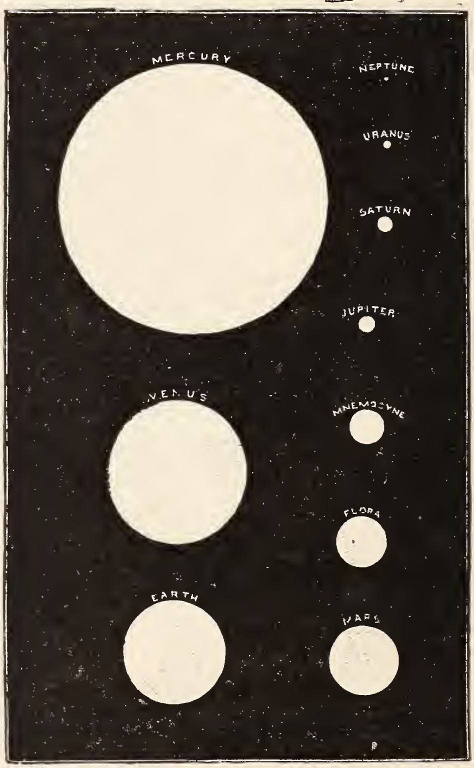

FIG. 56.—APPARENT MAGNITUDES OF THE SUN AS SEEN FROM DIFFERENT PLANETS.

eccentric ellipses or in parabolic arcs about the sun. The planes of their motion admit of the greatest variety in their situation. The direction of their motion is also totally undetermined. They have atmospheres of very great extent, which show themselves in various forms as tails, coma, haziness, etc.

Relative Surfaces of the Planets.—The comparative surfaces of the major planets, as they would appear to an observer situated at an equal distance from all of them, is given in the figure on page 191.

The relative apparent magnitudes of the sun, as seen from the various planets, is shown in the figure on page 192.

Flora and *Mnemosyne* are two of the asteroids.

A curious relation between the distances of the planets, known as BODE's law, deserves mention. If to the numbers

0, 3, 6, 12, 24, 48, 96, 192, 384,

each of which (the second excepted) is twice the preceding, we add 4, we obtain the series

4, 7, 10, 16, 28, 52, 100, 196, 388.

These last numbers represent approximately the distances of the planets from the sun (except for *Neptune*, which was not discovered when the so-called law was announced).

This is shown in the following table:

PLANETS.	Actual Distance.	BODE'S LAW.
Mercury	3·9	4·0
Venus	7·2	7·0
Earth	10·0	10·0
Mars	15·2	16·0
[Ceres]	27·7	28·0
Jupiter	52·0	52·0
Saturn	95·4	100·0
Uranus	191·8	196·0
Neptune	300·4	388 0

It will be observed that *Neptune* does not fall within this ingenious scheme. *Ceres* is one of the minor planets.

The relative brightness of the sun and the various planets has been measured by ZÖLLNER, and the results are given below. The column *per cent* shows the percentage of error indicated in the separate results:

SUN AND	Ratio: 1 to	Percent. of Error.
Moon	618,000	1·6
Mars	6,994.000,000	5·8
Jupiter	5.472,000,000	5·7
Saturn (ball alone)	130,980,000,000	5·0
Uranus	8,486,000,000,000	6·0
Neptune	79,620,000,000,000	5·5

The differences in the density, size, mass, and distance of the several planets, and in the amount of solar light and heat which they receive, are immense. The distance of *Neptune* is eighty times that of *Mercury*, and it receives only $\frac{1}{6400}$ as much light and heat from the sun. The density of the earth is about six times that of water, while *Saturn's* mean density is less than that of water.

The mass of the sun is far greater than that of any single planet in the system, or indeed than the combined mass of all of them. In general, it is a remarkable fact that the mass of any given planet exceeds the sum of the masses of all the planets of less mass than itself. This is shown in the following table, where the masses of the planets are taken as fractions of the sun's mass, which we here express as 1,000,000,000:

Mercury.	Mars.	Venus.	Earth.	Uranus.	Neptune.	Saturn.	Jupiter.	Sun.	PLANETS.
200	324	2,353	3,060	44,250	51,600	285,580	954,305	1,000,000,000	Masses.

The total mass of the small planets, like their number, is unknown, but it is probably less than one thousandth that of our earth, and would hardly increase the sum-total of the above masses of the solar system by more than one or two units. The sun's mass is thus over 700 times that of all the other bodies, and hence the fact of its central position in the solar system is explained. In fact, the *centre of gravity* of the whole solar system is very little outside the body of the sun, and will be inside of it when *Jupiter* and *Saturn* are in opposite directions from it.

Planetary Aspects.—The motions of the planets about the sun have been explained in Chapter V. From what is there said it appears that the best time to see one of the outer planets will be when it is in opposition; that is, when its geocentric longitude or its right ascension differs 180° or 12^h from that of the sun. At such a time the planet will rise at sunset and culminate at midnight. During the three months following opposition the planet will rise from three to six minutes earlier every day, so that, knowing when a planet is in opposition, it is easy to find it at any other time. For example, a month after opposition the planet will be two or three hours high about sunset, and will culminate about nine or ten o'clock. Of course the inner planets never come into opposition, and hence are best seen about the times of their greatest elongations.

Dimensions of the Solar System.—The figure gives a rough plan of part of the solar system as it would appear to a spectator immediately above or below the plane of the ecliptic. It is drawn approximately to scale, the mean distance of the earth (= 1) being half an inch. The mean distance of *Saturn* would be 4·77 inches, of *Uranus* 9·59

Fig. 57.

inches, of *Neptune* 15·03 inches. On the same scale the distance of the *nearest* fixed star would be 103,133 inches, or over one and one half miles.

The arrangement of the planets and satellites is, then—

The Inner Group.	Asteroids.	The Outer Group.
Mercury. Venus. Earth and Moon. Mars and 2 moons.	200 minor planets, and probably many more.	Jupiter and 4 moons. Saturn and 8 moons. Uranus and 4 moons. Neptune and 1 moon.

To avoid repetitions, the elements of the major planets and other data are collected into the two following tables, to which reference should be made by the student. The units in terms of which the various quantities are given are those familiar to us, as miles, days, etc., yet some of the distances, etc., are so immensely greater than any known to our daily experience that we must have recourse to illustrations to obtain any idea of them at all. For example, the distance of the sun is said to be 92½ *million* miles. It is of importance that some idea should be had of this distance, as it is the unit, in terms of which not only the distances in the solar system are expressed, but which serves as a basis for measures in the stellar universe. Thus when we say that the distance of the *nearest* star is over 200,000 times the mean distance of the sun, it becomes necessary to see if some conception can be obtained of one factor in this. Of the abstract number, 92,500,000, we have no conception. It is far too great for us to have counted. We have never taken in at one view even a million similar discrete objects. The largest tree has less than 500,000 leaves. To count from 1 to 200 requires, with very rapid counting, 60 seconds. Suppose this kept up for a day without intermission ; at the end we should have counted 288,000, which is about $\frac{1}{320}$ of 92,500,000. Hence over 10 months' uninterrupted counting by night and day would be required simply to enumerate the *number*, and long before the expiration of the task all *idea* of it would have vanished We may take other and perhaps more striking examples. We know, for instance, that the time of the fastest express-trains between New York and Chicago, which average 40 miles per hour, is about a day. Suppose such a train to start for the sun and to continue running at this rapid rate. It would take 363 years for the journey. Three hundred and sixty-three years ago there was not a European settlement in America.

A cannon-ball moving continuously across the intervening space at its highest speed would require about nine years to reach the sun. The report of the cannon, if it could be conveyed to the sun with the velocity of sound in air, would arrive there five years after the projectile. Such a distance is entirely inconceivable, and yet it is only a small fraction of those with which astronomy has to deal, even in our own system. The distance of *Neptune* is 30 times as great.

If we examine the dimensions of the various orbs, we meet almost equally inconceivable numbers, The diameter of the sun is 860,000 miles; its radius is but 430,000, and yet this is nearly twice the mean distance of the moon from the earth. Try to conceive, in looking at the moon in a clear sky, that if the centre of the sun could be placed at the centre of the earth, the moon would be far within the sun's surface. Or again, conceive of the force of gravity at the surface of the various bodies of the system. At the sun it is nearly 28 times that known to us. A pendulum beating seconds here would, if transported to the sun. vibrate with a motion more rapid than that of a watch-balance. The muscles of the strongest man would not support him erect on the surface of the sun: even lying down he would crush himself to death under his own weight of two tons. We may by these illustrations get some rough idea of the meaning of the numbers in these tables, and of the incapability of our limited ideas to comprehend the true dimensions of even the solar system.

ELEMENTS OF THE ORBITS OF THE EIGHT MAJOR PLANETS FOR 1850.

NAME.	Mean Motion in 365¼ Days.	Mean Distance from Sun. Astronomical Units.	Mean Distance from Sun. Millions of Miles.	Eccentricity of Orbit.	Longitude of Perihelion. ° ′ ″	Inclination to Ecliptic. ° ′ ″	Longitude of the Node. ° ′ ″	Mean Longitude of Planet, 1849 Dec. 31.0. ° ′ ″	Authority.
Mercury.	5381016·2925	0·3870988	35¾	·20560478	75 7 13·8	7 0 7·71	46 33 8·6	323 11 23·53	Leverrier.
Venus..	2106641·3980	0·7233322	66¾	·00684331	129 27 14·4	3 23 34·83	75 19 52·2	243 57 44·34	Leverrier.
	2106641·3040	0·723	.....	·00684311	129 27 42·9	3 23 35·01	75 19 53·1	243 57 23·82	G. W. Hill.
Earth..	1295977·4260	1.0	92½	·01677110	100 21 21·4	....	....	99 48 18·66	Leverrier.
	1295977·4212	1·0	.....	·01677120	100 21 41·0	....	....	99 48 17·71	Hansen.
Mars......	609050·8013	1·5236914	141	·09326113	333 17 53·5	1 51 2·28	48 23 53·0	83 9 16·92	Leverrier.
Jupiter...	109256·6197	5·202800	481	·0482519	11 54 58·2	1 18 41·37	98 56 16·9	159 56 12·94	Leverrier.
Saturn.	43996·0508	9.538852	882	·0559428	90 6 56·5	2 29 39·80	112 20 52·9	14 50 28·49	Leverrier.
	43996·209	9·5388	.....	·0560470	90 3 59·8	2 29 39·20	112 20 0·0	14 49 43·50	G. W. Hill.
Uranus...	15424·797	19·18338	1,774	·0463592	170 38 48·7	0 46 20·29	73 14 37·6	29 12 43·73	Newcomb.
Neptune.	7865·862	30·05437	2,780	·0089903	49 9 13·1	1 46 58·75	130 7 18·3	334 30 5·75	Newcomb.

Dimensions of the Bodies of the Solar System.

Name.	Masses.	Mean Angular Semidiameters		Angular Diameters at Distance Unity.				Mean Diameter in Miles.	Density.		Axial Rotation.	Gravity at Surface ⊕ = 1.	Periodic Time.	Orbital Velocity in Miles per Second.
		″	At Dist.	Polar. ′	″	Equatorial. ′	″		Water = 1.	Earth = 1.			Days.	
Sun......	Unity.	961·0	1·00	32	2·00	32	2·00	860,000	1·444	0·2552	25^d 5^m 38^s	27·71	......	....
Mercury	$\frac{1}{5000000}$	3·34	1·00	0	6·68	0	6·68	2,992	6·85	1·21	Unknown.	0·46	87·97	29·55
Venus...	$\frac{1}{425000}$	8·55	1·00	0	17·10	0	17 10	7,660	4·81	0·850	Unknown.	0·82	224·70	21·61
Earth...	$\frac{1}{326800}$	8·84	1·00	0	17·64	0	17·70	7,918	5·66	1·000	23^h 56^m $4·09^s$	1·00	365·26	18·38
Mars....	$\frac{1}{3093500}$	4·69	1·00	0	9·36	0	9·42	4,211	4·17	0·737	24^h 37^m $22·7^s$	0·39	686·98	14·99
													Years.	
Jupiter..	$\frac{1}{1047·88}$	18·26	5·20	0	184·2	0	195·8	86,000	1·378	0·2435	9^h 55^m $20·0^s$	2·64	11·86	8·06
Saturn...	$\frac{1}{3501·6}$	8·10	9·54	0	146·3	0	162·8	70,500	0·750	0·1325	10^h 14^m $23·8^s$	1·18	29·46	5·95
Uranus..	$\frac{1}{22600}$	1·84	19·2	0	70·7	0	70·7	31,700	1·28	0·226	Unknown.	0·90	84·02	4·20
Neptune	$\frac{1}{19380}$	1·28	30·0	0	77·0	0	77·0	34,500	1·15	0·204	Unknown.	0·89	164·78	3·36

CHAPTER II.

THE SUN.

GENERAL SUMMARY.

To enable the nature of the phenomena of the sun to be clearly understood, we preface our account of its physical constitution by a brief summary of its main features.

Photosphere.—To the simple vision the sun presents the aspect of a brilliant sphere. The visible shining *surface* of this sphere is called the *photosphere*, to distinguish it from the body of the sun as a whole. The apparently flat surface presented by a view of the photosphere is called the sun's *disk*.

Spots.—When the photosphere is examined with a telescope, small dark patches of varied and irregular outline are frequently found upon it. These are called the *solar spots*.

Rotation.—When the spots are observed from day to day, they are found to move over the sun's disk from east to west in such a way as to show that the sun rotates on its axis in a period of 25 or 26 days. The sun, therefore, has *axis*, *poles*, and *equator*, like the earth, the axis being the line around which it rotates.

Faculæ.—Groups of minute specks brighter than the general surface of the sun are often seen in the neighborhood of spots or elsewhere. They are called *faculæ*.

Chromosphere, or Sierra.—The solar photosphere is covered by a layer of glowing vapors and gases of very irregular depth. At the bottom lie the vapors of many metals, iron, etc., volatilized by the fervent heat which reigns there, while the upper portions are composed principally of hydrogen gas. This vaporous atmosphere is commonly called the *chromosphere*, sometimes the *sierra*. It is entirely invisible to direct vision, whether with the telescope or naked eye, except for a few seconds about the beginning or end of a total eclipse, but it may be seen on any clear day through the spectroscope.

Prominences, Protuberances, or Red Flames.—The gases of the chromosphere are frequently thrown up in irregular masses to vast heights above the photosphere, it may be 50,000, 100,000, or even 200,000 kilometres. Like the chromosphere, these masses have to be studied with the spectroscope, and can never be directly seen except when the sunlight is cut off by the intervention of the moon during a total eclipse. They are then seen as rose-colored flames, or piles of bright red clouds of irregular and fantastic shapes.

Corona.—During total eclipses the sun is seen to be enveloped by a mass of soft white light, much fainter than the chromosphere, and extending out on all sides far beyond the highest prominences. It is brightest around the edge of the sun, and fades off toward its outer boundary, by insensible gradations. This halo of light is called the *corona*, and is a very striking object during a total eclipse.

The Photosphere.

Aspect and Structure of the Photosphere.—The disk of the sun is circular in shape, no matter what side of the sun's globe is turned toward us, whence it follows that the sun itself is a sphere. The aspect of the disk, when viewed with the naked eye, or with a telescope of low power, is that of a uniform bright, shining surface, hence called the *photosphere.* With a telescope of higher power the photosphere is seen to be diversified with groups of spots, and under good con-

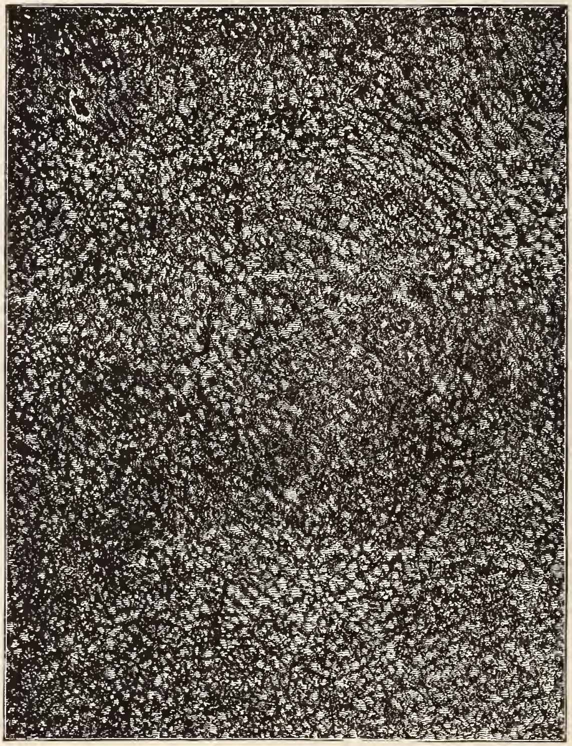

FIG. 58.—RETICULATED ARRANGEMENT OF THE SUN'S PHOTOSPHERE.
(From a photograph.)

ditions the whole mass has a mottled or curdled appearance. This mottling is caused by the presence of cloud-like forms, whose outlines though faint are yet distinguishable. The background is also covered with small white dots or forms still smaller than the clouds, These are the "rice-grains," so called. The clouds themselves are composed of small, intensely bright bodies, irregularly distributed, of tolerably definite shapes, which seem to be suspended in or superposed on a darker medium or background. The spaces between the bright dots vary in diameter from 2″ to 4″ (about 1400 to 2800 kilometres). The rice-grains themselves have been seen to be composed of smaller granules, sometimes not more than 0″.3 (135 miles) in diameter, clustered together. Thus there have been seen at least three orders of aggregation in the brighter parts of the photosphere: the larger cloud-like forms; the rice-grains; and, smallest of all, the granules.

Light and Heat from the Photosphere.—The *photosphere* is not equally bright all over the apparent disk. This is at once evident to the eye in observing the sun with a telescope. The centre of the disk is most brilliant, and the edges or *limbs* are shaded off so as to forcibly suggest the idea of an absorptive atmosphere, which, in fact, is the cause of this appearance.

Such absorption occurs not only for the rays by which we see the sun, the so-called *visual rays,* but for those which have the most powerful effect in decomposing the salts of silver, the so-called *chemical rays,* by which the ordinary photograph is taken.

The amount of heat received from different portions of the sun's disk is also variable, according to the part of the apparent disk examined. This is what we should expect. That is, if the intensity of any one of these radiations (as felt at the earth) varies from centre to circumference, that of every other should also vary, since they are all modifications of the same primitive motion of the sun's constituent particles. But the constitution of the sun's atmosphere is such that the law of variation for the three classes is different. The intensity of the radiation in the sun itself and inside of the absorptive atmosphere is probably nearly constant. The ray which leaves the centre of the sun's disk in passing to the earth traverses the smallest possible thickness of the solar atmosphere, while the rays from points of the sun's body which appear to us near the limbs pass, on the contrary, through the maximum thickness of atmosphere, and are thus longest subjected to its absorptive action.

This is plainly a rational explanation, since the part of the sun which is seen by us as the limb varies with the position of the earth in its orbit and with the position of the sun's surface in its rotation, and has itself no physical peculiarity. The various absorptions of different classes of rays correspond to this supposition, the more refrangible rays, violet and blue, suffering most absorption, as they must do, being composed of waves of shorter wave-length.

Amount of Heat Emitted by the Sun.—Owing to the absorption of the solar atmosphere, it follows that we receive only a portion—perhaps a very small portion—of the rays emitted by the sun's photosphere.

If the sun had no absorptive atmosphere, it would seem to us hotter, brighter, and more blue in color.

Exact notions as to how great this absorption is are hard to gain, but it may be said roughly that the best authorities agree that although it is quite possible that the sun's atmosphere absorbs half the emitted rays, it probably does not absorb four fifths of them.

The amount of this absorption is a practical question to us on the earth. So long as the central body of the sun continues to emit the same quantity of rays, it is plain that the thickness of the solar atmosphere determines the number of such rays reaching the earth. If in former times this atmosphere was much thicker, then less heat would have reached the earth. Glacial epochs may be explained in this way. If the central body of the sun has likewise had different emissive powers at different times, this again would produce a variation in the temperature of the earth.

Amount of Heat Radiated.—There is at present no way of determining accurately either the absolute amount of heat emitted from the central body or the amount of this heat stopped by the solar atmosphere itself. All that can be done is to measure (and that only roughly) the amount of heat really received by the earth, without attempting to define accurately the circumstances which this radiation has undergone before reaching the earth.

Pouillet has experimented upon this question, making allowance for the time that the sun is below the horizon of any place, and for the fact that the solar rays do not in general strike perpendicularly but obliquely upon any given part of the earth's surface. His conclusions may be stated as follows: if our own atmosphere were removed, the solar rays would have energy enough to melt a layer of ice 9 centimetres thick over the whole earth *daily*, or a layer of about 32 metres thick in a year.

This action is constantly at work over the whole of the sun's surface. To produce a similar effect by the combustion of coal would require that a layer of coal 5 metres thick spread all over the sun should be consumed every *hour*. This is equivalent to a *continuous* evolution of 10,000 horse-power on every square foot of the sun's surface. If the sun were of solid coal and produced its own heat by combustion, it would burn out in 6000 years.

Of this enormous outflow of heat the earth receives only $\frac{1}{2200000000}$. We have expressed the power of even this small fraction of the sun's heat in terms of the ice it would melt daily. If we compute how much coal it would require to melt the same amount, and then further calculate how much work this coal would do, we shall find that the sun sends to the earth an amount of heat which is equivalent to one horse-power continuously acting for every 30 square feet of the earth's surface. Most of this is expended in maintaining the earth's temperature; but a small portion, about $\frac{1}{1000}$, is stored away by animals and vegetables, and this slight fraction is the source upon which the human race depends. If this were withdrawn the race would perish.

Of the total amount of heat radiated by the sun the earth receives but an insignificant share. The sun is capable of heating the entire surface of a sphere whose radius is the earth's mean distance to the same degree that the earth is now heated. The surface of such a sphere is 2,170,000,000 times greater than the angular dimensions of the earth as seen from the sun, and hence the earth receives less than one two-billionth part of the solar radiation. The rest of the solar rays are, so far as we know, lost in space.

Solar Temperature.—From the amount of heat actually radiated by the sun, attempts have been made to determine the actual temperature of the solar surface. The estimates reached by various authorities differ widely, as the laws which govern the absorption within the solar envelope are almost unknown. Some such law of absorption has to be supposed in any such investigation, and the estimates have differed widely according to the adapted law.

SECCHI estimates this temperature at about 6,100,000° C. Other estimates are far lower, but, according to all sound philosophy, the temperature must far exceed any terrestrial temperature. There can be no doubt that if the temperature of the earth's surface were suddenly raised to that of the sun, no single chemical element would remain in its present condition. The most refractory materials would be at once volatilized.

We may concentrate the heat received upon several square feet (the surface of a huge burning-lens or mirror, for instance), examine its effects at the focus, and, making allowance for the condensation by the lens, see what is the minimum possible temperature of the sun. The temperature at the focus of the lens cannot be higher than that of the source of heat in the sun; we can only concentrate the heat received on the surface of the lens to one point and examine its effects. If a lens three feet in diameter be used, the most refractory materials, as fire-clay, platinum, the diamond, are at once melted or volatilized. The effect of the lens is plainly the same as if the earth were brought closer to the sun, in the ratio of the diameter of the focal image to that of the lens. In the case of the lens of three feet, allowing for the absorption, etc., this distance is yet greater than that of the moon from the earth, so that it appears that any comet or planet so close as this to the sun, if composed of materials similar to those in the earth, must be vaporized.

SUN-SPOTS AND FACULÆ.

A very cursory examination of the sun's disk with a small telescope will generally show one or more dark spots upon the photosphere. These are of various sizes, from minute black dots 1″ or 2″ in diameter (1000 kilometres or less) to large spots several minutes of arc in extent.

Solar spots generally have a dark central *nucleus* or *umbra*, surrounded by a border or *penumbra* of grayish tint, intermediate in shade between the central blackness and the bright photosphere. By increasing the power of the telescope, the spots are seen to be of very complex forms. The *umbra* is often extremely irregular in shape, and is sometimes crossed by bridges or ligaments of shining matter. The *penumbra* is composed of filaments of brighter and darker light, which are arranged in striæ. The general aspect of a spot under considerable magnifying power is shown in Fig. 59.

The first printed account of solar spots was given by FABRITIUS in 1611, and GALILEO in the same year (May, 1611) also described them.

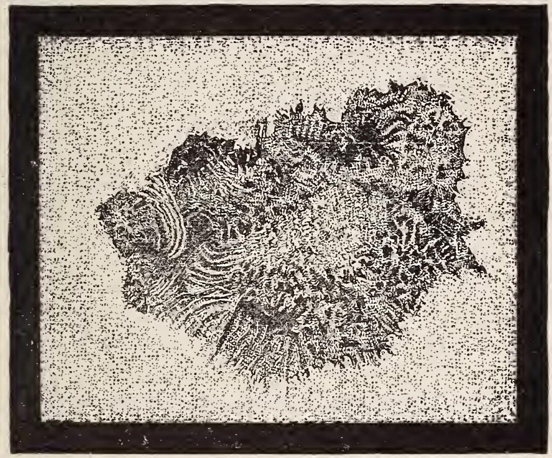

FIG. 59.—UMBRA AND PENUMBRA OF SUN-SPOT.

GALILEO's observations showed them to belong to the sun itself, and to move uniformly across the solar disk from east to west. A spot just visible at the east limb of the sun on any one day travelled slowly across the disk for 12 or 14 days, when it reached the west limb, behind which it disappeared. After about the same period, it reappears at the eastern limb, unless, as is often the case, it has in the mean time vanished.

The spots are not permanent in their nature, but are formed somewhere on the sun, and disappear after lasting a few days, weeks, or months. But so long as they last they move regularly from east to west on the sun's apparent disk, making one complete rotation in about 25 days. This period of 25 days is therefore approximately the rotation period of the sun itself.

Spotted Region.—It is found that the spots are chiefly confined to two zones, one in each hemisphere, extending from about 10° to 35° or 40° of heliographic latitude. In the polar region spots are scarcely ever seen, and on the solar equator they are much more rare than in latitudes 10° north or south. Connected with the spots, but lying on or above the solar surface, are *faculæ,* mottlings of light brighter than the general surface of the sun.

FIG. 60.—PHOTOGRAPH OF THE SUN.

Solar Axis and Equator.—The spots must revolve with the surface of the sun about his axis, and the directions of their motions must be approximately parallel to his equator. Fig. 61 shows the appearances as actually observed, the dotted lines representing the apparent paths of the spots across the sun's disk at different times of the year. In June and December these paths, to an observer on the earth, seem to be right lines, and hence at these times the observer must be in the plane of the solar equator. At other times the paths are ellipses, and in March and September the planes of these ellipses are most oblique, showing the spectator to be then furthest from the plane of the solar equator. The inclination of the solar equator to the ecliptic is about 7° 9′, and the axis of rotation is of course perpendicular to it.

Nature of the Spots.—The sun-spots are really depressions in the photosphere, as was first pointed out by ANDREW WILSON of Glasgow in 1774. When a spot is seen at the edge of the disk, it appears as a notch in the limb, and is

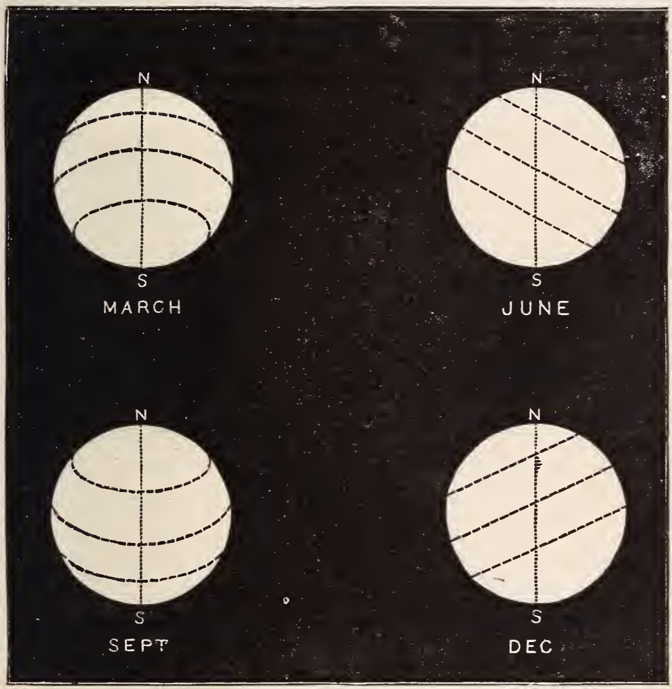

FIG. 61.—APPARENT PATH OF SOLAR SPOT AT DIFFERENT SEASONS.

elliptical in shape. As the rotation carries it further and further on to the disk, it becomes more and more nearly circular in shape, and after passing the centre of the disk the appearances take place in reverse order.

These observations were explained by WILSON, and more fully by Sir WILLIAM HERSCHEL, by supposing the sun to consist of an interior dark cool mass, surrounded by two layers of clouds. The outer layer, which forms the visible photosphere, was supposed extremely brilliant. The inner layer, which could not be seen except when a cavity existed in the photosphere, was supposed to be dark. The appearance of the edges of a spot, which has been described as the penumbra, was supposed to arise from those dark clouds. The spots themselves are, according to this view, nothing but openings through both of the atmospheres, the *nucleus* of the spot being simply the black surface of the inner sphere of the sun itself.

This theory, Fig. 62, accounts for the facts as they were known

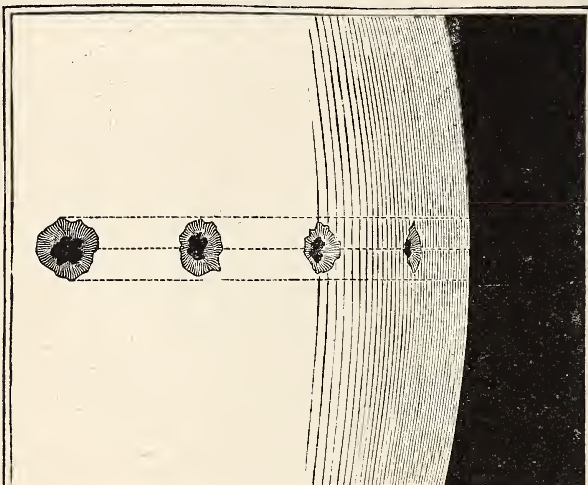

FIG. 62.—APPEARANCE OF A SPOT NEAR THE LIMB AND NEAR THE CENTRE OF THE SUN.

to HERSCHEL. But when it is confronted with the questions of the cause of the sun's heat and of the method by which this heat has been maintained constant in amount for centuries, it breaks down completely. The conclusions of WILSON and HERSCHEL, that the spots are depressions in the sun's surface, are undoubted. But the existence of a cool central and solid nucleus to the sun is now known to be impossible. The apparently black centres of the spots are so mostly by contrast. If they were seen against a perfectly black background, they would appear very bright, as has been proved by photometric measures. And a cool solid nucleus beneath such an atmosphere as HERSCHEL supposed would soon become gaseous by the conduction and radiation of the heat of the photosphere. The supply of solar heat, which has been very nearly constant during the historic period, in a sun so constituted would have sensibly diminished in a few hundred years. For these and other reasons the hypothesis of HERSCHEL must be modified, save as to the fact that the spots are really cavities in the photosphere.

Number and Periodicity of Solar Spots.—The number of solar spots which come into view varies from year to year. Although at first sight this might seem to be what we call a purely accidental circumstance, like the occurrence of cloudy and clear years on the earth, observations of sunspots establish the fact that this number varies *periodically.*

The periodicity of the spots will appear from the following summary:

From 1828 to 1831	the sun	was without	spots on only	1 day.
In 1833	"	"	"	139 days.
From 1836 to 1840	"	"	"	3 "
In 1843	"	"	"	147 "
From 1847 to 1851	"	"	"	2 "
In 1856	"	"	"	193 "
From 1858 to 1861	"	"	"	no day.
In 1867	"	"	"	195 days.

Every 11 years there is a minimum number of spots, and about 5 years after each minimum there is a maximum. If, instead of merely counting the number of spots, measurements are made on solar photographs of the extent of *spotted area,* the period comes out with greater distinctness. This periodicity of the area of the solar spots appears to be connected with magnetic phenomena on the earth's surface, and with the number of auroras visible. It has been supposed to be connected also with variations of temperature, of rainfall, and with other meteorological phenomena such as the monsoons of the Indian Ocean, etc. The cause of this periodicity is as yet unknown. It probably lies within the sun itself, and is similar to the cause of the periodic action of a geyser. As the periodic variations of the spots correspond to variations of the magnetic needle on the earth, it appears that there is a connection of an unknown nature between the sun and the earth.

The Sun's Chromosphere and Corona.

Phenomena of Total Eclipses.—The beginning of a total solar eclipse is marked simply by the small black notch made in the luminous disk of the sun by the advancing edge or limb of the moon. This always occurs on the western half of the sun, as the moon moves from west to east in its orbit. An hour or more must elapse before the moon has advanced sufficiently far in its orbit to cover the sun's disk. During this time the disk of the sun is gradually hidden until it becomes a thin crescent.

The actual amount of the sun's light may be diminished to two thirds or three fourths of its ordinary amount without its being strikingly perceptible to the eye. What is first noticed is the change which takes place in the color of the surrounding landscape, which begins to wear a ruddy aspect. This grows more and more pronounced, and gives to the adjacent country that weird effect which lends so much to the impressiveness of a total eclipse. The reason for the change of color is simple. We have already said that the sun's atmosphere absorbs a large proportion of the bluer rays, and as this absorption is dependent on the thickness of the solar atmosphere through which the rays must pass, it is plain that just before the sun is totally covered the rays by which we see it will be redder than ordinary sunlight, as they are those which come from points near the sun's limb, where they have to pass through the greatest thickness of the sun's atmosphere.

The color of the light becomes more and more lurid up to the moment when the sun has nearly disappeared. If the spectator is upon the top of a high mountain, he can then begin to see the moon's shadow rushing toward him at the rate of a kilometre in about a second. Just as the shadow reaches him there is a sudden increase of darkness; the brighter stars begin to shine in the dark lurid sky, the thin crescent of the sun breaks up into small points or dots of light, which suddenly disappear, and the moon itself, an intensely black ball, appears to hang isolated in the heavens.

An instant afterward the corona is seen surrounding the black disk of the moon with a soft effulgence quite different from any other light known to us. Near the moon's limb it is intensely bright, and to the naked eye uniform in structure; 5′ or 10′ from the limb this inner corona has a boundary more or less defined, and from this extend streamers and wings of fainter and more nebulous light. These are of various shapes, sizes, and brilliancy. No two solar eclipses yet observed have been alike in this respect.

These appearances, though changeable, do not change in the time the moon's shadow requires to pass from Vancouver's Island to Texas, for example, which is some fifty minutes.

Superposed upon these wings may be seen (sometimes with the naked eye) the red flames or protuberances which were first discovered during a solar eclipse. These need not be more closely described here, as they can now be studied at any time by aid of the spectroscope.

The total phase lasts for a few minutes (never more than six or seven), and during this time, as the eye becomes more and more accustomed to the faint light, the outer corona is seen to stretch further and further away from the sun's limb. At the eclipse of 1878, July 29th, it was seen to extend more than 6° (about 9,000,000 miles) from the sun's limb. Just before the end of the total phase there is a sudden increase of the brightness of the sky, due to the increased illumination of the earth's atmosphere near the observer, and in a moment more the sun's rays are again visible, seemingly as bright as ever. From the end of totality till the last contact the phenomena of the first half of the eclipse are repeated in inverse order.

Telescopic Aspect of the Corona.—Such are the appearances to the naked eye. The corona, as seen through a telescope, is, however, of a very complicated structure. The inner corona is usually composed of bright striæ or filaments separated by darker bands, and some of these latter are sometimes seen to be almost totally black. The appearances are extremely irregular, but they are often as if the inner corona were made up of brushes of light on a darker background.

The corona and red prominences are solar appendages. It was formerly doubtful whether the corona was an atmosphere belonging to the sun or to the moon. At the eclipse of 1860 it was proved by measurements that the red prominences belonged to the sun and not to the moon, since the moon gradually covered them by its motion, they remaining attached to the sun. The corona has also since been shown to be a solar appendage.

Gaseous Nature of the Prominences.—The eclipse of 1868 (July) was total in India, and was observed by many skilled astronomers. A discovery of M. JANSSEN's will make this eclipse forever memorable. He was provided with a spectroscope, and by it observed the prominences. One prominence in particular was of vast size, and when the spectroscope was turned upon it, its spectrum was discontinuous, showing the bright lines of hydrogen gas.

The brightness of the spectrum was so marked that JANSSEN determined to keep his spectroscope fixed upon it even after the reappear-

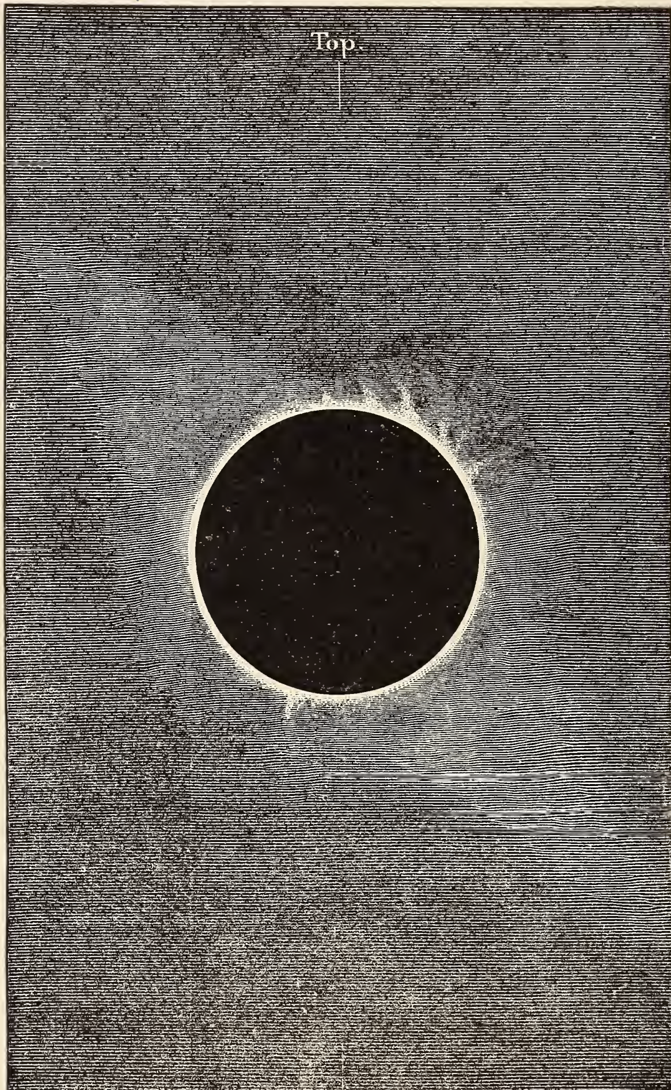

FIG. 63.—SUN'S CORONA DURING THE ECLIPSE OF JULY 29, 1878.

ance of sunlight, to see how long it could be followed. It was found that its spectrum could still be seen after the return of complete sunlight; and not only on that day, but on subsequent days, similar phenomena could be observed.

One great difficulty was conquered in an instant. The red flames which formerly were only to be seen for a few moments during the comparatively rare occurrences of total eclipses, and whose observation demanded long and expensive journeys to distant parts of the world, could now be regularly observed with all the facilities offered by a fixed observatory.

This great step in advance was independently made by Mr. LOCK-

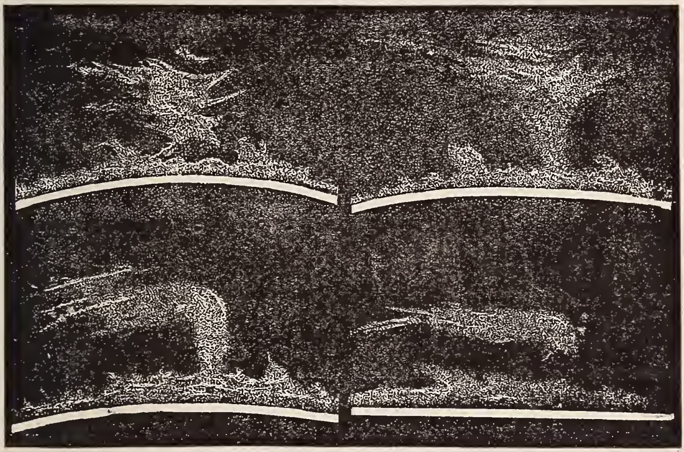

FIG. 64.—FORMS OF THE SOLAR PROMINENCES AS SEEN WITH THE SPECTROSCOPE.

YER, and his discovery was derived from pure theory, unaided by the eclipse itself. By this method the prominences have been carefully mapped day by day all around the sun, and it has been proved that around this body there is a vast atmosphere of hydrogen gas—the *chromosphere* or *sierra*. From out of this the prominences are projected sometimes to heights of 100,000 kilometres or more.

It will be necessary to recall the main facts of observation which are fundamental in the use of the spectroscope. When a brilliant point is examined with the spectroscope, it is spread out by the prism into a band—the spectrum. Using two prisms, the spectrum becomes longer, but the light of the surface, being spread over a greater area, is enfeebled. Three, four, or more prisms spread out the spectrum proportionally more. If the spectrum is of an incandescent solid or liquid, it is always continuous, and it can be enfeebled to any degree; so that any part of it can be made as feeble as desired.

This method is precisely similar in principle to the use of the telescope in viewing stars in the daytime. The telescope lessens the brilliancy of the sky, while the disk of the star is kept of the same intensity, as it is a point in itself. It thus becomes visible. The spectrum of a glowing gas will consist of a definite number of lines, say three—A, B, C, for example. Now suppose the spectrum of this gas to be superposed on the continuous spectrum of the sun; by using only one prism, the solar spectrum is short and brilliant, and every part of it may be more brilliant than the line spectrum of the gas. By increasing the dispersion (the number of prisms), the solar spectrum is proportionately enfeebled. If the ratio of the light of the bodies themselves, the sun and the gas, is not too great, the continuous spectrum may be so enfeebled that the line spectrum will be visible when superposed upon it, and the spectrum of the gas may then be seen even in the presence of true sunlight. Such was the process imagined and successfully carried out by Mr. LOCKYER, and such is in essence the method of viewing the prominences to-day adopted.

The Coronal Spectrum.—In 1869 (August 7th) a total solar eclipse was visible in the United States. It was probably observed by more astronomers than any preceding eclipse. Two American astronomers, Professor YOUNG, of Dartmouth College, and Professor HARKNESS, of the Naval Observatory, especially observed the spectrum of the corona. This spectrum was found to consist of one faint greenish line crossing a faint continuous spectrum. The place of this line in the maps of the solar spectrum published by KIRCHHOFF was occupied by a line which he had attributed to the *iron* spectrum, and which had been numbered 1474 in his list, so that it is now spoken of as 1474 K. This line is probably due to some gas which must be present in large and possibly variable quantities in the corona, and which is not known to us on the earth, in this form at least. It is probably a gas even lighter than hydrogen, as the existence of this line has been traced 10′ or 20′ from the sun's limb nearly all around the disk.

In the eclipse of July 29th, 1878, which was total in Colorado and Texas, the continuous spectrum of the corona was found to be crossed by the dark lines of the solar spectrum, showing that the coronal light was composed in part of reflected sunlight.

Sources of the Sun's Heat.

Theories of the Sun's Constitution.—No considerable fraction of the heat radiated from the sun returns to it from the celestial spaces. But we know the sun is daily radiating into space 2,170,000,000 times as much heat as is daily received by the earth, and it follows that unless the supply of heat is infinite (which we cannot believe) this enormous daily radiation must in time exhaust the supply. When the supply is exhausted, or even seriously trenched upon, the result to the inhabitants of the earth will be fatal. A slow diminution of the daily supply of heat would produce a slow change of climates from hotter toward colder. The serious results of a fall of 50° in the mean annual temperature of the earth will be evident when we remember that such a fall would change the climate of France to that of Spitzbergen. The temperature of the sun cannot be kept up by the mere combustion of its materials. If the sun were solid carbon, and if a constant and adequate supply of oxygen were also present, it has been shown that, at the present rate of radiation, the heat arising from the combustion of the mass would not last more than 6000 years.

An explanation of the solar heat and light has been suggested, which depends upon the fact that great amounts of heat and light are produced by the collision of two rapidly moving heavy bodies, or even by the passage of a heavy body like a meteorite through the earth's atmosphere. In fact, if we had a certain mass available with which to produce heat in the sun, and if this mass were of the best possible materials to produce heat by burning, it can be shown that, by burning it at the surface of the sun, we should produce vastly less heat than if we simply allowed it to fall into the sun. In the last case, if it fell from the earth's distance, it would give 6000 times more heat by its fall than by its burning.

The *least* velocity with which a body from space could fall upon the sun's surface is in the neighborhood of 280 miles in a second of time, and the velocity may be as great as 350 miles. The meteoric theory of solar heat is in effect that the heat of the sun is kept up by the impact of meteors upon its surface.

No doubt immense numbers of meteorites fall into the sun daily and hourly, and to each one of them a certain considerable portion of heat is due. It is found that, to account for the present amount of radiation, meteorites equal in mass to the whole earth would have to fall into the sun every century. It is extremely improbable that a mass one tenth as large as this is added to the sun in this way per century, if for no other reason because the earth itself and every planet would receive far more than its present share of meteorites, and would become quite hot from this cause alone.

There is still another way of accounting for the sun's constant supply of energy, and this has the advantage of appealing to no cause outside of the sun itself in the explanation. It is by supposing the heat, light, etc., to be generated by a constant and gradual contraction of the dimensions of the solar sphere. As the globe cools by radiation into space, it must contract. In so contracting its ultimate constituent parts are drawn nearer together by their mutual attraction, whereby a form of energy is developed which can be transformed into heat, light, electricity, or other physical forces.

This theory is in complete agreement with the known laws of force. It also admits of precise comparison with facts, since the laws of heat enable us, from the known amount of heat radiated, to infer the exact amount of contraction in inches which the linear dimensions of the sun must undergo in order that this supply of heat may be kept unchanged, as it is practically found to be. With the present size of the sun, it is found that it is only necessary to suppose that its diameter is diminishing at the rate of about 220 feet per year, or 4 miles per century, in order that the supply of heat radiated shall be constant. It is plain that such a change as this may be taking place, since we possess no instruments sufficiently delicate to have detected a change of even ten times this amount since the invention of the telescope.

It may seem a paradoxical conclusion that the cooling of a body may cause it to become hotter. This indeed is true only when we suppose the interior to be gaseous, and not solid or liquid. It is, however, proved by theory that this law holds for gaseous masses.

We cannot say whether the sun has yet begun to liquefy in his interior parts, and hence it is impossible to predict at present the duration of his constant radiation. Theory shows us that after about 5,000,000 years, the sun radiating heat as at present, and still remaining gaseous, will be reduced to one half of his present volume. It seems probable that somewhere about this time the solidification will have begun, and it is roughly estimated, from this line of argument, that the present conditions of heat radiation cannot last greatly over 10,000,000 years.

The future of the sun (and hence of the earth) cannot, as we see, be traced with great exactitude. The past can be more closely followed if we assume (which is tolerably safe) that the sun up to the present has been a gaseous and not a solid or liquid mass. Four hundred years ago, then, the sun was about 16 miles greater in diameter than now; and if we suppose this process of contraction to have regularly gone on at the same rate (an uncertain supposition), we can fix a date when the sun filled any given space, out even to the orbit of *Neptune;* that is, to the time when the solar system consisted of but one body, and that a gaseous or nebulous one. It will subsequently be seen that the ideas here reached *à posteriori* have a striking analogy to the *à priori* ideas of KANT and LA PLACE.

It is not to be taken for granted, however, that the amount of heat to be derived from the contraction of the sun's dimensions is infinite, no matter how large the primitive dimensions may have been. A body falling from any distance to the sun can only have a certain finite velocity depending on this distance and the mass of the sun itself, which, even if the fall be from an infinite distance, cannot exceed, for the sun, 350 miles per second. In the same way the amount of heat generated by the contraction of the sun's volume from any size to any other is finite and not infinite.

It has been shown that if the sun has always been radiating heat at its present rate, and if it had originally filled all space, it has required 18,000,000 years to contract to its present volume. In other words, assuming the present rate of radiation, and taking the most favorable case, the age of the sun does not exceed 18,000,000 years. The earth is, of course, less aged. The supposition lying at the base of this estimate is that the radiation of the sun has been constant throughout the whole period. This is quite unlikely, and any changes in this datum affect greatly the final number of years which we have assigned. While this *number* may be greatly in error, yet the method of obtaining it seems, in the present state of science, to be satisfactory, and the main conclusion remains that the past of the sun is finite, and that in all probability its future is a limited one. The exact number of centuries that it is to last are of no moment even were the data at hand to obtain them: the essential point is that, so far as we can see, the sun, and incidentally the solar system, has a finite past and a limited future, and that, like other natural objects, it passes through its regular stages of birth, vigor, decay, and death, in one order of progress.

CHAPTER III.

THE INFERIOR PLANETS.

MOTIONS AND ASPECTS.

THE inferior planets are those whose orbits lie between the sun and the orbit of the earth. Commencing with the more distant ones, they comprise *Venus* and *Mercury*.

The real and apparent motions of these planets have already been briefly described in Part I., Chapter V. It will be remembered that, in accordance with KEPLER's third law, their periods of revolution around the sun are less than that of the earth. Consequently they overtake the latter between successive inferior conjunctions.

The interval between these conjunctions is about four months in the case of *Mercury*, and between nineteen and twenty months in that of *Venus*. At the end of this period each repeats the same series of motions relative to the sun. What these motions are can be readily seen by studying Fig. 65. In the first place, suppose the earth at any point, *E*, of its orbit, and if we draw a line, *E L* or *E M*, from *E*, tangent to the orbit of either of these planets, it is evident that the angle which this line makes with that drawn to the sun is the greatest elongation of the planet from the sun. The orbits being eccentric, this elongation varies with the position of the earth. In the case of *Mercury* it ranges from 16° to 29°, while in the case of *Venus*, the orbit of which is nearly circular, it varies very little from 45°. These planets, therefore, seem to have an oscillating motion, first swinging

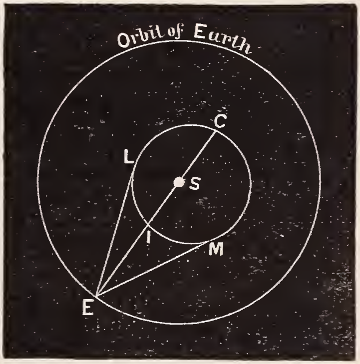

FIG. 65.

toward the east of the sun, and then toward the west of it, as already explained. Since, owing to the annual revolution of the earth, the sun has a constant eastward motion among the stars, these planets must have, on the whole, a corresponding though intermittent motion in the same direction. Therefore the ancient astronomers supposed their period of revolution to be one year, the same as that of the sun.

If, again, we draw a line ESC from the earth through the sun, the point I, in which this line cuts the orbit of the planet, or the point of inferior conjunction, will be the least distance of the planet from the earth, while the second point C, or the point of superior conjunction, on the opposite side of the sun, will be the greatest distance. Owing to the difference of these distances the apparent magnitude of these planets, as seen from the earth, is subject to great variations.

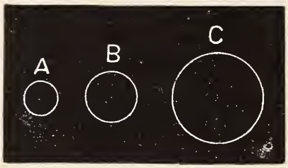

Fig. 66.—Apparent Magnitudes of the Disk of Mercury.

Fig. 66 shows these variations in the case of *Mercury*, A representing its apparent magnitude when at its greatest distance, B when at its mean distance, and C when at its least distance. In the case of *Venus* (Fig. 67) the variations are much greater than in that of *Mercury*, the greatest distance, 1.72, being more than six times the least distance, which is only 0.28. The variations of apparent magnitude are therefore great in the same proportion.

In thus representing the apparent angular magnitude of these planets, we suppose their whole disks to be visible, as they would be if they shone by their own light. But since they can be seen only by the reflected light of the sun, only those portions of the disk can be seen which are at the same time visible from the sun and from the earth. A very little consideration will show that the proportion of the disk which can be seen constantly diminishes as the planet approaches the earth, and looks larger.

When the planet is at its greatest distance, or in superior conjunction (C, Fig. 65), its whole illuminated hemisphere can be seen from the earth. As it moves around and approaches the earth, the illuminated hemisphere is gradually turned from us. At the point of greatest elongation, M or L, one half the hemisphere is visible, and the planet has the form of the moon at first or second quarter. As it approaches inferior conjunction, the apparent visible disk assumes the form of a crescent, which becomes thinner and thinner as the planet approaches the sun.

Fig. 68 shows the apparent disk of *Mercury* at various times during its synodic revolution. The planet will appear brightest when this disk has the greatest surface. This occurs about half way between greatest elongation and inferior conjunction.

In consequence of the changes in the brilliancy of these planets produced by the variations of distance, and those produced by the

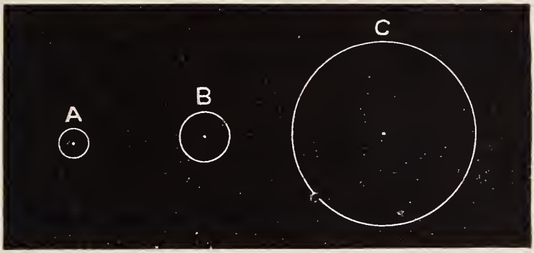

FIG. 67.—APPARENT MAGNITUDES OF THE DISK OF VENUS.

variations in the proportion of illuminated disk visible from the earth, partially compensating each other, their actual brilliancy is not subject to such great variations as might have been expected. As a general rule, *Mercury* shines with a light exceeding that of a star of the first magnitude. But owing to its proximity to the sun,

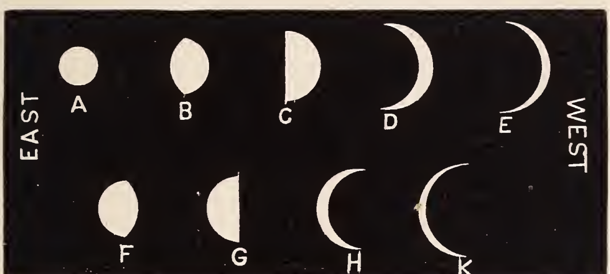

FIG. 68.—APPEARANCE OF MERCURY AT DIFFERENT POINTS OF ITS ORBIT.

it can never be seen by the naked eye except in the west a short time after sunset, and in the east a little before sunrise. It is then of necessity near the horizon, and therefore does not seem so bright as if it were at a greater altitude. In our latitudes we might almost say that it is never visible except in the morning or evening twilight.

On the other hand, the planet *Venus* is, next to the sun and moon, the most brilliant object in the heavens. It is so much brighter than any fixed star that there can seldom be any difficulty in identifying it. The unpractised observer might under some circumstances find a difficulty in distinguishing between *Venus* and *Jupiter*, but the different motions of the two planets will enable him to distinguish them if they are watched from night to night during several weeks.

Atmosphere and Rotation of Mercury.

The various phases of *Mercury*, as dependent upon its various positions relative to the sun, have already been shown. If the planet were an opaque sphere, without inequalities and without an atmosphere, the apparent disk would always be bounded by a circle on one side and an ellipse on the other, as represented in the figure. Whether any variation from this simple and perfect form has ever been detected is an open question, the balance of evidence being very strongly in the negative. Since no spots are visible upon it, it would follow that unless variations of form due to inequalities on its surface, such as mountains, can be detected, it is impossible to determine whether the planet rotates on its axis.

We may regard it as doubtful whether any evidence of an atmosphere of *Mercury* has been obtained, and it is certain that we know nothing definite respecting its physical constitution.

Atmosphere and Rotation of Venus.

As *Venus* sometimes comes nearer the earth than any other primary planet, astronomers have examined its surface with great attention ever since the invention of the telescope. But no conclusive evidence respecting the rotation of the planet and no proof of any changes or any inequalities on its surface have ever been obtained.

Atmosphere of Venus.—The evidence of an atmosphere of *Venus* is perhaps more conclusive than in the case of any other planet. When *Venus* is observed very near its inferior conjunction, and when it therefore presents the view of a very thin crescent, it is found that this crescent extends over more than 180°. This would be evidently impossible unless the sun illuminated more than one half the planet. We therefore conclude that *Venus* has an atmosphere which exercises so powerful a refraction upon the light of the sun that the latter illuminates several degrees more than one half the globe. A phenomenon which must be attributed to the same cause has several times been observed during transits of *Venus*. During the transit of December 8th, 1874, most of the observers who enjoyed a fine steady atmosphere saw that when *Venus* was partially projected on the sun, the outline of that part of its disk outside the sun could be distinguished by a delicate line of light. From these several observations it would seem that the refractive power of the atmosphere of *Venus* is greater than that of the earth.

Transits of Mercury and Venus.

When *Mercury* or *Venus* passes between the earth and sun, so as to appear projected on the sun's disk, the phenomenon is called a *transit.* If these planets moved around the sun in the plane of the ecliptic, it is evident that there would be a transit at every inferior conjunction.

The longitude of the descending node of *Mercury* at the present time is 227°, and therefore that of the ascending node 47°. The earth has these longitudes on May 7th and November 9th. Since a transit can occur only within a few degrees of a node, *Mercury* can transit only within a few days of these epochs.

The longitude of the descending node of *Venus* is now about 256° and therefore that of the ascending node is 76°. The earth has these longitudes on June 6th and December 7th of each year. Transits of *Venus* can therefore occur only within two or three days of these times.

Recurrence of Transits of Mercury.—The following table shows the dates of occurrence of transits of *Mercury* during the present century. They are separated into May transits, which occur near the descending node, and November ones, which occur near the ascending node. November transits are the most numerous, because *Mercury* is then nearer the sun, and the transit limits are wider.

1799, May 6.	1802, Nov. 9.
1832, May 5.	1815, Nov. 11.
1845, May 8.	1822, Nov. 5.
1878, May 6.	1835, Nov. 7.
1891, May 9.	1848, Nov. 10.
	1861, Nov. 12.
	1868, Nov. 5.
	1881, Nov. 7.
	1894, Nov. 10.

Recurrence of Transits of Venus.—For many centuries past and to come, transits of *Venus* occur in a cycle more exact than those of

Mercury. It happens that *Venus* makes 13 revolutions around the sun in nearly the same time that the earth makes 8 revolutions; that is, in eight years. During this period there will be 5 inferior conjunctions of *Venus*, because the latter has made 5 revolutions more than the earth. Consequently, if we wait eight years from an inferior conjunction of *Venus*, we shall, at the end of that time, have another inferior conjunction, the fifth in regular order, at nearly the same point of the two orbits. It will, therefore, occur at the same time of the year, and in nearly the same position relative to the node of *Venus*.

After a pair of transits 8 years apart, an interval of over 100 years must elapse before the occurrence of another pair as is shown in the following table. The dates and intervals of the transits for three cycles nearest to the present time are as follows:

			Intervals.
1518, June 2.	1761, June 5.	2004, June 8	8 years.
1526, June 1.	1769, June 3.	2012, June 6.	105½ "
1631, Dec. 7.	1874, Dec. 9.	2117, Dec. 11.	8 "
1639, Dec. 4.	1882, Dec. 6.	2125, Dec. 8	121½ "

SUPPOSED INTRAMERCURIAL PLANETS.

Some astronomers are of opinion that there is a small planet or a group of planets revolving around the sun inside the orbit of *Mercury*. To this supposed planet the name *Vulcan* has been given; but astronomers generally discredit the existence of any such planet of considerable size.

The evidence in favor of the existence of such planets may be divided into three classes, as follows, which will be considered in their order:

(1) A motion of the perihelion of the orbit of *Mercury*, supposed to be due to the attraction of such a planet or group of planets.

(2) Transits of dark bodies across the disk of the sun which have been supposed to be seen by various observers during the past century.

(3) The observation of certain unidentified objects by Professor WATSON and Mr. LEWIS SWIFT during the total eclipse of the sun, July 29th, 1878.

(1) In 1858 LE VERRIER made a careful collection of all the observations on the transits of *Mercury* which had been recorded since the invention of the telescope. The result of that investigation was

that the observed times of transit could not be reconciled with the calculated motion of the planet, as due to the gravitation of the other bodies of the solar system. He found, however, that if, in addition to the changes of the orbit due to the attraction of the known planets, he supposed a motion of the perihelion amounting to 36′ in a century, the observations could all be satisfied. Such a motion might be produced by the attraction of an unknown planet inside the orbit of *Mercury*. Since, however, a single planet, in order to produce this effect, would have to be of considerable size, and since no such object had ever been observed during a total eclipse of the sun, he concluded that there was probably a group of planets much too small to be separately distinguished.

(2) It is to be noted that if such planets existed they would frequently pass over the disk of the sun. During the past fifty years the sun has been observed almost every day with the greatest assiduity by eminent observers, armed with powerful instruments, who have made the study of the sun's surface and spots the principal work of their lives. None of these observers has ever recorded the transit of an unknown planet. This evidence, though negative in form, is, under the circumstances, conclusive against the existence of such a planet of such magnitude as to be visible in transit with ordinary instruments.

(3) The observations of Professor WATSON during the total eclipse above mentioned seem to afford the strongest evidence yet obtained in favor of the real existence of the planet. His mode of proceeding was briefly this: Sweeping to the west of the sun during the eclipse, he saw two objects in positions where, supposing the pointing of his telescope accurately known, no fixed star existed. There is, however, a pair of known stars, one of which is about a degree distant from one of the unknown objects, and the other about the same distance and direction from the second. It is probable that Professor WATSON's supposed planets were this pair of stars.

Since the above was written Prof. WATSON's observations have been repeated under exceptionally favorable circumstances at the eclipse of May 6, 1883, and no trace of his supposed planets was seen, while much smaller stars were observed.

CHAPTER IV.

THE MOON.

When it became clearly understood that the earth and moon were to be regarded as bodies of one class, and that the old notion of an impassable gulf between the character of bodies celestial and bodies terrestrial was unfounded, the question whether the moon was like the earth in all its details became one of great interest. The point of most especial interest was whether the moon could, like the earth, be peopled by intelligent inhabitants. Accordingly, when the telescope was invented by Galileo, one of the first objects examined was the moon. With every improvement of the instrument the examination became more thorough, so that at present the topography of the moon is much better known than that of the State of Arkansas, for example.

With every improvement in the means of research, it has become more and more evident that the surface of the moon is totally unlike that of our earth. There are no oceans, seas, rivers, air, clouds, or vapor. We can hardly suppose that animal or vegetable life exists under such circumstances, the fundamental conditions of such existence on our earth being entirely wanting. We might almost as well suppose a piece of granite or lava to be the abode of life as the surface of the moon.

The length of one mile on the moon would, as seen from the earth, subtend an angle of about 1″ of arc. More exactly, the angle subtended would range between 0″.8 and 0″.9, according to the varying distance of the moon. In order that an object may be plainly visible to the naked eye, it must subtend an angle of nearly 1′. Consequently a magnifying power of 60 is required to render a round object one mile in diameter on the surface of the moon plainly visible. Starting from this fact, we may readily form the following table, showing the diameters of the smallest objects that can be seen with different magnifying powers, always assuming that vision with these powers is perfect:

Power 60;	diameter of object 1 mile.
Power 150;	diameter 2000 feet.
Power 500;	diameter 600 feet.
Power 1000;	diameter 300 feet.
Power 2000;	diameter 150 feet.

If telescopic power could be increased indefinitely, there would of course be no limit to the minuteness of an object visible on the moon's surface. But the necessary imperfections of all telescopes are such that only in extraordinary cases can anything be gained by increasing the magnifying power beyond 1000. The influence of warm and cold currents in our atmosphere will forever prevent the advantageous use of high magnifying powers. After a certain limit we see nothing more by increasing the power, vision becoming indistinct in proportion as the power is increased. It is hardly likely that an object less than 600 feet in extent can ever be seen on the moon by any telescope whatever, unless it becomes possible to mount the instrument above the atmosphere of the earth. It is therefore only the great features on the surface of the moon, and not the minute ones, which can be made out with the telescope.

FIG. 69.—ASPECT OF THE MOON'S SURFACE.

Character of the Moon's Surface.—The most striking point of difference between the earth and moon is seen in the total absence from the latter of anything that looks like an undulating surface. No formations similar to our valleys and mountain-chains have been detected. The lowest surface of the moon which can be seen with the telescope appears to be nearly smooth and flat, or, to speak more exactly, spherical (because the moon is a sphere). This surface has different shades of color in different regions. Some portions are of a bright silvery tint, while others have a dark gray appearance. These differences of tint seem to arise from differences of material.

Upon this surface as a foundation are built numerous formations of various sizes, but all of a very simple character. Their general form can be made out by the aid of Fig. 69, and their dimensions by the scale of miles at the bottom of it. The largest and most prominent features are known as craters. They have a typical form consisting of a round or oval rugged wall rising from the plane in the manner of a circular fortification. These walls are frequently from three to six thousand metres in height, very rough and broken. In their interior we see the plane surface of the moon already described. It is, however, generally covered with fragments or broken up by small inequalities so as not to be easily made out. In the centre of the craters we frequently find a conical formation rising up to a considerable height, and much larger than the inequalities just described. In the craters we have a vague resemblance to volcanic formations upon the earth, the principal difference being that their magnitude is very much greater than anything known here. The diameter of the larger ones ranges from 50 to 200 kilometres, while the smallest are so minute as to be hardly visible with the telescope.

When the moon is only a few days old, the sun's rays strike very obliquely upon the lunar mountains, and they cast long shadows. From the known position of the sun, moon, and earth, and from the measured length of these shadows, the heights of the mountains can be calculated. It is thus found that some of the mountains near the south pole rise to a height of 8000 or 9000 metres (from 25,000 or 30,000 feet) above the general surface of the moon. Heights of from 3000 to 7000 metres are very common over almost the whole lunar surface.

The question of the origin of the lunar features has a bearing on theories of terrestrial geology as well as upon various questions respecting the past history of the moon itself. It has been considered in this aspect by various geologists.

Lunar Atmosphere.—The question whether the moon has an atmosphere has been much discussed. The only conclusion which has yet been reached is that no positive evidence of an atmosphere has ever been obtained, and that if one exists it is certainly several hundred times rarer than the atmosphere of our earth.

Light and Heat of the Moon.—Many attempts have been made to measure the ratio of the light of the full moon and that of the sun. The results have been very discordant, but all have agreed in showing that the sun emits several hundred thousand times as much light as the full moon. The last and most careful determination is that of ZÖLLNER, who finds the sun to be 618,000 times as bright as the full moon.

The moon must reflect the heat as well as the light of the sun, and must also radiate a small amount of its own heat. By collecting the moon's rays in the focus of one of his large reflecting telescopes, Lord ROSSE was able to show that a certain amount of heat is actually received from the moon, and that this amount varies with the moon's phase, as it should do. As a general result of all his researches, it may be supposed that about six sevenths of the heat given out by the moon is radiated and one seventh reflected.

Is there any Change on the Surface of the Moon?—When the surface of the moon was first found to be covered by craters having the appearance of vòlcanoes at the surface of the earth, it was very naturally thought that these supposed volcanoes might be still in activity, and exhibit themselves to our telescopes by their flames. Not the slightest sound evidence of any incandescent eruption at the moon's surface has been found, however.

Several instances of supposed changes of shape of features on the moon's surface have been described in recent times.

The question whether these changes are proven is one on which the opinions of astronomers differ. The difficulty of reaching a certain conclusion arises from the fact that each feature necessarily varies in appearance, owing to the different directions in which the sun's light falls upon it. Sometimes the changes are very difficult to account for, even when it is certain that they do not arise from any change on the moon itself. Hence while some regard the apparent changes as real, others regard them as due only to differences in the mode of illumination.

CHAPTER V.

THE PLANET MARS.

DESCRIPTION OF THE PLANET.

Mars is the next planet beyond the earth in the order of distance from the sun, being about half as far again as the earth. It has a decided red color, by which it may be readily distinguished from all the other planets. Owing to the considerable eccentricity of its orbit, its distance, both from the sun and from the earth, varies in a larger proportion than does that of the other outer planets.

At the most favorable oppositions, its distance from the earth is about 0.38 of the astronomical unit, or, in round numbers, 57,000,000 kilometres (35,000,000 of miles). This is greater than the least distance of *Venus,* but we can nevertheless obtain a better view of *Mars* under these circumstances than of *Venus,* because when the latter is nearest to us its dark hemisphere is turned toward us, while in the case of *Mars* and of the outer planets the hemisphere turned toward us at opposition is fully illuminated by the sun.

The period of revolution of *Mars* around the sun is a little less than two years, or, more exactly, 687 days. The successive oppositions occur at intervals of two years and one or two months, the earth having made during this interval a little more than two revolutions around the sun, and the planet *Mars* a little more than one. The dates of several past and future oppositions are shown in the following table:

1881	December 26th.
1884	January 31st.
1886	March 6th.

Owing to the unequal motion of the planet, arising from the eccentricity of its orbit, the intervals between successive oppositions vary from two years and one month to two years and two and a half months.

Mars necessarily exhibits phases, but they are not so well marked as in the case of *Venus*, because the hemisphere which it presents to the observer on the earth is always more than half illuminated. The greatest phase occurs when its direction is 90° from that of the sun, and even then six sevenths of its disk is illuminated, like that of the moon, three days before or after full moon. The phases of *Mars* were observed by GALILEO in 1610.

Rotation of Mars.—The early telescopic observers noticed that the disk of *Mars* did not appear uniform in color and brightness, but had a variegated aspect. In 1666 Dr. ROBERT HOOKE found that the markings on *Mars* were permanent and moved around in such a way as to show that the planet revolved on its axis. The markings given in his drawings can be traced at the present day, and are made use of to determine the exact period of rotation of the planet. So well is the rotation fixed by them that the astronomer can now determine the exact number of times the planet has rotated on its axis since these old drawings were made. The period has been found to be $24^h\ 37^m\ 22^s \cdot 7$, a result which appears certain to one or two tenths of a second. It is therefore less than an hour greater than the period of rotation of the earth.

Surface of Mars.—The most interesting result of these markings on *Mars* is the probability that its surface is diversified by land and water, covered by an atmosphere, and altogether very similar to the surface of the earth. Some portions of the surface are of a decided red color, and thus give rise to the well-known fiery aspect of the planet. Other parts are of a greenish hue, and are therefore supposed to be seas. The most striking features are two brilliant white regions, one lying around each pole of the planet. It has been supposed that this appearance is due to immense masses of snow and ice surrounding the poles. If this were so, it would indicate that the processes of evaporation, cloud formation, and condensation of vapor into rain and snow go on at the surface of *Mars* as at the surface of the earth. A certain amount of color is given to this theory by supposed changes in the magnitude of these ice-caps. But the problem of establishing such changes is one of extreme difficulty. The only way in which an adequate idea of this difficulty can be formed is by the student himself looking at *Mars* through a telescope.

If he will then note how hard it is to make out the different shades of light and darkness on the planet, and how they must vary in aspect under different conditions of clearness in our own atmosphere, he will readily perceive that much evidence is necessary to establish great changes. All we can say, therefore, is that the formation of the ice-caps in winter and their melting in summer has some evidence in its favor, but is not yet completely proven.

SATELLITES OF MARS.

Until the year 1877 *Mars* was supposed to have no satellites, none having ever been seen in the most powerful telescopes. But in August of that year Professor HALL, of the Naval Observatory, instituted a systematic search with the great equatorial, which resulted in the discovery of two such objects.

These satellites are by far the smallest celestial bodies known. It is of course impossible to measure their diameters, as they appear in the telescope only as points of light. The outer satellite is probably about six miles and the inner one about seven miles in diameter. The outer one was seen with the telescope at a distance from the earth of 7,000,000 times this diameter. The proportion would be that of a ball two inches in diameter viewed at a distance equal to that between the cities of Boston and New York. Such a feat of telescopic seeing is well fitted to give an idea of the power of modern optical instruments.

Professor HALL found that the outer satellite, which he called *Deimos*, revolves around the planet in $30^h\ 16^m$, and the inner one, called *Phobos*, in $7^h\ 38^m$. The latter is only 5800 miles from the centre of *Mars*, and less than 4000 miles from its surface. It would therefore be almost possible with one of our telescopes on the surface of *Mars* to see an object the size of a large animal on the satellite.

This short distance and rapid revolution make the inner satellite of *Mars* one of the most interesting bodies with which we are acquainted. It performs a revolution in its orbit in less than half the time that *Mars* revolves on its axis. In consequence, to the inhabitants of *Mars* it would seem to rise in the west and set in the east. It will be remembered that the revolution of the moon around the earth and of the earth on its axis are both from west to east; but the

Fig. 70.—Telescopic View of Mars.

latter revolution being the more rapid, the apparent diurnal motion of the moon is from east to west. In the case of the inner satellite of *Mars*, however, this is reversed, and it therefore appears to move in the actual direction of its orbital motion. The rapidity of its phases is also equally remarkable. It is less than two hours from new moon to first quarter, and so on. Thus the inhabitants of *Mars* may see their inner moon pass through all its phases from new to full and again to new in a single night.

CHAPTER VI.

THE MINOR PLANETS.

When the solar system was first mapped out in its true proportions by Copernicus and Kepler, only six primary planets were known; namely, *Mercury, Venus,* the *Earth, Mars, Jupiter,* and *Saturn.* These succeeded each other according to a nearly regular law, as we have shown in Chapter I., except that between *Mars* and *Jupiter* a gap was left where an additional planet might be inserted, and the order of distances be thus made complete. It was therefore supposed by the astronomers of the seventeenth and eighteenth centuries that a planet might be found in this region. A search for this object was instituted toward the end of the last century, but before it had made much progress a planet in the place of the one so long expected was found by Piazzi, of Palermo. The discovery was made on the first day of the present century, 1801, January 1st.

In the course of the following seven years the astronomical world was surprised by the discovery of three other planets, all in the same region, though not revolving in the same orbits. Seeing four small planets where one large one ought to be, Olbers was led to his celebrated hypothesis that these bodies were the fragments of a large planet which had been broken to pieces by the action of some unknown force.

A generation of astronomers now passed away without the discovery of more than these four. In 1845 a fifth planet of the group was found. In 1847 three more were discovered, and discoveries have since been made at a rate which thus far shows no signs of diminution. The number has now reached 225, and the discovery of additional ones seems to be going on as fast as ever. The frequent announcements of the discovery of planets which appear in the public prints all refer to bodies of this group.

The minor planets are distinguished from the major ones by many characteristics. Among these we may mention their small size; their positions, all being situated between the orbits of *Mars* and *Jupiter;* the great eccentricities and inclinations of their orbits.

Number of Small Planets.—It would be interesting to know how many of these planets there are in all, but it is as yet impossible even to guess at the number. As already stated, fully 200 are now known, and the number of new ones found every year ranges from 7 or 8 to 10 or 12. If ten additional ones are found every year during the remainder of the century, 400 will then have been discovered.

A minor planet presents no sensible disk, and therefore looks exactly like a small star. It can be detected only by its motion among the surrounding stars, which is so slow that hours must elapse before it can be noticed.

Magnitudes.—It is impossible to make any precise measurement of the diameters of the minor planets. These can, however, be estimated by the amount of light which the planet reflects. Supposing the proportion of light reflected about the same as in the case of the larger planets, it is estimated that the diameters of the three or four largest, which are those first discovered, range between 300 and 600 kilometres, while the smallest are probably from 20 to 50 kilometres in diameter. The average diameter of all that are known is perhaps less than 150 kilometres; that is, scarcely more than one hundredth that of the earth. The volumes of solid bodies vary as the cubes of their diameters; it might therefore take a million of these planets to make one of the size of the earth.

Form of Orbits.—The orbits of the minor planets are much more eccentric than those of the larger ones; their distance from the sun therefore varies very widely.

Origin of the Minor Planets.—The question of the origin of these bodies was long one of great interest. The features which we have described associate themselves very naturally with the hypothesis of OLBERS, that we here have the fragments of a single large planet which in the beginning revolved in its proper place between the orbits of *Mars* and *Jupiter*. No support has been given to OLBERS' hypothesis by subsequent investigations, and it is no longer considered by astronomers to have any foundation. So far as can be judged, these bodies have been revolving around the sun as separate planets ever since the solar system itself was formed.

CHAPTER VII.

JUPITER AND HIS SATELLITES.

THE PLANET JUPITER.

Jupiter is much the largest planet in the system. His mean distance is nearly 800,000,000 kilometres (480,000,-000 miles). His diameter is 140,000 kilometres, corresponding to a mean apparent diameter, as seen from the sun, of 36″.5. His linear diameter is about $\frac{1}{10}$, his surface is $\frac{1}{100}$, and his volume $\frac{1}{1000}$ that of the sun. His mass is $\frac{1}{1048}$, and his density is thus nearly the same as the sun's; *viz.*, 0.24 of the earth's. He rotates on his axis in $9^h\ 55^m\ 20^s$.

He is attended by four satellites, which were discovered by GALILEO on January 7th, 1610. He named them, in honor of the MEDICIS, the *Medicean stars*. They are now known as Satellites I, II, III, and IV, I being the nearest.

The surface of *Jupiter* has been carefully studied with the telescope, particularly within the past twenty years. Although further from us than *Mars*, the details of his disk are much easier to recognize. The most characteristic features are given in the drawings appended. These features are, *first*, the dark bands of the equatorial regions, and, *secondly*, the cloud-like forms spread over nearly the whole surface. At the limb all these details become indistinct, and finally vanish, thus indicating a highly absorptive atmosphere. The light from the centre of the disk is twice as bright as that from the poles. The bands can be seen with instruments no more powerful than those used by GALILEO, yet he makes no mention of them.

The color of the bands is reddish. The position of the bands varies in latitude, and the shapes of the limiting curves also change from day to day; but in the main they remain as permanent features of the region to which they belong. Two such bands are usually visible, but often

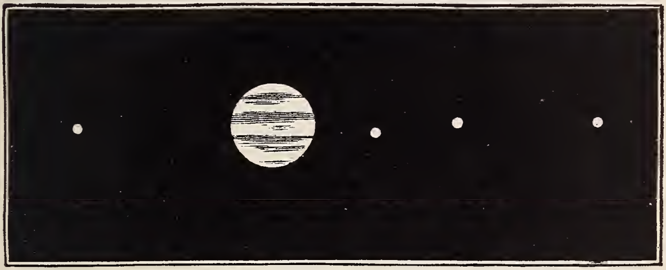

FIG. 71.—TELESCOPIC VIEW OF JUPITER AND HIS SATELLITES.

more are seen. HERSCHEL, in the year 1793, attributed the aspects of the bands to zones of the planet's atmosphere more tranquil and less filled with clouds than the remaining portions, so as to permit the true surface of the planet to be seen through these zones, while the prevailing clouds in the other regions give a brighter tint to these latter. The color of the bands seems to vary from time to time, and their bordering lines sometimes alter with such rapidity as to show that these borders are formed of something like clouds.

The clouds themselves can easily be seen at times, and they have every variety of shape, sometimes appearing as brilliant circular white masses, but oftener they are similar in form to a series of white *cumulus* clouds such as are frequently seen piled up near the horizon on a summer's day. The bands themselves seem frequently to be veiled over with something like the thin *cirrus* clouds of our atmosphere.

FIG. 72.—TELESCOPIC VIEW OF JUPITER, WITH A SATELLITE AND ITS SHADOW SEEN ON THE DISK.

Such clouds can be tolerably accurately observed, and may be used to determine the rotation-time of the planet. These observations show that the clouds have often a motion of their own, which is also evident from other considerations.

The following results of observation of spots situated in various regions of the planet will illustrate this:

			h.	m.	s.
CASSINI............	1665,	rotation-time =	9	56	00
HERSCHEL.........	1778,	" =	9	55	40
HERSCHEL.........	1779,	" =	9	50	48
SCHROETER.........	1785,	" =	9	56	56
BEER and MÄDLER .	1835,	" =	9	55	26
AIRY	1835,	" =	9	55	21
SCHMIDT...........	1862,	" =	9	55	29

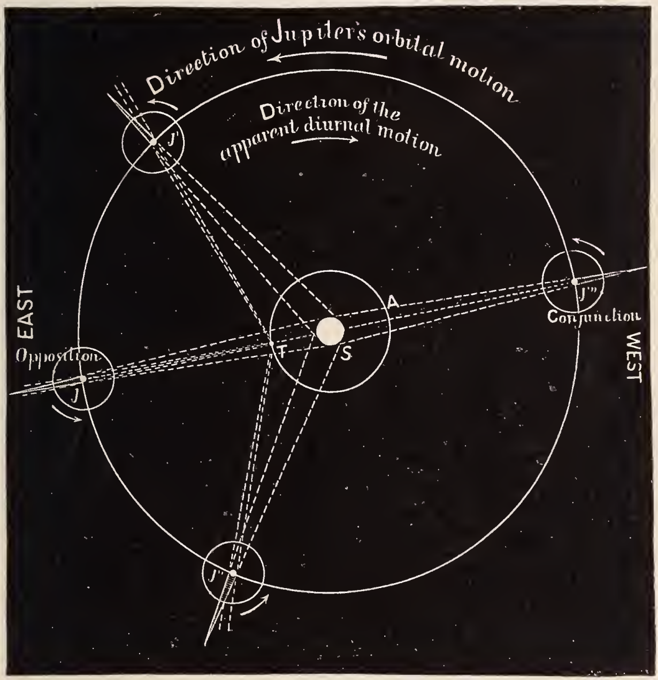

FIG. 73.

THE SATELLITES OF JUPITER.

Motions of the Satellites.—The four satellites move about *Jupiter* from west to east in nearly circular orbits. When one of these satellites passes between the sun and *Jupiter*, it casts a shadow upon *Jupiter's* disk (see Fig. 73) precisely as the shadow of our moon is thrown upon the earth in a solar eclipse. If the satellite passes through *Jupiter's* own shadow in its revolution, an eclipse of this satellite takes place. If it passes between the earth and *Jupiter*, it is projected upon *Jupiter's* disk, and we have a transit; if *Jupiter* is between the earth and the satellite, an occultation of the latter occurs. All these phenomena can be seen with a common telescope, and the times of observation are all found predicted in the *Nautical Almanac*. These shadows being seen black upon *Jupiter's* surface, show that this planet shines by reflecting the light of the sun.

Telescopic Appearance of the Satellites.—Under ordinary circumstances, the satellites of *Jupiter* are seen to have disks; that is, not to be mere points of light. Under very favorable conditions, markings have been seen on these disks.

The satellites completely disappear from telescopic view when they enter the shadow of the planet. This seems to show that neither planet nor satellite is self-luminous to any great extent. If the satellite were self-luminous, it would be seen by its own light; and if the planet were luminous, the satellite might be seen by the reflected light of the planet.

The motions of these objects are connected by two curious and important relations discovered by LA PLACE, and expressed as follows:

I. *The mean motion of the first satellite added to twice the mean motion of the third is exactly equal to three times the mean motion of the second.*

II. *If to the mean longitude of the first satellite we add twice the mean longitude of the third, and subtract three times the mean longitude of the second, the difference is always* 180°.

The first of these relations is shown in the following table of the mean daily motions of the satellites:

Satellite I in one day moves..............	203°.4890
" II " "	101°.3748
" III " "	50°.3177
" IV " "	21°.5711
Motion of Satellite I......................	203°.4890
Twice that of Satellite III....	100°.6354
Sum..................................	304°.1244
Three times motion of Satellite II..........	304°.1244

Observations showed that this condition was fulfilled as exactly as possible, but the discovery of LA PLACE consisted in showing that if the approximate coincidence of the mean motions was once established, they could never deviate from exact coincidence with the law. The case is analogous to that of the moon, which always presents the same face to us and which always will, since the relation being once approximately true, it will become exact and ever remain so.

The discovery of the gradual propagation of light by means of these satellites has already been described, and it has also been explained that they are of use in the rough determination of longitudes. To facilitate their observation, the Nautical Almanac gives complete ephemerides of their phenomena. A specimen of a portion of such an ephemeris for 1865, March 7th, 8th, and 9th, is added. The times are Washington mean times.

1865—MARCH.

			d.	*h.*	*m.*	*s.*
I	Eclipse	Disapp.	7	18	27	38.5
I	Occult.	Reapp.	7	21	56	
III	Shadow	Ingress	8	7	27	
III	Shadow	Egress	8	9	58	
III	Transit	Ingress	8	12	31	
II	Eclipse	Disapp.	8	13	1	22.7
III	Transit	Egress	8	15	6	
II	Eclipse	Reapp.	8	15	24	11.1
II	Occult.	Disapp.	8	15	27	
I	Shadow	Ingress	8	15	43	
I	Transit	Ingress	8	16	58	
I	Shadow	Egress	8	17	57	
II	Occult.	Reapp.	8	17	59	
I	Transit	Egress	8	19	13	
I	Eclipse	Disapp.	9	12	55	59.4
I	Occult.	Reapp.	9	16	25	

Suppose an observer near New York City to have determined his local time accurately. This is about 13^m faster than Washington time. On 1865, March 8th, he would look for the reappearance of II at about $15^h\ 34^m$ of his local time. Suppose he observed it at $15^h\ 36^m\ 22^s.7$ of his time: then his meridian is $12^m\ 11^s.6$ east of Washington. The difficulty of observing these eclipses with accuracy, and the fact that the aperture of the telescope employed has an important effect on the appearances seen, have kept this method from a wide utility, which it at first seemed to promise.

CHAPTER VIII.

SATURN AND ITS SYSTEM.

General Description.

Saturn is the most distant of the major planets known to the ancients. It revolves around the sun in 29½ years, at a mean distance of about 1,400,000,000 kilometres (882,000,000 miles). The angular diameter of the ball of the planet is about 16″.2, corresponding to a true diameter of about 110,000 kilometres (70,500 miles). Its diameter is therefore nearly nine times and its volume about 700 times that of the earth. It is remarkable for its small density, which, so far as known, is less than that of any other heavenly body, and even less than that of water. It revolves on its axis in $10^h\ 14^m\ 24^s$, or less than half a day.

Saturn is perhaps the most remarkable planet in the solar system, being itself the centre of a system of its own, altogether unlike anything else in the heavens. Its most noteworthy feature is a pair of rings which surround it at a considerable distance from the planet itself. Outside of these rings revolve no less than eight satellites, or twice the greatest number known to surround any other planet. The planet, rings, and satellites are altogether called the *Saturnian system.* The general appearance of this system, as seen in a small telescope, is shown in Fig. 74.

To the naked eye *Saturn* is of a dull yellowish color, shining with about the brilliancy of a star of the first magnitude. It varies in brightness, however, with the way in which its ring is seen, being brighter the wider the ring appears. It comes into opposition at intervals of one year and from twelve to fourteen days. The following are the

FIG. 74.—TELESCOPIC VIEW OF THE SATURNIAN SYSTEM.

times of some of these oppositions, by studying which one will be enabled to recognize the planet:

1882	November 14th.
1883	November 28th.
1884	December 11th.

During these years it will be best seen in the autumn and winter.

When viewed with a telescope, the physical appearance of the ball of *Saturn* is quite similar to that of *Jupiter*, having light and dark belts parallel to the direction of its rotation.

The Rings of Saturn.

The rings are the most remarkable and characteristic feature of the Saturnian system. Fig. 75 gives two views of the ball and rings. The upper one shows one of their aspects as actually presented in the telescope, and the lower one shows what the appearance would be if the planet were viewed from a direction at right angles to the plane of the ring (which it never can be from the earth).

The first telescopic observers of *Saturn* were unable to see the rings in their true form, and were greatly perplexed to account for the appearance which the planet presented. Galileo described the planet as "tri-corporate," the two ends of the ring having, in his imperfect telescope, the appearance of a pair of small planets attached to the central one. "On each side of old *Saturn* were servitors who aided him on his way." This supposed discovery was announced to his friend Kepler in this logogriph:

"smaismrmilmepoetalevmibunenugttaviras," which, being transposed, becomes—

"Altissimum planetam tergeminum observavi" (I have observed the most distant planet to be tri-form).

The phenomenon constantly remained a mystery to its first observer. In 1610 he had seen the planet accompanied, as he supposed, by two lateral stars; in 1612 the latter had vanished and the central body alone remained. After that Galileo ceased to observe *Saturn*.

The appearances of the ring were also incomprehensible to Hevelius, Gassendi, and others. It was not until 1655 (after seven years of observation) that the celebrated Huyghens discovered the true explanation of the remarkable and recurring series of phenomena present by the tri-corporate planet.

He announced his conclusions in the following logogriph:

"aaaaaa ccccc d eeeee g h iiiiiii llll mm nnnnnnnnn oooo pp q rr s ttttt uuuuu," which, when arranged, read—

"Annulo cingitur, tenui, plano, nusquam coherente, ad eclipticam inclinato" (it is girdled by a thin plane ring, nowhere touching, inclined to the ecliptic).

This description is complete and accurate.

In 1675 it was found by Cassini, that what Huyghens had seen as a single ring was really two. A division extended all the way around near the outer edge. This division is shown in the figures.

In 1850 the Messrs. Bond, of Harvard College Observatory, found

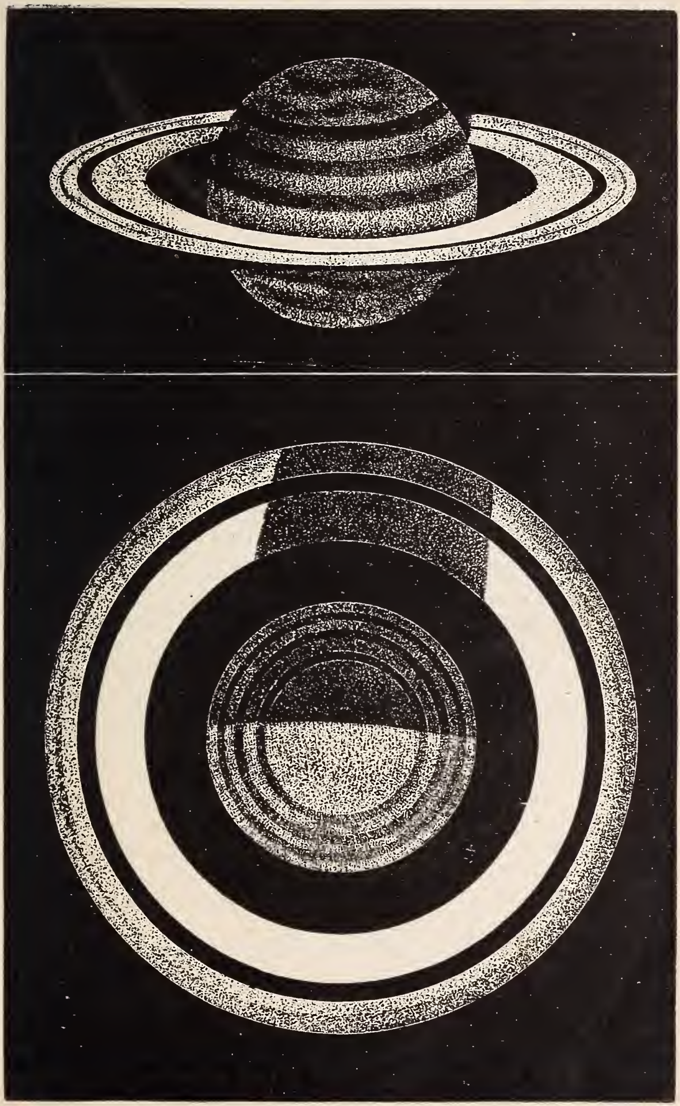

FIG. 75.—RINGS OF SATURN.

that there was a third ring, of a dusky and nebulous aspect, inside the other two, or rather attached to the inner edge of the inner ring. It is therefore known as *Bond's dusky ring.* It had not been before fully described owing to its darkness of color, which made it a difficult object to see except with a good telescope. It is not separated from the bright ring, but seems as if attached to it. The latter shades off toward its inner edge, and merges gradually into the dusky ring. The latter extends about half way from the inner edge of the bright ring to the ball of the planet.

Aspect of the Rings.—As *Saturn* revolves around the sun, the plane of the rings remains parallel to itself. That is, if we consider a straight line passing through the centre of the planet, perpendicular to the plane of the ring, as the axis of the latter, this axis will always point in the same direction. In this respect the motion is similar to that of the earth around the sun. The ring of *Saturn* is inclined about 27° to the plane of its orbit. Consequently, as the planet revolves around the sun, there is a change in the direction in which the sun shines upon it similar to that which produces the change of seasons upon the earth, as shown in Fig. 32.

The corresponding changes for *Saturn* are shown in Fig 76. During each revolution of *Saturn* the plane of the ring passes through the sun twice. This occurred in the years 1862 and 1878, at two opposite points of the orbit, as shown in the figure. At two other points, midway between these, the sun shines upon the plane of the ring at its greatest inclination, about 27°. Since the earth is little more than one tenth as far from the sun as *Saturn* is, an observer always sees *Saturn* nearly, but not quite, as if he were upon the sun. Hence at certain times the rings of *Saturn* are seen edgeways; while at other times they are at an inclination of 27°, the aspect depending upon the position of the planet in its orbit. The following are the times of some of the phases:

1878, February 7th.—The edge of the ring was turned toward the sun. It could then be seen only as a thin line of light.

1885.—The planet having moved forward 90°, the south side of the rings may be seen at an inclination of 27°.

1891, December.—The planet having moved 90° further, the edge of the ring is again turned toward the sun.

1899.—The north side of the ring is inclined toward the sun, and is seen at its greatest inclination.

The rings are extremely thin in proportion to their extent. Consequently, when their edges are turned toward the earth, they appear as a thin line of light, which can be seen only with powerful telescopes. With such telescopes, the planet appears as if it were pierced through by a piece of very fine wire, the ends of which project on each side more than the diameter of the planet. It has frequently been remarked that this appearance is seen on one side of the planet, when no trace of the ring can be seen on the other.

There is sometimes a period of a few weeks during which the plane of the ring, extended outward, passes between the sun and the earth. That is, the sun shines on one side of the ring, while the other or dark side is turned toward the earth. In this case it seems to be established that only the edge of the ring is visible. If this be

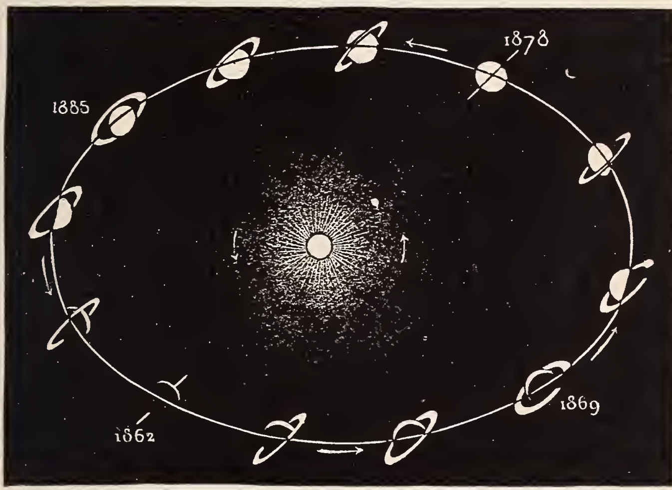

FIG. 76.—DIFFERENT ASPECTS OF THE RING OF SATURN AS SEEN FROM THE EARTH.

so, the substance of the rings cannot be transparent to the sun's rays, else it would be seen by the light which passes through it.

Constitution of the Rings of Saturn.—The nature of these objects has been a subject both of wonder and of investigation by mathematicians and astronomers ever since they were discovered. They were at first supposed to be solid bodies; indeed, from their appearance it was difficult to conceive of them as anything else. The question then arose: What keeps them from falling on the planet? It was shown by LA PLACE that a homogeneous and solid ring surrounding the planet could not remain in a state of equilibrium, but must be precipitated upon the central ball by the smallest disturbing force.

It is now established beyond reasonable doubt that the rings do not form a continuous mass, but are really a countless multitude of small separate particles, each of which revolves on its own account. These satellites are individually far too small to be seen in any telescope, but so numerous that when viewed from the distance of the earth they appear as a continuous mass, like particles of dust floating in a sunbeam.

SATELLITES OF SATURN.

Outside the rings of *Saturn* revolve its eight satellites, the order and discovery of which are shown in the following table:

No.	NAME.	Distance from Planet.	Discoverer.	Date of Discovery.
1	Mimas	3·3	Herschel	1789, September 17.
2	Enceladus	4·3	Herschel	1789, August 28.
3	Tethys	5·3	Cassini	1684, March.
4	Dione	6·8	Cassini	1684, March.
5	Rhea	9·5	Cassini	1672, December 23.
6	Titan	20·7	Huyghens	1655, March 25.
7	Hyperion	26·8	Bond	1848, September 16.
8	Japetus	64·4	Cassini	1671, October.

The distances from the planet are given in radii of the latter. The satellites *Mimas* and *Hyperion* are visible only in the most powerful telescopes. The brightest of all is *Titan*, which can be seen in a telescope of the smallest ordinary size. *Japetus* has the remarkable peculiarity of appearing nearly as bright as *Titan* when seen west of the planet, and so faint as to be visible only in large telescopes when on the other side. This appearance is explained by supposing that, like our moon, it always presents the same face to the planet, and that one side of it is dark and the other side light. When west of the planet, the bright side is turned toward the earth and the satellite is visible. On the other side of the planet, the dark side is turned toward us, and it is nearly invisible. Most of the remaining five satellites can ordinarily be seen with telescopes of moderate power.

CHAPTER IX.

THE PLANET URANUS.

Uranus was discovered on March 13th, 1781, by Sir William Herschel (then an amateur observer) with a ten-foot reflector made by himself. He was examining a portion of the sky near H *Geminorum,* when one of the stars in the field of view attracted his notice by its peculiar appearance. On further scrutiny, it proved to have a planetary disk, and a motion of over 2″ per hour. Herschel at first supposed it to be a comet in a distant part of its orbit, and under this impression parabolic orbits were computed for it by various mathematicians. None of these, however, satisfied subsequent observations, and it was finally determined that the new body was a planet revolving in a nearly circular orbit. We can scarcely comprehend now the enthusiasm with which this discovery was received. No new body (save comets) had been added to the solar system since the discovery of the third satellite of *Saturn* in 1684, and all the major planets of the heavens had been known for thousands of years.

Uranus revolves about the sun in 84 years. Its apparent diameter as seen from the earth varies little, being about 3″.9. Its true diameter is about 50,000 kilometres, and its figure is, so far as we know, exactly spherical.

In physical appearance it is a small greenish disk without markings. It is possible that the centre of the disk is slightly brighter than the edges. At its nearest approach to the earth, it shines as a star of the sixth magnitude, and is just visible to an acute eye when the attention is directed to its place. In small telescopes with low powers, its appearance is not markedly different from that of stars of about its own brilliancy.

Sir WILLIAM HERSCHEL suspected that *Uranus* was accompanied by six satellites.

Of the existence of two of these satellites there has never been any doubt. None of the other four satellites described by HERSCHEL has ever been seen, and he was undoubtedly mistaken in supposing them to exist. Two additional ones were discovered by LASSELL in 1847, and they are, with the satellites of *Mars*, the faintest objects in the solar system. Neither of them is identical with any of the missing ones of HERSCHEL. As Sir WILLIAM HERSCHEL had suspected six satellites, the following names for the true satellites are generally adopted to avoid confusion:

			DAYS.
I.	*Ariel*....................................	Period =	2.520383
II.	*Umbriel*..................................	" =	4.144181
III.	*Titania*, HERSCHEL'S (II.).................	" =	8.705897
IV.	*Oberon*, HERSCHEL'S (IV.)..................	" =	13.463269

It is likely that *Ariel* varies in brightness on different sides of the planet, and the same phenomenon has also been suspected for *Titania*.

The most remarkable feature of the satellites of *Uranus* is that their orbits are nearly perpendicular to the ecliptic instead of having a small inclination to that plane, like those of all the orbits of both planets and satellites previously known. To form a correct idea of the position of the orbits, we must imagine them tipped over until their north pole is nearly 8° below the ecliptic, instead of 90°

above it. The pole of the orbit which should be considered as the north one is that from which, if an observer look down upon a revolving body, the latter would seem to turn in a direction opposite that of the hands of a watch. When the orbit is tipped over more than a right angle, the motion from a point in the direction of the north pole of the ecliptic will seem to be the reverse of this; it is therefore sometimes considered to be *retrograde*. This term is frequently applied to the motion of the satellites of *Uranus*, but is rather misleading, since the motion, being nearly perpendicular to the ecliptic, is not exactly expressed by the term.

The four satellites move in the same plane. This fact renders it highly probable that the planet *Uranus* revolves on its axis in the same plane with the orbits of the satellites, and is therefore an oblate spheroid like the earth. This conclusion is founded on the consideration that if the planes of the satellites were not kept together by some cause, they would gradually deviate from each other owing to the attractive force of the sun upon the planet. The different satellites would deviate by different amounts, and it would be extremely improbable that all the orbits would at any time be found in the same plane. Since we see them in the same plane, we conclude that some force keeps them there, and the oblateness of the planet would cause such a force.

CHAPTER X.

THE PLANET NEPTUNE.

AFTER the planet *Uranus* had been observed for some thirty years, tables of its motion were prepared by BOUVARD. He had as data available for this purpose not only the observations since 1781, but also observations extending back as far as 1695, in which the planet was observed and supposed to be a fixed star. As one of the chief difficulties in the way of obtaining a theory of the planet's motion was the short period of time during which it had been regularly observed, it was to be supposed that these ancient observations would materially aid in obtaining exact accordance between the theory and observation. But it was found that, after allowing for all perturbations produced by the known planets, the ancient and modern observations, though undoubtedly referring to the same object, were yet not to be reconciled with each other, but differed systematically. BOUVARD was forced to omit the older observations in his tables, which were published in 1820, and to found his theory upon the modern observations alone. By so doing, he obtained a good agreement between theory and the observations of the few years immediately succeeding 1820.

BOUVARD seems to have formulated the idea that a possible cause for the discrepancies noted might be the existence of an unknown planet, but the meagre data at his disposal forced him to leave the subject untouched. In

1830 it was found that the tables which represented the motion of the planet well in 1820–25 were 20″ in error, in 1840 the error was 90″, and in 1845 it was over 120″.

These progressive and systematic changes attracted the attention of astronomers to the subject of the theory of the motion of *Uranus*. The actual discrepancy (120″) in 1845 was not a quantity large in itself. Two stars of the magnitude of *Uranus*, and separated by only 120″, would be seen as one to the unaided eye. It was on account of its systematic and progressive increase that suspicion was excited. Several astronomers attacked the problem in various ways. The elder STRUVE, at Pulkova, prosecuted a search for a new planet along with his double-star observations; BESSEL, at Koenigsberg, set a student of his own, FLEMING, at a new comparison of observation with theory, in order to furnish data for a new determination; ARAGO, then Director of the Observatory at Paris, suggested this subject in 1845 as an interesting field of research to LE VERRIER, then a rising mathematician and astronomer. Mr. J. C. ADAMS, a student in Cambridge University, England, had become aware of the problems presented by the anomalies in the motion of *Uranus*, and had attacked this question as early as 1843. In October, 1845, ADAMS communicated to the Astronomer Royal of England elements of a new planet so situated as to produce the perturbations of the motion of *Uranus* which had actually been observed. Such a prediction from an entirely unknown student, as ADAMS then was, did not carry entire conviction with it. A series of accidents prevented the unknown planet being looked for by one of the largest telescopes in England, and so the matter apparently dropped. It may be noted, however, that we now know

ADAMS' elements of the new planet to have been so near the truth that if it had been really looked for by the powerful telescope which afterward discovered its satellite, it could scarcely have failed of detection.

BESSEL'S pupil FLEMING died before his work was done, and BESSEL'S researches were temporarily brought to an end. STRUVE'S search was unsuccessful. Only LE VERRIER continued his investigations, and in the most thorough manner. He first computed anew the perturbation of *Uranus* produced by the action of *Jupiter* and *Saturn.* Then he examined the nature of the irregularities observed. These showed that if they were caused by an unknown planet, it could not be between *Saturn* and *Uranus,* or else *Saturn* would have been more affected than was the case.

The new planet was outside of *Uranus* if it existed at all, and as a rough guide BODE'S law was invoked, which indicated a distance about twice that of *Uranus.* In the summer of 1846 LE VERRIER obtained complete elements of a new planet, which would account for the observed irregularities in the motion of *Uranus,* and these were published in France. They were very similar to those of ADAMS, which had been communicated to Professor CHALLIS, the Director of the Observatory of Cambridge, England.

A search was immediately begun by CHALLIS for such an object, and as no star-maps were at hand for this region of the sky, he began mapping the surrounding stars. In so doing the new planet was actually observed, both on August 4th and 12th, 1846, but the observations remaining unreduced, and so the planetary nature of the object was not recognized.

In September of the same year LE VERRIER wrote to Dr. GALLE, then Assistant at the Observatory of Berlin, asking him to search for the new planet, and directing him to the place where it should be found. By the aid of an excellent star-chart of this region, which had just been completed, the planet was found September 23d, 1846.

The strict rights of discovery lay with LE VERRIER, but the common consent of mankind has always credited

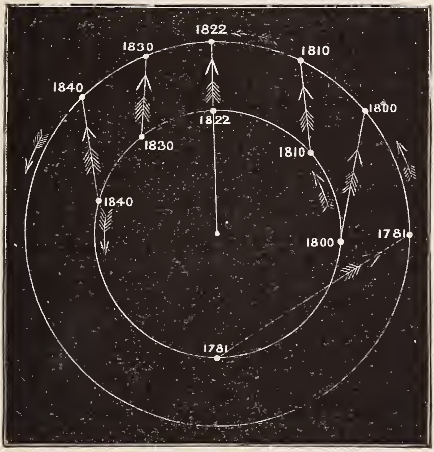

FIG. 77.

ADAMS with an equal share in the honor attached to this most brilliant achievement. Indeed, it was only by the most unfortunate succession of accidents that the discovery did not attach to ADAMS' researches. One thing must in fairness be said, and that is that the results of LE VERRIER, which were reached after a most thorough investigation of the whole ground, were announced with an entire confidence which, perhaps, was lacking in the other case.

This brilliant discovery created more enthusiasm than even the discovery of *Uranus,* as it was by an exercise of far higher qualities that it was achieved. It appeared to savor of the marvellous that a mathematician could say to a working astronomer that by pointing his telescope to a certain small area, within it should be found a new major planet. Yet so it was.

The general nature of the disturbing force which revealed the new planet may be seen by Fig. 77, which shows the orbits of the two planets, and their respective motions between 1781 and 1840. The inner orbit is that of *Uranus,* the outer one that of *Neptune.* The arrows passing from the former to the latter show the directions of the attractive force of *Neptune.* It will be seen that the two planets were in conjunction in the year 1822. Since that time *Uranus* has, by its more rapid motion, passed more than 90° beyond *Neptune,* and will continue to increase its distance from the latter until the beginning of the next century.

Our knowledge regarding *Neptune* is mostly confined to a few numbers representing the elements of its motion. Its mean distance is more than 4,000,000,000 kilometres (2,775,000,000 miles); its periodic time is 164.78 years; its apparent diameter is 2.6 seconds, corresponding to a true diameter of 55,000 kilometres. Gravity at its surface is about nine tenths of the corresponding terrestrial surface gravity. Of its rotation and physical condition nothing is known. Its color is a pale greenish blue. It is attended by one satellite, which was discovered by Mr. Lassell, of England, in 1847. The satellite requires a telescope of twelve inches' aperture or upward to be well seen.

CHAPTER XI.

THE PHYSICAL CONSTITUTION OF THE PLANETS.

It is remarkable that the eight large planets of the solar system, considered with respect to their physical constitution as revealed by the telescope and the spectroscope, may be divided into four pairs, the planets of each pair having a great similarity, and being quite different from the adjoining pair.

Mercury and Venus.—Passing outward from the sun, the first pair we encounter will be *Mercury* and *Venus*. The most remarkable feature of these two planets is a negative rather than a positive one, being the entire absence of any certain evidence of change on their surfaces. We have already shown that *Venus* has a considerable atmosphere, while there is no evidence of any such atmosphere around *Mercury*. They have therefore not been proved alike in this respect, yet, on the other hand, they have not been proved different. In every other respect than this the similarity appears perfect. No permanent markings have ever been certainly seen on the disk of either. If, as is possible, the atmosphere of both planets is filled with clouds and vapor, no change, no openings, and no formations among these cloud masses are visible from the earth. Whenever either of these planets is in a certain position relative to the earth and the sun, it seemingly presents the same appearance, and not the slightest change occurs in that appearance from the rotation of the planet on its axis, which every analogy of the solar system leads us to believe must take place.

When studied with the spectroscope, the spectra of *Mercury* and *Venus* do not differ strikingly from that of the sun. This would seem to indicate that the atmospheres of these planets do not exert any decided absorption upon the rays of light which pass through them; or, at least, they absorb only the same rays which are absorbed by the atmosphere of the sun and by that of the earth. The one point of difference is that the lines of the spectrum produced by the absorption of our own atmosphere appear darker in the spectrum of *Venus*. If this were so, it would indicate that the atmosphere of *Venus* is similar in constitution to that of our earth, because it absorbs the same rays. But the means of measuring the darkness of the lines are as yet so imperfect that it is impossible to speak with certainty on a point like this.

The Earth and Mars.—These planets are distinguished from all the others in that their visible surfaces are marked by permanent features, which show them to be solid, and which can be seen from the other heavenly bodies. It is true that we cannot study the earth from any other body, but we can form a very correct idea how it would look if seen in this way (from the moon, for instance). Wherever the atmosphere was clear, the outlines of the continents and oceans would be visible, while they would be invisible where the air was cloudy.

Now, so far as we can judge from observations made at so great a distance, never much less than forty millions of miles, the planet *Mars* presents to our telescopes very much the same general appearance that the earth would if observed from an equally great distance. The only exception is that the visible surface of *Mars* is seemingly much less obscured by clouds than that of the earth would be. In other words, that planet has a more sunny sky than ours. It is, of course, impossible to say what conditions we might find could we take a much closer view of *Mars*: all we can assert is, that so far as we can judge from this distance, its surface is like that of the earth.

This supposed similarity is strengthened by the spectroscopic observations.

Jupiter and Saturn.—The next pair of planets is *Jupiter* and *Saturn*. Their peculiarity is that no solid crust or surface is visible from without. In this respect they differ from the earth and *Mars*, and resemble *Mercury* and *Venus*. But they differ from the latter in the very important point that constant changes can be seen going on at their surfaces. The preponderance of evidence is in favor of the view that these planets have no solid crusts whatever, but consist of masses of molten matter, surrounded by envelopes of vapor constantly rising from the interior.

This view is further strengthened by their very small specific gravity, which can be accounted for by supposing that the liquid interior is nothing more than a comparatively small central core, and that the greater part of the bulk of each planet is composed of vapor of small density.

That the visible surfaces of *Jupiter* and *Saturn* are covered by some kind of an atmosphere follows not only from the motion of the cloud forms seen there, but from the spectroscopic observations.

Uranus and Neptune.—These planets have a strikingly similar aspect when seen through a telescope. They differ from *Jupiter* and *Saturn* in that no changes or variations of color or aspect can be made out upon their surfaces; and from the earth and *Mars* in the absence of any permanent features. Telescopically, therefore, we might classify them with *Mercury* and *Venus,* but the spectroscope reveals a constitution entirely different from that of any other planets. The most marked features of their spectra are very dark bands, evidently produced by the absorption of dense atmospheres. Owing to the extreme faintness of the light which reaches us from these distant bodies, the regular lines of the solar spectrum are entirely invisible in their spectra, yet these dark bands which are peculiar to them have been seen by several astronomers.

This classification of the eight planets into pairs is rendered yet more striking by the fact that it applies to what we have been able to discover respecting the rotations of these bodies. The rotation of the inner pair, *Mercury* and *Venus,* has eluded detection, notwithstanding their comparative proximity to us. The next pair, the earth and *Mars,* have perfectly definite times of rotation, because their outer surfaces consist of solid crusts, every part of which must rotate in the same time. The next pair, *Jupiter* and *Saturn,* have well-established times of rotation, but these times are not perfectly definite, because the surfaces of these planets are not solid, and different portions of their mass may rotate in slightly different times. *Jupiter* and *Saturn* have also in common a very rapid rate of rotation. Finally, the outer pair, *Uranus* and *Neptune,* seem to be surrounded by atmospheres of such density that no evidence of rotation can be gathered. Thus it seems that of the eight planets only the central four have yet certainly indicated a rotation on their axes.

CHAPTER XII.

METEORS.

Phenomena and Causes of Meteors.

During the present century evidence has been collected that countless masses of matter, far too small to be seen with the most powerful telescopes, are moving through the planetary spaces. This evidence is afforded by the phenomena of "aerolites," "meteors," and "shooting-stars." Although these several phenomena have been observed and noted from time to time since the earliest historic era, it is only recently that a complete explanation has been reached.

Aerolites.—Reports of the falling of large masses of stone or iron to the earth have been familiar to antiquarian students for many centuries. The problem where such a body could come from, or how it could get into the atmosphere to fall down again, formerly seemed so nearly incapable of solution that it required some credulity to admit the facts. When the evidence became so strong as to be indisputable, theories of their origin began to be propounded. One theory quite fashionable in the early part of this century was that they were thrown from volcanoes in the moon. This theory has little to support it.

The proof that aerolites did really fall to the ground first became conclusive by the fall being connected with other more familiar phenomena. Nearly every one who is at all observant of the heavens is familiar with *bolides*, or fire-balls—brilliant objects having the appearance of rockets, which are occasionally seen moving with great velocity through the upper regions of the atmosphere. Scarcely a year passes in which such a body of extraordinary brilliancy is not seen. Generally these bodies, bright though they may be, vanish without leaving any trace, or making themselves evident to any sense but that of sight. But on rare occasions their appearance is followed at an interval of several minutes by loud explosions like the discharge of a battery of artillery. The fall of these aerolites is always accompanied by light and sound, though the light may be invisible in the daytime.

When chemical analysis was applied to aerolites, they were proved to be of extramundane origin, because they contained chemical combinations not found in terrestrial substances. It is true that they contained no new chemical elements, but only a combination of the elements which are found on the earth. These combinations are now so familiar to mineralogists that they can distinguish an aerolite from a mineral of terrestrial origin by a careful examination. One of the most frequent components of these bodies is iron.

Meteors.—Although the meteors we have described are of dazzling brilliancy, yet they run by insensible gradations into phenomena, which any one can see on any clear night. The most brilliant meteors of all are likely to be seen by one person only two or three times in his life. Meteors having the appearance and brightness of a distant rocket may be seen several times a year. Smaller ones occur more frequently; and if a careful watch be kept, it will be found that several of the faintest class of all, familiarly known as *shooting-stars*, can be seen on every clear night. We can draw no distinction between the most brilliant meteor illuminating the whole sky, and perhaps making a noise like thunder, and the faintest shooting-star, except one of degree. There seems to be every gradation between these extremes, so that all should be traced to some common cause.

Cause of Meteors.—There is now no doubt that all these phenomena have a common origin, and that they are due to the earth encountering innumerable small bodies in its annual course around the sun. The great difficulty in connecting meteors with these invisible bodies arises from the brilliancy and rapid disappearance of the meteors. The question may be asked, Why do they burn with so great an evolution of light on reaching our atmosphere? To answer this question we must have recourse to the mechanical theory of heat. Heat is a vibratory motion in the particles of solid bodies and a progressive motion in those of gases. By making this motion more rapid we make the body warmer. By simply blowing air against any combustible body with sufficient velocity it can be set on fire, and, if incombustible, the body will be made red-hot and finally melted. Experiments to determine the degree of temperature thus produced have been made which show that a velocity of about 50 metres per second corresponds to a rise of temperature of one degree Centigrade. From this the temperature due to any velocity can be readily calculated on the principle that the increase of temperature is proportional to the "energy" of the particles, which again is proportional to the square of the velocity. Hence a velocity of 500 metres per second would correspond to a rise of 100° above the actual temperature of the air, so that if the latter was at the freezing-point the body would be raised to the temperature of boiling water. A velocity of 1500 metres per second would produce a red heat.

The earth moves around the sun with a velocity of about 30,000 metres per second; consequently if it met a body at rest the concussion between the latter and the atmosphere would correspond to a temperature of more than 300,000°. This would instantly dissolve any known substance.

It must be remembered that when we speak of these enormous temperatures, we are to consider them as *potential*, not *actual*, temperatures. We do not mean that the body is actually raised to a temperature of 300,000°, but only that the air acts upon it as if it were put into a furnace heated to this temperature; that is, it is rapidly destroyed by the intensity of the heat.

This potential temperature is independent of the density of the medium, being the same in the rarest as in the densest atmosphere. But the actual effect on the body is not so great in a rare as in a dense atmosphere. Every one knows that he can hold his hand for some time in air at the temperature of boiling water. The rarer the air the higher the temperature the hand would bear without injury. In an atmosphere as rare as ours at the height of 50 miles, it is probable that the hand could be held for an indefinite period, though its temperature should be that of red-hot iron; hence the meteor is not consumed so rapidly as if it struck a dense atmosphere with planetary velocity. In the latter case it would probably disappear like a flash of lightning.

The amount of heat evolved is measured not by that which would result from the combustion of the body, but by the *vis viva* (energy of motion) which the body loses in the atmosphere. The student of physics knows that motion, when lost, is changed into a definite amount of heat. If we calculate the amount of heat which is equivalent to the energy of motion of a pebble having a velocity of 20 miles a second, we shall find it sufficient to raise about 1300 times the pebble's weight of water from the freezing to the boiling point. This is many times as much heat as could result from burning even the most combustible body.

The detonation which sometimes accompanies the passage of very brilliant meteors is not caused by an explosion of the meteor, but by the concussion produced by its rapid motion through our atmosphere. This concussion is of much the same nature as that produced by a flash of lightning. The air is suddenly condensed in front of the meteor, while a vacuum is left behind it.

The invisible bodies which produce meteors in the way just described have been called *meteoroids.* Meteoric phenomena depend very largely upon the nature of the meteoroids, and the direction and velocity with which they are moving relatively to the earth. With very rare exceptions, they are so small and fusible as to be entirely dissipated in the upper regions of the atmosphere. Even of those so hard and solid as to produce a brilliant light and the loudest detonation, only a small proportion reach the earth. On rare occasions the body is so hard and massive as to reach the earth without being entirely consumed. The potential heat produced by its passage through the atmosphere is then all expended in melting and destroying its outer layers, the inner nucleus remaining unchanged. When such a body first strikes the denser portion of the atmosphere, the resistance becomes so great that the body is generally broken to pieces. Hence we very often find not simply a single aerolite, but a small shower of them.

Heights of Meteors.—Many observations have been made to determine the height at which meteors are seen. This is effected by two observers stationing themselves several miles apart and mapping out the courses of such meteors as they can observe. In the case of very brilliant meteors, the path is often determined with considerable precision by the direction in which it is seen by accidental observers in various regions of the country over which it passes. This observation is nothing but a simultaneous determination of the parallax of a meteor as seen from two stations. See Fig. 17.

Meteors and shooting-stars commonly commence to be visible at a height of about 160 kilometres, or 100 statute miles. The separate results vary widely, but this is a rough mean of them. They are generally dissipated at about half this height, and therefore above the highest atmosphere which reflects the rays of the sun. From this it may be inferred that the earth's atmosphere rises to a height of at least 160 kilometres. This is a much greater height than it was formerly supposed to have.

Meteoric Showers.

As already stated, the phenomena of shooting-stars may be seen by a careful observer on almost any clear night. In general, not more than three or four of them will be seen in an hour, and these will be so minute as hardly to attract notice. But they sometimes fall in such numbers as to present the appearance of a meteoric shower. On rare occasions the shower has been so striking as to fill the beholders with terror. The ancient and mediæval records contain many accounts of these phenomena which have been brought to light through the researches of antiquarians.

It has long been known that some showers of this class occur at an interval of about a third of a century. One was observed by Humboldt, on the Andes, on the night of November 12th, 1799, lasting from two o'clock until daylight. A great shower was seen in this country in 1833, and is well known to have struck the negroes of the Southern States with terror. The theory that the showers occur at intervals of 34 years was propounded by Olbers, who predicted a return of the shower in 1867. This prediction was completely fulfilled, but instead of appearing in the year 1867 only, it was first noticed in 1866. On the night of November 13th of that year a remarkable shower was seen in Europe, while on the corresponding night of the year following it was again seen in this country, and, in fact, was repeated for two or three years, gradually dying away.

The occurrence of a shower of meteors evidently shows that the earth encounters a swarm of meteoroids. The recurrence at the same time of the year, when the eart his in the same point of its orbit, shows that the earth meets the swarm at the same point in successive years. All the meteoroids of the swarm must of course be moving in the same direction, else they would soon be widely scattered. This motion is connected with the *radiant point*, a well-marked feature of a meteoric shower.

Radiant Point.—Suppose that, during a meteoric shower, we mark the path of each meteor on a star-map, as in the figure. If we continue the paths backward in a straight line, we shall find that they all meet near one and the same point of the celestial sphere; that is, they move as if they all radiated from this point. The latter is, therefore, called the *radiant point.* In the figure the lines do not all pass accurately through the same point. This is owing to the unavoidable errors made in marking out the path.

It is found that the radiant point is always in the same position among the stars, wherever the observer may be situated, and that *as the stars apparently move toward the west, the radiant point moves with them.*

The radiant point is due to the fact that the meteoroids which strike the earth during a shower are all moving in the same direction. Their motions will all be parallel; hence when the bodies strike our atmosphere the paths described by them in their passage will all be parallel straight lines. A straight line seen by an observer at any point is projected as a great circle of the celestial sphere, of which the observer supposes himself to be the centre. If we draw a line from the observer parallel to the paths of the meteors, the direction of that line will represent a point of the sphere through which all the paths will seem to pass; this will, therefore, be the radiant point in a meteoric shower.

Orbits of Meteoric Showers.—From what has just been said it will be seen that the position of the radiant point indicates the direction in which the meteoroids move relatively to the earth. If we also knew the velocity with which they are really moving in space, we could make allowance for the motion of the earth, and thus determine the direction of their actual motion in space. It is not a difficult problem to calculate the actual direction and velocity of the meteoric swarm in space. Having this direction and velocity, the orbit of the swarm around the sun admits of being calculated.

Relations of Meteors and Comets.—The *velocity* of the meteoroids does not admit of being determined from observation. One element necessary for determining the orbits of these bodies is, therefore, wanting. In the case of the

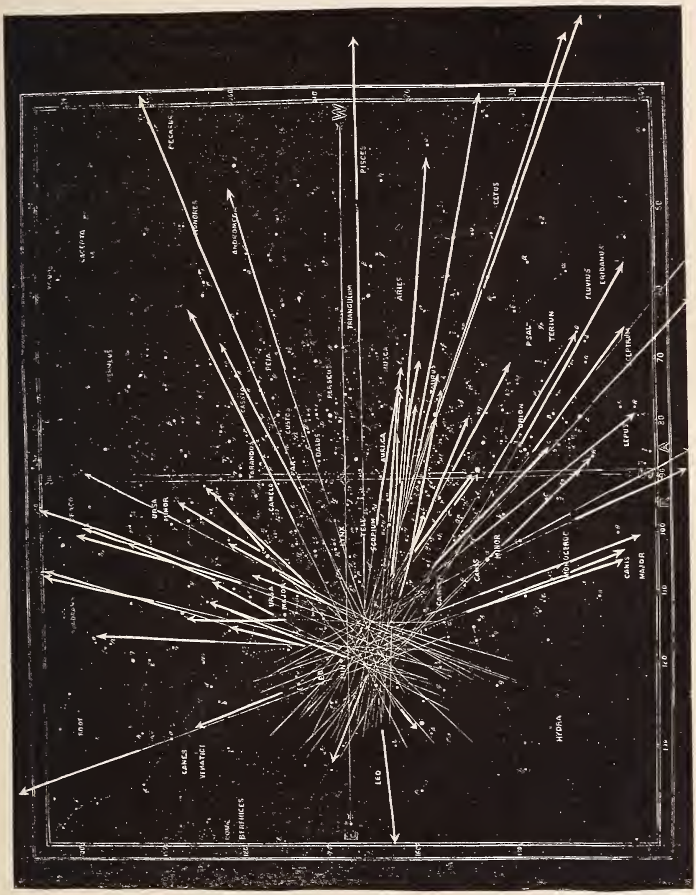

Fig. 78.—Radiant Point of Meteoric Shower.

showers of 1799, 1833, and 1866, commonly called the November showers, this element is given by the time of revolution around the sun. Since the showers occur at intervals of about a third of a century, it is highly probable this is the periodic time of the swarm around th esun. The periodic time being known, the velocity at any distance from the sun admits of calculation from the theory of gravitation. Thus we have all the data for determining the real orbits of the group of meteors around the sun.

The calculations necessary for this purpose were made by LE VERRIER and other astronomers shortly after the great shower of 1866. The following was the orbit as given by LE VERRIER:

Period of revolution	33.25 years.
Eccentricity of orbit	0.9044.
Least distance from the sun	0.9890.
Inclination of orbit	165° 19′.
Longitude of the node	51° 18′.
Position of the perihelion	(near the node).

The publication of this orbit brought to the attention of the world an extraordinary coincidence which had never before been suspected. In December, 1865, a faint telescopic comet was discovered. Its orbit was calculated as follows:

Period of revolution	33.18 years.
Eccentricity of orbit	0.9054.
Least distance from the sun	0.9765.
Inclination of orbit	162° 42′.
Longitude of the node	51° 26′.
Longitude of the perihelion	42° 24′.

The publication of the cometary orbit and that of the orbit of the meteoric group were made independently within a few days of each other by two astronomers, neither of whom had any knowledge of the work of the other. Comparing them, the result is evident. *The swarms of meteor-*

oids which cause the November showers move in the same orbit with this comet.

The comet passed its perihelion in January, 1866. The most striking meteoric shower commenced in the following November, and was repeated during several years. It seems, therefore, that the meteoroids which produce these showers follow after TEMPEL'S comet, moving in the same orbit with it. This shows a curious relation between comets and meteors, of which we shall speak more fully in the next chapter. When this fact was brought out, the question naturally arose whether the same thing might not be true of other meteoric showers.

Other Showers of Meteors.—Although the November showers (which occur about November 14) are the only ones so brilliant as to strike the ordinary eye, it has long been known that there are other nights of the year (notably August 10) in which more shooting-stars than usual are seen, and in which the large majority radiate from one point of the heavens. This shows conclusively that they arise from swarms of meteoroids moving together around the sun.

The Zodiacal Light.—If we observe the western sky during the winter or spring months, about the end of the evening twilight, we shall see a stream of faint light, a little like the Milky Way, rising obliquely from the west, and directed along the ecliptic toward a point south-west from the zenith. This is called the *zodiacal light.* It may also be seen in the east before daylight in the morning during the autumn months, and has sometimes been traced all the way across the heavens. Its origin is still involved in obscurity, but it seems probable that it arises from an extremely thin cloud either of meteoroids or of semi-gaseous matter like that composing the tail of a comet, spread all around the sun inside the earth's orbit. Its spectrum is probably that of reflected sunlight, a result which gives color to the theory that it arises from a cloud of meteoroids revolving round the sun.

CHAPTER XIII.

COMETS.

Aspect of Comets.

Comets are distinguished from the planets both by their aspects and their motions. They come into view without anything to herald their approach, continue in sight for a few weeks or months, and then gradually vanish in the distance. They are commonly considered as composed of three parts: the *nucleus*, the *coma* (or hair), and the *tail.*

The nucleus of a comet is, to the naked eye, a point of light resembling a star or planet. Viewed in a telescope, it generally has a small disk, but shades off so gradually that it is difficult to estimate its magnitude. In large comets it is sometimes several hundred miles in diameter.

The nucleus is always surrounded by a mass of foggy light, which is called the *coma.* To the naked eye the nucleus and coma together look like a star seen through a mass of thin fog, which surrounds it with a sort of halo. The nucleus and coma together are generally called the *head* of the comet.

The *tail* of the comet is simply a continuation of the coma extending out to a great distance, and always directed away from the sun. It has the appearance of a stream of milky light, which grows fainter and broader as it recedes from the head. Like the coma it shades off so gradually that it is impossible to fix any boundaries to it. The length of the tail varies from 2° or 3° to 90° or more. Generally the more brilliant the head of the comet, the longer and brighter is the tail.

The above description applies to comets which can be plainly seen by the naked eye. Half a dozen telescopic comets may be discovered in a single year, while one of the brighter class may not be seen for ten years or more.

When comets are studied with a telescope, it is found that they are subject to extraordinary changes of structure.

Fig. 79.—Telescopic Comet without a Nucleus.

Fig. 80.—Telescopic Comet with a Nucleus.

To understand these changes, we must begin by saying that comets do not, like the planets, revolve around the sun in nearly circular orbits, but always in orbits so elongated that the comet is visible in only a very small part of its course. See page 278, Fig. 82.)

The Vaporous Envelopes.

If a comet is very small, it may undergo no changes of aspect during its entire course. If it is an unusually bright one, a bow surrounding the nucleus on the side toward the sun will develop as the comet approaches the sun. This bow will gradually rise up and spread out on all sides, finally assuming the form of a semicircle having the nucleus in its centre, or, to speak with more precision, the form of a parabola having the nucleus near its focus. The two ends of this parabola will extend out further and further so as to form a part of the tail, and finally be lost in it. Other bows will successively form around the nucleus, all slowly rising from it like clouds of vapor. These distinct vaporous masses are called the *envelopes:* they shade off gradually into the coma so as to be with difficulty distinguished from it, and indeed may be considered as part of it. These appearances are apparently caused by masses of vapor streaming up from that side of the nucleus nearest the sun, and gradually spreading around the comet on each side. The form of a bow is not the real form of the envelopes, but only the apparent one in which we see them projected against the background of the sky. Perhaps their forms can be best imagined by supposing the sun to be directly above the comet, and a fountain, throwing a liquid horizontally on all sides, to be built upon that part of the comet which is uppermost. Such a fountain would throw its water in the form of a sheet, falling on all sides of the cometic nucleus, but not touch-

FIG. 81.—FORMATION OF ENVELOPES.

ing it. Two or three vapor surfaces of this kind are sometimes seen around the comet, the outer one enclosing each of the inner ones, but no two touching each other.

THE PHYSICAL CONSTITUTION OF COMETS.

To tell exactly what a comet is, we should be able to show how all the phenomena it presents would follow from the properties of matter, as we learn them at the surface of the earth. This, however, no one has been able to do, many of the phenomena being such as we should not expect from the known constitution of matter. All we can do, therefore, is to present the principal characteristics of comets, as shown by observation, and to explain what is wanting to reconcile these characteristics with the known properties of matter.

In the first place, all comets which have been examined with the spectroscope show a spectrum composed, in part at least, of bright lines or bands. The positions and characters of these bands leave no doubt that *carbon*, *hydrogen*, and *nitrogen*, and probably *oxygen* are present in the cometary matter. More than twenty comets have been examined since the invention of the spectroscope and all agree in giving the same evidence. In some recent comets *sodium* has also been discovered.

In the last chapter it was shown that swarms of minute particles called meteoroids follow certain comets in their orbits. This is no doubt true of all comets. We can only regard these meteoroids as fragments or *débris* of the comet. On this theory a telescopic comet which has no nucleus is simply a cloud of these minute bodies. The nucleus of the brighter comets may either be a more condensed mass of such bodies or it may be a solid or liquid body itself.

If the reader has any difficulty in reconciling this theory of detached particles with the view already presented, that the envelopes from which the tail of the comet is formed consist of layers of vapor, he must remember that vaporous masses, such as clouds, fog, and smoke, are really composed of minute separate particles of water or carbon.

Formation of the Comet's Tail.—The tail of the comet is not a permanent appendage, but is composed of the masses of vapor which we have already described as ascending from the nucleus, and afterward moving away from the sun. The tail which we see on one evening is not absolutely the same we saw the evening before, a portion of the latter having been dissipated, while new matter has taken its place, as with the stream of smoke from a steamship. The motion of the vaporous matter which forms the tail being always away from the sun, there seems to be a repulsive force exerted by the sun upon it. The form of the comet's tail, on the supposition that it is composed of matter driven away from the sun with a uniformly accelerated velocity, has been several times investigated, and found to represent the observed form of the tail so nearly as to leave little doubt of its correctness. We may, therefore, regard it as an observed fact that the vapor which rises from the nucleus of the comet is repelled by the sun instead of being attracted toward it, as larger masses of matter are.

No adequate explanation of this repulsive force has ever been given.

MOTIONS OF COMETS.

Previous to the time of NEWTON, no certain knowledge respecting the actual motions of comets in the heavens had been acquired, except that they did not move around the sun in ellipses like the planets.

When NEWTON investigated the mathematical results of the theory of gravitation, he found that a body moving under the attraction of the sun might describe either of the three conic sections, the ellipse, parabola, or hyperbola. Bodies moving in an ellipse, as the planets, would complete their orbits at regular intervals of time, according to laws already laid down. But if the body moved in a parabola or an hyperbola, it would never return to the sun after once passing it, but would move off to infinity. It was, therefore, very natural to conclude that comets might be bodies which resemble the planets in moving under the sun's attraction, but which, instead of describing

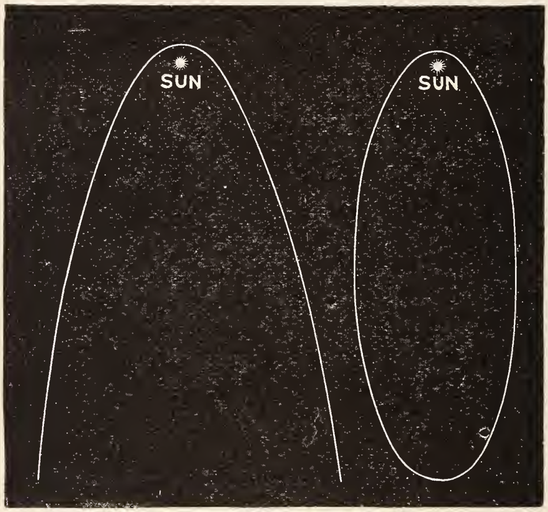

FIG. 82.—ELLIPTIC AND PARABOLIC ORBITS.

an ellipse in regular periods, like the planets, move in parabolic or hyperbolic orbits, and therefore only approach the sun a single time during their whole existence.

This theory is now known to be essentially true for most of the observed comets. A few are indeed found to be revolving around the sun in elliptic orbits, which differ from those of the planets only in being much more eccentric. But the greater number which have been observed have receded from the sun in orbits which we are unable to distinguish from parabolas, though it is possible they may be extremely elongated ellipses. Comets are therefore divided with respect to their motions into two classes: (1) *periodic comets*, which are known to move in elliptic orbits, and to return to the sun at fixed intervals; and (2) *parabolic comets*, apparently moving in parabolas, never to return.

The first discovery of the periodicity of a comet was made by HALLEY in connection with the great comet of 1682. Examining the records of past observations, he found that a comet moving in nearly the same orbit with that of 1682 had been seen in 1607, and still another in 1531. He was therefore led to the conclusion that these three comets were really one and the same object, returning to the sun at intervals of about 75 or 76 years. He therefore predicted that it would appear again about the year 1758. The comet was first seen

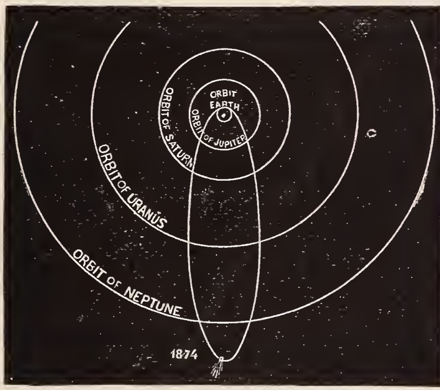

FIG. 83.—ORBIT OF HALLEY'S COMET.

on Christmas-day, 1758, and passed its perihelion March 12th, 1759, only one month before the predicted time. At present it is possible to predict the places of some of the best known periodic comets almost as accurately as the positions of the planets.

We give a figure showing the position of the orbit of HALLEY'S comet relative to the orbits of the four outer planets. It attained its greatest distance from the sun, far beyond the orbit of *Neptune*, about the year 1873, and then commenced its return journey. The figure shows the position of the comet in 1874. It was then far beyond the reach of the most powerful telescope, but its distance and direction admit of being calculated with so much precision that a telescope could be pointed at it at any required moment.

Remarkable Comets.

It is familiarly known that bright comets were in former years objects of great terror, being supposed to presage the fall of empires, the death of monarchs, the approach of earthquakes, wars, pestilence, and every other calamity which could afflict mankind. In showing the entire groundlessness of such fears, science has rendered one of its greatest benefits to mankind.

In 1456 the comet known as Halley's, appearing when the Turks were making war on Christendom, caused

Fig. 84.—Medal of the Great Comet of 1680–81.

such terror that Pope Calixtus ordered prayers to be offered in the churches for protection against it. This is supposed to be the origin of the popular myth that the Pope once issued a bull against the comet.

The number of comets visible to the naked eye, so far as recorded, has generally ranged from twenty to forty in a century. Only a small portion of these, however, have been so bright as to excite universal notice.

Comet of 1680.—One of the most remarkable of these brilliant comets is that of 1680. It inspired such terror that a medal, of which we present a figure, was struck upon the Continent of Europe to quiet apprehension. A free translation of the inscription is: "The star threatens evil things; trust only! God will turn them to good."* What makes this comet especially remarkable in history is that NEWTON calculated its orbit, and showed that it moved around the sun in a conic section, in obedience to the law of gravitation.

Great Comet of 1811.—It has a period of over 3000 years, and its aphelion distance is about 40,000,000,000 miles.

Great Comet of 1843.—One of the most brilliant comets which have appeared during the present century was that of February, 1843. It was visible in full daylight close to the sun. Considerable terror was caused in some quarters lest it might presage the end of the world, which had been predicted for that year by MILLER. At perihelion it passed nearer the sun than any other body has ever been known to pass, the least distance being only about one fifth of the sun's semidiameter. With a very slight change of its original motion, it would have actually fallen into the sun.

Great Comet of 1858.—Another comet remarkable for the length of time it remained visible was that of 1858. It is frequently called after the name of DONATI, its first discoverer. No comet visiting our neighborhood in recent times has afforded so favorable an opportunity for studying its physical constitution. Its greatest brilliancy occurred about the beginning of October, when its tail was 40° in length and 10° in breadth at its outer end. Its period is 1950 years.

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* The student should notice the care which the author of the inscription has taken to make it consolatory, to make it rhyme, and to give implicitly the year of the comet by writing certain Roman numerals larger than the other letters.

Fig. 85.—Donati's Comet of 1858.

Great Comet of 1882.—It is yet too soon to speak of the results of the observations on this magnificent object. Its splendor will not soon be forgotten by those who have seen it.

Encke's Comet and the Resisting Medium.—Of telescopic comets, that which has been most investigated by astronomers is known as ENCKE's comet. Its period is between three and four years. Viewed with a telescope, it is not different in any respect from other telescopic comets, appearing simply as a mass of foggy light, somewhat brighter near one side. Under the most favorable circumstances, it is just visible to the naked eye. The circumstance which has lent most interest to this comet is that the observations which have been made upon it seem to indicate that it is gradually approaching the sun. ENCKE attributed this change in its orbit to the existence in space of a resisting medium, so rare as to have no appreciable effect upon the motion of the planets, and to be felt only by bodies of extreme tenuity, like the telescopic comets. The approach of the comet to the sun is shown, not by direct observation, but only by a gradual diminution of the period of revolution. It will be many centuries before this period would be so far diminished that the comet would actually touch the sun.

If the change in the period of this comet were actually due to the cause which ENCKE supposed, then other faint comets of the same kind ought to be subject to a similar influence. But the investigations which have been made in recent times on these bodies show no deviation of the kind. It might, therefore, be concluded that the change in the period of ENCKE's comet must be due to some other cause. There is, however, one circumstance which leaves us in doubt. ENCKE's comet passes nearer the sun than any other comet of short period which has been observed with sufficient care to decide the question. It may, therefore, be supposed that the resisting medium, whatever it may be, is densest near the sun, and does not extend out far enough for the other comets to meet it. The question is one very difficult to settle. The fact is that all comets exhibit slight anomalies in their motions which prevent us from deducing conclusions from them with the same certainty that we should from those of the planets. One of the chief difficulties in investigating the orbits of comets with all rigor is due to the difficulty of obtaining accurate positions of the centre of so ill-defined an object as the nucleus.

PART III.

THE UNIVERSE AT LARGE.

INTRODUCTION.

In our studies of the heavenly bodies, we have hitherto been occupied almost entirely with those of the solar system. Although this system comprises the bodies which are most important to us, yet they form only an insignificant part of creation. Besides the earth on which we dwell, only seven of the bodies of the solar system are plainly visible to the naked eye, whereas some 2000 stars or more can be seen on any clear night.

The material universe, as revealed by the telescope, consists principally of shining bodies, many millions in number, a few of the nearest and brightest of which are visible to the naked eye as stars. They extend out as far as the most powerful telescope can penetrate, and no one knows how much farther. Our sun is simply one of these stars, and does not, so far as we know, differ from its fellows in any essential characteristic. From the most careful estimates, it is rather less bright than the average of the nearer stars, and overpowers them by its brilliancy only because it is so much nearer to us.

The distance of the stars from each other, and therefore from the sun, is immensely greater than any of the distances which we have hitherto had to consider in the solar system. In fact, the nearest known star is about seven thousand times as far as the planet *Neptune.* If we suppose the orbit of this planet to be represented by a child's hoop, the nearest star would be three or four miles away. We have no reason to suppose that contiguous stars are, on the average, nearer than this, except in special cases where they are collected together in clusters.

The total number of the stars is estimated by millions, and they are probably separated by these wide intervals. It follows that, in going from the sun to the nearest star, we would be simply taking one step in the universe. The most distant stars visible in great telescopes are probably several thousand times more distant than the nearest one, and we do not know what may lie beyond.

The point we wish principally to impress on the reader in this connection is that, although the stars and planets present to the naked eye so great a similarity in appearance, there is the greatest possible diversity in their distances and characters. The planets, though many millions of miles away, are comparatively near us, and form a little family by themselves, which is called the solar system. The fixed stars are at distances incomparably greater—the nearest star being thousands of times more distant than the farthest planet. The planets are, so far as we can see, worlds somewhat like this on which we live, while the stars are suns, generally larger and brighter than our own. Each star may, for aught we know, have planets revolving around it, but their distance is so immense that the largest planets will remain invisible with the most powerful telescopes man can ever hope to construct.

The classification of the heavenly bodies thus leads us to this curious conclusion. Our sun is one of the family of stars, the other members of which stud the heavens at night, or, in other words, the stars are suns like that which makes the day. The planets, though they look like stars, are not such, but bodies more like the earth.

The great universe of stars, including the creation in its largest extent, is called the *stellar system,* or *stellar universe.* We have first to consider how it looks to the naked eye.

CHAPTER I.

CONSTELLATIONS.

General Aspect of the Heavens.

When we view the heavens with the unassisted eye, the stars appear to be scattered nearly at random over the surface of the celestial vault. The only deviation from an entirely random distribution which can be noticed is a certain grouping of the brighter ones into constellations. A few stars are comparatively much brighter than the rest, and there is every gradation of brilliancy, from that of the brightest to those which are barely visible. We also notice at a glance that the fainter stars outnumber the bright ones; so that if we divide the stars into classes according to their brilliancy, the fainter classes will contain the most stars.

The total number one can see will depend very largely upon the clearness of the atmosphere and the keenness of the eye. There are in the whole celestial sphere about 6000 stars visible to an ordinarily good eye. Of these, however, we can never see more than a fraction at any one time, because one half of the sphere is always below the horizon. If we could see a star in the horizon as easily as in the zenith, one half of the whole number, or 3000, would be visible on any clear night. But stars near the horizon are seen through so great a thickness of atmosphere as greatly to obscure their light; consequently only the brightest ones can there be seen. As a result of this obscuration, it is not likely that more than 2000 stars can ever be taken in at a single view by any ordinary eye. About 2000 other stars are so near the south pole that they never rise in our latitudes. Hence out of the 6000 supposed to be visible, only 4000 ever come within the range of our vision, unless we make a journey toward the equator.

The Galaxy.—Another feature of the heavens, which is less striking than the stars, but has been noticed from the earliest times, is the *Galaxy*, or *Milky Way*. This object consists of a magnificent stream or belt of white milky light 10° or 15° in breadth, extending obliquely around the celestial sphere. During the spring months it nearly coincides with our horizon in the early evening, but it can readily be seen at all other times of the year spanning the heavens like an arch. It is for a portion of its length split longitudinally into two parts, which remain separate through many degrees, and are finally united again. The student will obtain a better idea of it by actual examination than from any description. He will see that its irregularities of form and lustre are such that in some places it looks like a mass of brilliant clouds.

Lucid and Telescopic Stars.—When we view the heavens with a telescope, we find that there are innumerable stars too small to be seen by the naked eye. We may therefore divide the stars, with respect to brightness, into two great classes.

Lucid Stars are those which are visible without a telescope.

Telescopic Stars are those which are not so visible.

When Galileo first directed his telescope to the heavens, about the year 1610, he perceived that the Milky Way was composed of stars too faint to be individually seen by the unaided eye. We thus have the interesting fact that although telescopic stars cannot be seen one by one, yet in the region of the Milky Way they are so numerous that they shine in masses like brilliant clouds. HUYGHENS in 1656 resolved a large portion of the Galaxy into stars, and concluded that it was composed entirely of them. KEPLER considered it to be a vast ring of stars surround ing the solar system, and remarked that the sun must be situated near the centre of the ring. This view agrees very well with the one now received, only that the stars which form the Milky Way, instead of lying around the solar system, are at a distance so vast as to elude all our powers of calculation.

Such are in brief the more salient phenomena which are presented to an observer of the starry heavens. We shall now consider how these phenomena have been classified by an arrangement of the stars according to their brilliancy and their situation.

MAGNITUDES OF THE STARS.

In ancient times the stars were arbitrarily classified into six orders of magnitude. The fourteen brightest visible in our latitude were designated as of the first magnitude, while those which were barely visible to the naked eye were said to be of the sixth magnitude. This classification, it will be noticed, is entirely arbitrary, since there are no two stars which are absolutely of the same brightness; that is, if all the stars were arranged in the order of their actual brilliancy, we should find a regular gradation from the brightest to the faintest, no two being precisely the same. Therefore the brightest star of any one magnitude is about of the same brilliancy with the faintest one of the next higher magnitude. Between the north pole and 35° south declination there are:

14	stars	of the	first	magnitude.
48	"	"	second	"
152	"	"	third	"
313	"	"	fourth	"
854	"	"	fifth	"
3974	"	"	sixth	"
5355	of the first six magnitudes.			

Of these, however, nearly 2000 of the sixth magnitude are so faint that they can be seen only by an eye of extraordinary keenness. A star of the second magnitude is four tenths as bright as one of the first; one of the third is four tenths as bright as one of the second, and so on.

The Constellations and Names of the Stars.

The earliest astronomers divided the stars into groups, called constellations, and gave special proper names both to these groups and to many of the more conspicuous stars.

We have evidence that more than 3000 years before the commencement of the Christian chronology the star *Sirius*, the brightest in the heavens, was known to the Egyptians under the name of *Sothis*. The seven stars of the *Great Bear*, so conspicuous in our northern sky, were known under that name to Homer and Hesiod, as well as the group of the *Pleiades*, or Seven Stars, and the constellation of *Orion*. Indeed, it would seem that all the earlier civilized nations, Egyptians, Chinese, Greeks, and Hindoos, had some arbitrary division of the surface of the heavens into irregular and often fantastic shapes, which were distinguished by names.

In early times the names of heroes and animals were given to the constellations, and these designations have come down to the present day. Each object was supposed to be painted on the surface of the heavens, and the stars were designated by their position upon some portion of the object. The ancient and mediæval astronomers would speak of "the bright star in the left foot of *Orion*," "the eye of the *Bull*," "the heart of the *Lion*," "the head of *Perseus*," etc. These figures are still retained upon some star-charts, and are useful where it is desired to compare the older descriptions of the constellations with our modern maps. Otherwise they have ceased to serve any purpose, and are not generally found on maps designed for purely astronomical uses.

The Arabians, who used this clumsy way of designating stars, gave special names to a large number of the brighter ones. Some of these names are in common use at the present time, as *Aldebaran*, *Fomalhaut*, etc.

In 1654 BAYER, of Germany, mapped down the constellations upon charts, designating the brighter stars of each constellation by the letters of the Greek alphabet. When this alphabet was exhausted he introduced the letters of the Roman alphabet. In general, the brightest star was designated by the first letter of the alphabet, α, the next by the following letter, β, etc.

On this system, a star is designated by a certain Greek letter, followed by the genitive of the Latin name of the constellation to which it belongs. For example. α *Canis Majoris*, or, in English, α of the Great Dog, is the designation of *Sirius*, the brightest star in the heavens. The seven stars of the *Great Bear* are called α *Ursæ Majoris*, β *Ursæ Majoris*, etc. *Arcturus* is α *Boötis*. The reader will here see a resemblance to our way of designating individuals by a Christian name followed by the family name. The Greek letters furnish the Christian names of the separate stars, while the name of the constellation is that of the family. As there are only fifty letters in the two alphabets used by BAYER, it will be seen that only the fifty brightest stars in each constellation could be designated by this method.

When by the aid of the telescope many more stars than these were laid down, some other method of denoting them became necessary. FLAMSTEED, who observed before and after 1700, prepared an extensive catalogue of stars, in which those of each constellation were designated by numbers in the order of right ascension. These numbers were entirely independent of the designations of BAYER—that is, he did not omit the BAYER stars from his system of numbers, but numbered them as if they had no Greek letter. Hence those stars to which BAYER applied letters have two designations, the number and the letter. The fainter stars are designated either by their R.A. and δ, or by their numbers in some catalogue of stars.

NUMBERING AND CATALOGUING THE STARS.

As telescopic power is increased, we still find stars of fainter and fainter light. But the number cannot go on increasing forever in the same ratio as with the brighter magnitudes, because, if it did, the whole sky would be a blaze of starlight.

If telescopes with powers far exceeding our present ones were made, they would no doubt show new stars of the 20th and 21st magnitudes. But it is highly probable that the *number* of such successive orders of stars would not increase in the same ratio as is observed in the 8th, 9th, and 10th magnitudes, for example. The enormous labor of estimating the number of stars of such classes will long prevent the accumulation of statistics on this question; but this much is certain, that in special regions of the sky, which have been searchingly examined by various telescopes of successively increasing apertures, the number of new stars found is by no means in proportion to the increased instrumental power. If this is found to be true elsewhere, the conclusion may be that, after all, the stellar system can be experimentally shown to be of finite extent, and to contain only a finite number of stars.

We have already stated that in the whole sky an eye of average power will see about 6000 stars. With a telescope this number is greatly increased, and the most powerful telescopes of modern times will probably show more than 20,000,000 stars. As no trustworthy estimate has ever been made, there is great uncertainty upon this point, and the actual number may range anywhere between 15,000,000 and 40,000,000. Of this number, not one out of twenty has ever been catalogued at all.

The southern sky has many more stars of the first seven magnitudes than the northern, and the zones immediately north and south of the equator, although greater in surface than any others of the same width in declination, are absolutely poorer in such stars.

This will be much better understood by consulting the graphical representation on page 294. On this chart are laid down all the stars of the British Association Catalogue (a dot for each star), and beside these the Milky Way is represented. The relative richness of the various zones can be at once seen.

The distribution and number of the brighter stars (1st to 7th magnitude) can be well understood from this chart.

In ARGELANDER'S *Durchmusterung* of the stars of the northern heavens there are recorded as belonging to the northern hemisphere:

10	stars	between the	1.0	magnitude	and the	1.9	magnitude.
37	"	"	2.0	"	"	2.9	"
128	"	"	3.0	"	"	3.9	"
310	"	"	4.0	"	"	4.9	"
1,016	"	"	5.0	"	"	5.9	"
4,328	"	"	6.0	"	"	6.9	"
13,593	"	"	7.0	"	"	7.9	"
57,960	"	"	8.0	"	"	8.9	"
237,544	"	"	9.0	"	"	9.5	"

The Northern Milky Way, from Heis; the Southern, from Sir J. Herschel.—Drawn by Richard A. Proctor.

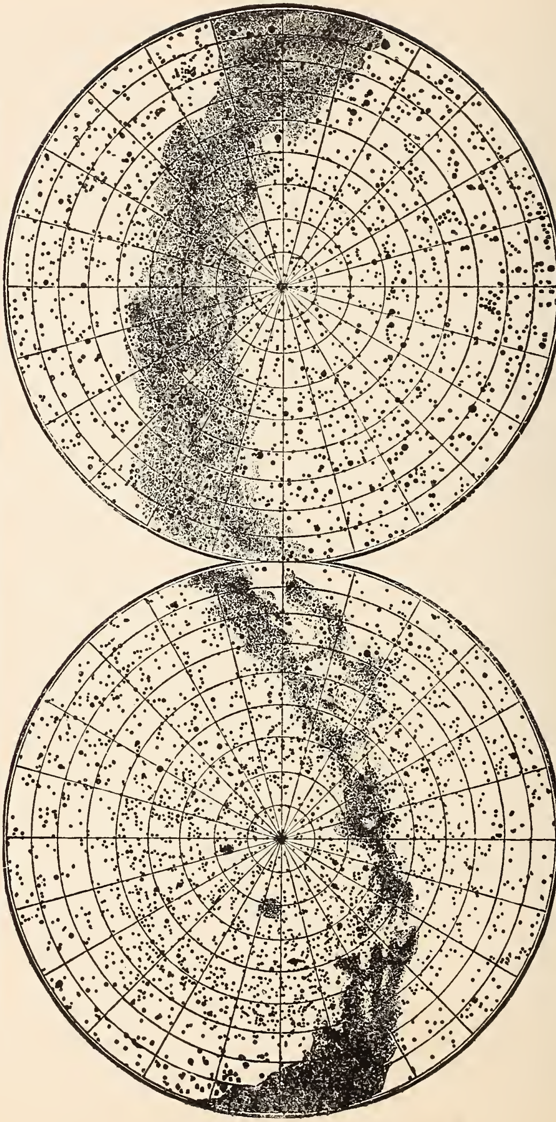

Fig. 85.—The Stars to Sixth Magnitude in the B. A. Catalogue on an Equal Surface Projection.

In all 314,926 stars from the first to the 9.5 magnitudes are enumerated in the northern sky, so that there are about 600,000 in the whole heavens.

We may readily compute the amount of light received by the earth on a clear but moonless night from these stars. Let us assume that the brightness of an average star of the first magnitude is about 0.5 of that of *α Lyræ*. A star of the 2d magnitude will shine with a light expressed by $0.5 \times 0.4 = 0.20$, and so on. (See p. 291.)

The total	brightness of	10	1st	magnitude	stars is	5.0
"	"	37	2d	"	"	7.4
"	"	122	3d	"	"	10.1
"	"	310	4th	"	"	9.9
"	"	1,016	5th	"	"	13.0
"	"	4,322	6th	"	"	22.1
"	"	13,593	7th	"	"	27.8
"	"	57,960	8th	"	"	47.4
					Sum =	142.7

It thus appears that from the stars to the 8th magnitude, inclusive, we receive 143 times as much light as from *α Lyræ*. *α Lyræ* has been determined by Zöllner to be about 44,000,000,000 times fainter than the sun, so that the proportion of starlight to sunlight can be computed. It also appears that the stars of magnitudes too high to allow them to be individually visible to the naked eye are yet so numerous as to affect the general brightness of the sky more than the so-called lucid stars (1st to 6th magnitude). The sum of the last two numbers of the table is greater than the sum of all the others.

Note.—The individual stars and constellations can be better learned by the student from a Star Atlas than by any maps which can be given on a page so small as these.

CHAPTER II.

VARIABLE AND TEMPORARY STARS.

Stars Regularly Variable.

All stars do not shine with a constant light. Since the middle of the seventeenth century, stars variable in brilliancy have been known. The period of a variable star means the interval of time in which it goes through all its changes, and returns to its original brilliancy.

The most noted variable stars are *Mira Ceti* (*o Ceti*) and *Algol* (*β Persei*). *Mira* appears about twelve times in eleven years, and remains at its greatest brightness (sometimes as high as the 2d magnitude, sometimes not above the 4th) for some time, then gradually decreases for about 74 days, until it becomes invisible to the naked eye, and so remains for about five or six months. From the time of its reappearance as a lucid star till the time of its maximum is about 43 days. The *mean* period, or the interval from minimum to minimum, is about 333 days, but this period varies greatly. The brilliancy of the star at the maxima also varies.

Algol has been known as a variable star since 1667. This star is commonly of the 2d magnitude; after remaining so about $2\frac{1}{2}$ days, it falls to 4^m in the short time of $4\frac{1}{2}$ hours, and remains of 4^m for 20 minutes. It then commences to increase in brilliancy, and in another $3\frac{1}{2}$ hours it is again of the 2d magnitude, at which point it remains for the rest of its period, about $2^d\ 12^h$.

These two examples of the class of variable stars give a rough idea of the extraordinary nature of the phenomena they present. A closer examination of others discloses minor variations of great complexity and apparently without law.

About 90 variable stars are well known, and as many more are suspected to vary. In nearly all cases the mean period can be fairly well determined, though anomalies of various kinds frequently appear. The principal anomalies are:

First. The period is seldom constant. For some stars the changes of the period seem to follow a regular law; for others no law can be fixed.

Second. The time from a minimum to the next maximum is usually shorter than from this maximum to the next minimum.

Third. Some stars (as *β Lyræ*) have not only one maximum between two consecutive principal minima, but two such maxima. For *β Lyræ*, according to ARGELANDER, $3^d\ 2^h$ after the principal minimum comes the first maximum; then, $3^d\ 7^h$ after this, a secondary minimum in which the star is by no means so faint as in the principal minimum, and finally $3^d\ 3^h$ afterward comes the principal maximum, the whole period being $12^d\ 21^h\ 47^m$.

The course of one period is illustrated in the following table, supposing the period to begin at $0^d\ 0^h$. Opposite each phase is given the intensity of light in terms of *γ Lyræ* = 1.

Phases of β Lyræ.			Relative Intensity.
Principal Minimum	0^d	0^h	0.40
First Maximum	3^d	2^h	0.83
Second Minimum	6^d	9^h	0.58
Principal Maximum	9^d	12^h	0.89
Principal Minimum	12^d	22^m	0.40

The periods of 94 well-determined variable stars being tabulated, it appears that they are as follows:

Period between		No. of Stars.	Period between		No. of Stars.
1 d. and	20 d.	13	350 d. and	400 d.	13
20	50	1	400	450	8
50	100	4	450	500	3
100	150	4	500	550	0
150	200	5	550	600	0
200	250	9	600	650	1
250	300	14	650	700	0
300	350	18	700	750	1
					$\Sigma = 94$

It is natural that there should be few known variables of periods of 500 days and over, but it is not a little remarkable that the periods of over half of these variables should fall between 250 and 450 days.

The color of over 80 per cent of the variable stars is red or orange. Red stars (of which 600 to 700 are known) are now receiving close attention, as there is a strong likelihood of finding among them many new variables.

The spectra of variable stars show changes which appear to be connected with the variations in their light.

Temporary or New Stars.

There are a few cases known of apparently *new* stars which have suddenly appeared, attained more or less brightness, and slowly decreased in magnitude, either disappearing totally, or finally remaining as comparatively faint objects.

The most famous one was that of 1572, which attained a brightness greater than that of *Sirius* or *Jupiter* and approached to *Venus*, being even visible to the eye in daylight. Tycho Brahe first observed this star in November, 1572, and watched its gradual increase in light until its maximum in December. It then began to diminish in brightness, and in January, 1573, it was fainter than *Jupiter*. In February it was of the 1st magnitude, in April of the 2d, in July of the 3d, and in October of the 4th. It continued to diminish until March, 1574, when it became invisible, as the telescope was not then in use. Its color, at first intense white, decreased through yellow and red. When it arrived at the 5th magnitude its color again became white, and so remained till its disappearance. Tycho measured its distance carefully from nine stars near it, and near its place there is now a star of the 10th or 11th magnitude, which is possibly the same star.

The history of temporary stars is in general similar to that of the star of 1572, except that none have attained so great a degree of brilliancy. More than a score of such objects are known to have appeared, many of them before the making of accurate observations, and the conclusion is probable that many have appeared without recognition. Among telescopic stars there is but a small chance of detecting a new or temporary star.

Several supposed cases of the disappearance of stars exist, but here there are so many possible sources of error that great caution is necessary in admitting them.

Two temporary stars have appeared since the invention of the spectroscope (1859), and the conclusions drawn from a study of their spectra are most important as throwing light upon the phenomena of variable stars in general.

The general theory of variable stars which has now the most evidence in its favor is this: These bodies are, from some general cause not fully understood, subject to eruptions of glowing hydrogen gas from their interior, and to the formation of dark spots on their surfaces. These eruptions and formations have in most cases a greater or less tendency to a regular period.

In the case of our sun (which is a variable star) the period is 11 years, but in the case of many of the stars it is much shorter. Ordinarily, as in the case of the sun and of a large majority of the stars, the variations are too slight to affect the total quantity of light to any visible extent. But in the case of the variable stars this spot-producing power and the liability to eruptions are very much greater, and thus we have changes of light which can be readily perceived by the eye. Some additional strength is given to this theory by the fact just mentioned, that so large a proportion of the variable stars are red. It is well known that glowing bodies emit a larger proportion of red rays and a smaller proportion of blue ones the cooler they become. It is therefore probable that the red stars have the least heat. This being the case, it is more easy to produce spots on their surface; and if their outside surface is so cool as to become solid, the glowing hydrogen from the interior when it did burst through would do so with more power than if the surrounding shell were liquid or gaseous.

There is, however, at least one star of which the variations may be due to an entirely different cause; namely, *Algol*. The extreme regularity with which the light of this object fades away and disappears suggests the possibility that a dark body may be revolving around it, and partially eclipsing it at every revolution. The law of variation of its light is so different from that of the light of other variable stars as to suggest a different cause. Most others are near their maximum for only a small part of their period, while *Algol* is at its maximum for nine tenths of it. Others are subject to nearly continuous changes, while the light of *Algol* remains constant during nine tenths of its period.

CHAPTER III.

MULTIPLE STARS.

CHARACTER OF DOUBLE AND MULTIPLE STARS.

WHEN we examine the heavens with telescopes, we find many cases in which two or more stars are extremely close together, so as to form a pair, a triplet, or a group. It is evident that there are two ways to account for this appearance.

1. We may suppose that the stars happen to lie nearly in the same straight line from us, but have no connection with each other. It is evident that in this case a pair of stars might appear double, although the one was hundreds or thousands of times farther off than the other. It is, moreover, impossible, from mere inspection, to determine which is the farther off.

2. We may suppose that the stars are really near together, as they appear, and are to be considered as forming a connected pair or group.

A couple of stars in the first case is said to be *optically double.*

Stars which are really physically connected are said to be *physically double.*

If the lucid stars are equally distributed over the celestial sphere, the chances are 80 to 1 against any two being within three minutes of each other, and the chances are 500,000 to 1 against the six visible stars of the *Pleiades* being accidentally associated as we see them. When the millions of telescopic stars are considered, there is a greater probability of such accidental juxtaposition. But the probability of many such cases occurring is so extremely small that astronomers regard all the closest pairs as physically connected. Of the 600,000 stars of the first ten magnitudes, about 10,000, or one out of every 60, has a companion within a distance of 30″ of arc. This proportion is many times greater than could possibly be the result of chance distribution.

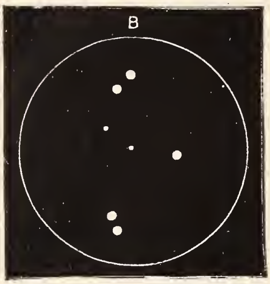

FIG. 86.—THE QUADRUPLE STAR ε LYRÆ.

There are several cases of stars which appear double to the naked eye. *ε Lyræ* is such a star and is an interesting object, from the fact that each of the two stars which compose it is itself double. This minute pair of points, capable of being distinguished as double only by the most perfect eye (without the telescope), is really composed of two pairs of stars wide apart, with a group of smaller stars between and around them. The figure shows the appearance in a telescope of considerable power.

Revolutions of Double Stars—Binary Systems.—It is evident that if double stars are endowed with the property of mutual gravitation, they must be revolving around each other, as the earth and planets revolve around the sun, else they would be drawn together as a single star.

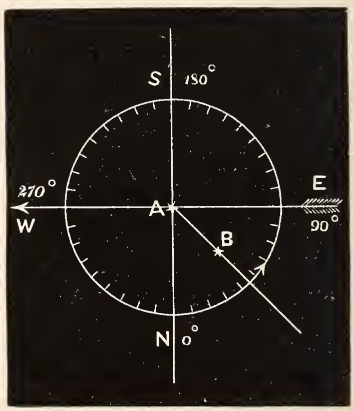

FIG. 87.—POSITION-ANGLE OF A DOUBLE STAR.

The method of determining the period of revolution of a binary star is illustrated by the figure, which is supposed to represent the field of view of an inverting telescope pointed toward the south. The arrow shows the direction of the apparent diurnal motion. The telescope is supposed to be so pointed that the brighter star may be in the centre of the field. The numbers around the surrounding circle then show the angle of position, supposing the smaller star to be in the direction of the number.

Fig. 87 is an example of a pair of stars in which the position-angle is about 44°.

If, by measures of this sort extending through a series of years, the distance or position-angle of a pair of stars is found to change *periodically*, it shows that one star is revolving around the other. Such a pair is called a *binary star* or *binary system*. The only distinction which we can make between binary systems and ordinary double stars is founded on the presence or absence of this observed motion. It is probable that nearly all the very close double stars are really binary systems, but that many hundreds of years are required to perform a revolution in some instances, so that the motion has not yet been detected.

The discovery of binary systems is one of great scientific interest, because from them we learn that the law of gravitation includes the stars as well as the solar system in its scope, and may thus be regarded as truly universal.

CHAPTER IV.

NEBULÆ AND CLUSTERS.

Discovery of Nebulæ.

In the star-catalogues of Ptolemy, Hevelius, and the earlier writers, there was included a class of nebulous or cloudy stars, which were in reality star-clusters. They appeared to the naked eye as masses of soft diffused light of greater or less extent. In this respect they were quite analogous to the Milky Way. In the telescope, the nebulous appearance of these spots vanishes, and they are seen to consist of clusters of stars.

As the telescope was improved, great numbers of such patches of light were found, some of which could be resolved into stars, while others could not. The latter were called *nebulæ* and the former *star-clusters.*

About 1656 Huyghens described the great nebula of *Orion*, one of the most remarkable and brilliant of these objects. During the last century Messier, of Paris, made a list of 103 northern nebulæ, and Lacaille noted a few of those of the southern sky. Sir William Herschel with his great telescopes first gave proof of the enormous number of these masses. In 1786 he published a catalogue of one thousand new nebulæ and clusters. This was followed in 1789 by a catalogue of a second thousand, and in 1802 by a third catalogue of five hundred new objects of this class. Sir John Herschel added about two thousand more nebulæ. The general catalogue of nebulæ and clusters of stars of the latter astronomer, published in 1864, contains 5079 nebulæ. Over two thirds of these were first discovered by the HERSCHELS.

CLASSIFICATION OF NEBULÆ AND CLUSTERS.

In studying these objects, the first question we meet is this: Are all these bodies clusters of stars which look diffused only because they are so distant that our telescopes cannot distinguish them separately? or are some of them in reality what they seem to be; namely, diffused masses of matter?

In his early memoirs of 1784 and 1785, Sir WILLIAM HERSCHEL took the first view. He considered the Milky Way as nothing but a congeries of stars, and all nebulæ naturally seemed to him to be but stellar clusters, so distant as to cause the individual stars to disappear in a general milkiness or nebulosity.

In 1791, however, his views underwent a change. He had discovered a *nebulous star* (properly so called), or a star which was undoubtedly similar to the surrounding stars, and which was encompassed by a halo of nebulous light.

He says: "Nebulæ can be selected so that an insensible gradation shall take place from a coarse cluster like the *Pleiades* down to a milky nebulosity like that in *Orion*, every intermediate step being represented. This tends to confirm the hypothesis that all are composed of stars more or less remote.

"A comparison of the two *extremes* of the series, as a coarse cluster and a nebulous star, indicates, however, that *the nebulosity about the star is not of a starry nature.*

"Considering a typical nebulous star, and supposing the nucleus and chevelure to be connected, we may, first, suppose the whole to be of stars, in which case either the nucleus is enormously larger than other stars of its stellar magnitude, or the envelope is composed of stars indefinitely small; or, second, we must admit that the star is *involved in a shining fluid of a nature totally unknown to us.*

"The shining fluid might exist independently of stars. The light of this fluid is no kind of reflection from the star in the centre. If this matter is self-luminous, it seems more fit to produce a star by its condensation than to depend on the star for its existence.

"Both diffused nebulosities and planetary nebulæ are better accounted for by the hypothesis of a shining fluid than by supposing them to be distant stars."

This was the first exact statement of the idea that, beside stars and star-clusters, we have in the universe a totally distinct series of objects, probably much more simple in their constitution. Observations on the spectra of these bodies have entirely confirmed the conclusions of HERSCHEL.

Nebulæ and clusters were divided by HERSCHEL into classes. He

FIG. 88.—SPIRAL NEBULA.

applied the name *planetary nebulæ* to certain circular or elliptic nebulæ which in his telescope presented disks like the planets. *Spiral nebulæ* are those whose convolutions have a spiral shape. This class is quite numerous.

The different kinds of nebulæ and clusters will be better understood from the cuts and descriptions which follow than by formal definitions. It must be remembered that there is an almost infinite variety of such shapes.

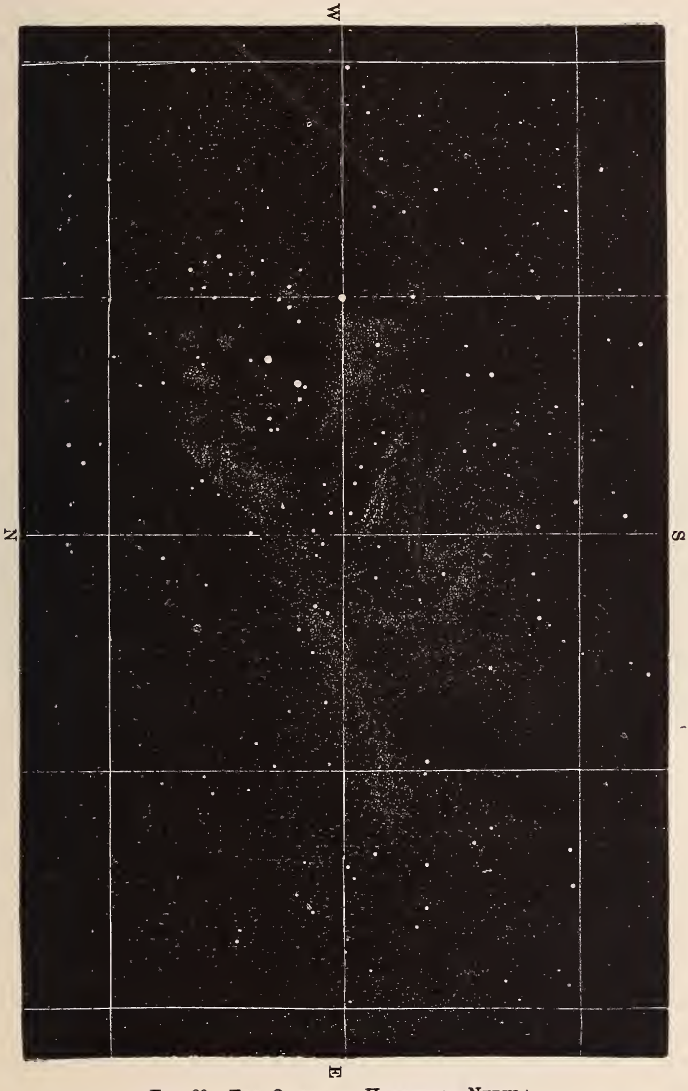

FIG. 89.—THE OMEGA OR HORSESHOE NEBULA.

STAR-CLUSTERS.

The most noted of all the clusters is the *Pleiades*, which have already been briefly described in connection with the constellation *Taurus*. The average naked eye can easily distinguish six stars within it, but under favorable conditions ten, eleven, twelve, or more stars can be counted. With the telescope, over a hundred stars are seen.

The clusters represented in Figs. 90 and 91 are good examples of their classes. The first is globular and contains several thousand small stars. The second is a cluster of about 200 stars, of magnitudes varying from the ninth to the thirteenth and fourteenth, in which the brighter stars are scattered.

FIG. 90.—GLOBULAR CLUSTER.

FIG. 91 —COMPRESSED CLUSTER.

Clusters are probably subject to central powers or forces. This was seen by Sir WILLIAM HERSCHEL in 1789. He says:

"Not only were *round* nebulæ and clusters formed by central powers, but likewise every cluster of stars or nebula that shows a gradual condensation or increasing brightness toward a centre. This theory of central power is fully established on grounds of observation which cannot be overturned.

"Clusters can be found of 10 diameter with a certain degree of compression and stars of a certain magnitude, and smaller clusters of 4′, 3′, or 2′ in diameter, with smaller stars and greater compression, and so on through resolvable nebulæ by imperceptible steps, to the smallest and faintest [and most distant] nebulæ. Other clusters there are, which lead to the belief that either they are more compressed or are composed of larger stars. Spherical clusters are probably not more different in size among themselves than different individuals of plants of the same species. As it has been shown that the spherical figure of a cluster of stars is owing to central powers, it follows that those clusters which, *cæteris paribus*, are the most complete in this figure must have been the longest exposed to the action of these causes.

"The maturity of a sidereal system may thus be judged from the disposition of the component parts.

"Though we cannot see any individual nebula pass through all its stages of life, we can select particular ones in each peculiar stage," and thus obtain a single view of their entire course of development.

Spectra of Nebulæ and Clusters, and Fixed Stars.

In 1864, five years after the invention of the spectroscope, the examination of the spectra of the nebulæ led to the discovery that while the spectra of stars were invariably continuous and crossed with dark lines similar to those of the solar spectrum, those of many nebulæ were *discontinuous*, showing these bodies to be composed of glowing gas.

The spectrum of most clusters is continuous, indicating that the individual stars are truly stellar in their nature. In a few cases, however, clusters are composed of a mixture of nebulosity (usually near their centre) and of stars, and the spectrum in such cases is compound in its nature, so as to indicate radiation both by gaseous and solid matter.

Spectra of Fixed Stars.

Stellar spectra are found to be, in the main, similar to the solar spectrum; *i.e.*, composed of a continuous band of the prismatic colors, across which dark lines or bands were laid, the latter being fixed in position. These results show the fixed stars to resemble our own sun in general constitution, and to be composed of an incandescent nucleus surrounded by a gaseous and absorptive atmosphere of lower temperature. This atmosphere around many stars is different in constitution from that of the sun, as is shown by the different position and intensity of the various black lines and bands which are due to the absorptive action of the atmospheres of the stars.

It is probable that the hotter a star is the more simple a spectrum it has; for the brightest, and therefore probably the hottest stars, such as *Sirius*, give spectra showing only very thick hydrogen lines and a few very thin metallic lines, while the cooler stars, such as our sun, are shown by their spectra to contain a much larger number of metallic elements than stars of the type of *Sirius*, but no non-metallic elements (oxygen possibly excepted). The coolest stars give band-spectra characteristic of compounds of metallic with non-metallic elements, and of the non metallic elements uncombined.

Motion of Stars in the Line of Sight.

Spectroscopic observations of stars not only give information in regard to their chemical and physical constitution, but have been applied so as to determine approximately the velocity in kilometres per second with which the stars are approaching to or receding from the earth along the line joining earth and star. The theory of such a determination is briefly as follows:

In the solar spectrum we find a group of dark lines, as a, b, c, which always maintain their relative position. From laboratory experiments, we can show that the three bright lines of incandescent hydrogen (for example) have always the same relative position as the solar dark lines a, b, c. From this it is inferred that the solar dark lines are due to the presence of hydrogen in its absorptive atmosphere.

Now, suppose that in a stellar spectrum we find three dark lines a', b', c', whose relative position is exactly the same as that of the solar lines a, b, c. Not only is their relative position the same, but the characters of the lines themselves, so far as the fainter spectrum of the star will allow us to determine them, are also similar; that is, a' and a, b' and b, c' and c are alike as to thickness, blackness, nebulosity of edges, etc. etc. From this it is inferred that the star really contains in its atmosphere the substance whose existence has been shown in the sun.

If we contrive an apparatus by which the stellar spectrum is seen in the lower half, say, of the eye-piece of the spectroscope, while the spectrum of hydrogen is seen just above it, we find in some cases this remarkable phenomenon. The three dark stellar lines, a', b', c', instead of being exactly coincident with the three hydrogen lines a, b, c, are seen to be all thrown to one side or the other by a like amount; that is, the whole group a', b', c', while preserving its relative distances the same as those of the comparison group a, b, c, is shifted toward either the violet or red end of the spectrum by a small yet measurable amount. Repeated experiments by different instruments and observers show always a shifting in the same direction and of like amount. The figure shows the shifting of the *F* line in the spectrum of *Sirius*, compared with one fixed line of hydrogen.

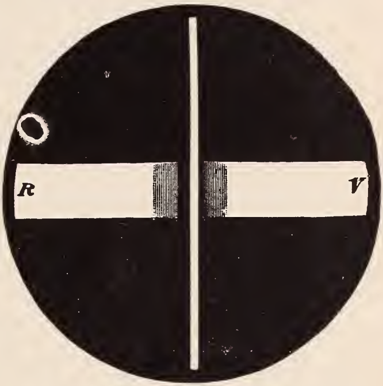

Fig. 92.—F Line in Spectrum of Sirius.

This displacement of the spectral lines is to be accounted for by a motion of the star toward or from the earth. It is shown in Physics that if the source of the light which gives the spectrum a', b', c' is moving away from the earth, this group will be shifted toward the red end of the spectrum; if toward the earth, then the whole group will be shifted toward the blue end. The amount of this shifting is a function of the velocity of recession or approach, and this velocity in miles per second can be calculated from the measured displacement. This has been done for many stars. The results agree well, when the difficult nature of the research is considered. The rates of motion vary from insensible amounts to 100 kilometres per second; and in some cases agree remarkably with the velocities computed from the proper motions and probable parallaxes.

CHAPTER V.

MOTIONS AND DISTANCES OF THE STARS.

PROPER MOTIONS.

WE have already stated that, to the unaided vision, the fixed stars appear to preserve the same relative position in the heavens through many centuries, so that if the ancient astronomers could again see them, they could hardly detect the slightest change in their arrangement. But accurate measurements have shown that there are slow changes in the positions of the brighter stars, consisting in a motion forward in a straight line and with uniform velocity. These motions are, for the most part, so slow that it would require thousands of years for the change of position to be perceptible to the unaided eye. They are called *proper motions,* since they are peculiar to the star itself.

In general, the proper motions even of the brightest stars are only a fraction of a second in a year, so that thousands of years would be required for them to change their place in any striking degree, and hundreds of thousands to make a complete revolution around the heavens.

PROPER MOTION OF THE SUN.

It is *a priori* evident that stars, in general, must have proper motions, when once we admit the universality of gravitation. That any fixed star should be entirely at rest would require that the attractions on all sides of it should be exactly balanced. Any change in the position of this star would break up this balance, and thus, in general, it follows that stars must be in motion, since all of them cannot occupy such a critical position as has to be assumed.

If but one fixed star is in motion, this affects all the rest, and we cannot doubt but that every star, our sun included, is in motion by amounts which vary from small to great. If the sun alone had a motion, and the other stars were at rest, the consequence of this would be that all the fixed stars would appear to be retreating *en masse* from that point in the sky toward which we were moving. Those nearest us would move more rapidly, those more distant less so. And in the same way, the stars from which the solar system was receding would seem to be approaching each other. If the stars, instead of being quite at rest, as just supposed, had motions proper to themselves, then we should have a double complexity. They would still appear to an observer in the solar system to have motions. One part of these motions would be truly proper to the stars, and one part would be due to the advance of the sun itself in space.

Observations can show us only the *resultant* of these two motions. It is for reasoning to separate this resultant into its two components. At first the question is to determine whether the results of observation indicate any solar motion at all. If there is none, the proper motions of stars will be directed along all possible lines. If the sun does truly move, then there will be a general agreement in the resultant motions of the stars near the ends of the line along which it moves, while those at the sides, so to speak, will show comparatively less systematic effect. It is as if one were riding in the rear of a railway train and watching the rails over which it has just passed. As we recede from any point, the rails at that point seem to come nearer and nearer together.

If we were passing through a forest, we should see the trunks of the trees from which we were going apparently come nearer and nearer together, while those on the sides of us would remain at their constant distance, and those in front would grow further and further apart.

These phenomena, which occur in a case where we are sensible of our own motion, serve to show how we may deduce a motion, otherwise unknown, from the appearances which are presented by the stars in space.

In this way, acting upon suggestions which had been thrown out previously to his own time, HERSCHEL demonstarted that the sun, together with all its system, was moving through space in an unknown and majestic orbit of its own. The centre round which this motion is directed cannot yet be assigned. We can only determine the point in the heavens toward which our course is directed—"the apex of solar motion."

A number of astronomers have since investigated this motion with a view of determining the exact point in the heavens toward which the sun is moving. Their results differ slightly, but the points toward which the sun is moving all fall in the constellation *Hercules*. The amount of the motion is such that if the sun were viewed at right angles to the direction of motion from an average star of the first magnitude, it would appear to move about one third of a second per year.

DISTANCES OF THE FIXED STARS.

The ancient astronomers supposed all the fixed stars to be situated at a short distance outside of the orbit of the planet *Saturn*, then the outermost known planet. The idea was prevalent that Nature would not waste space by leaving a great region beyond *Saturn* entirely empty.

When COPERNICUS announced the theory that the sun was at rest and the earth in motion around it, the problem of the distance of the stars acquired a new interest. It was evident that if the earth described an annual orbit, then the stars would appear in the course of a year to oscillate back and forth in corresponding orbits, unless they were so immensely distant that these oscillations were too small to be seen. The apparent oscillation of *Saturn* produced in this way was described in Part I. It amounts to some 6° on each side of the mean position. These oscillations were, in fact, those which the ancients represented by the motion of the planet around a small epicycle. But no such oscillation had ever been detected in a fixed star. This fact seemed to present an almost insuperable difficulty in the reception of the Copernican system. Very naturally, therefore, as the instruments of observation were from time to time improved, this apparent annual oscillation of the stars was ardently sought for.

The problem is identical with that of the annual parallax of the fixed stars, which has been already described. This parallax of a heavenly body is the angle which the mean distance of the earth from the sun subtends when seen from the body. The distance of the body from the sun is inversely as the parallax (nearly). Thus the mean distance of *Saturn* being 9.5, its annual parallax exceeds 6°, while that of *Neptune*, which is three times as far, is about 2°. It was very evident, without telescopic observation, that the stars could not have a parallax of one half a degree. They must therefore be at least twelve times as far as *Saturn* if the Copernican system were true.

When the telescope was applied to measurement, a continually increasing accuracy began to be gained by the improvement of the instruments. Yet for several generations the parallax of the fixed stars eluded measurement. Very often indeed did observers think they had detected a parallax in some of the brighter stars, but their successors, on repeating their measures with better instruments, and investigating their methods anew, found their conclusions erroneous. Early in the present century it became certain that even the brighter stars had not, in general, a parallax as great as 1″, and thus it became certain that they must lie at a greater distance than 200,000 times that which separates the earth from the sun.

Success in actually measuring the parallax of the stars was at length obtained almost simultaneously by two astronomers, Bessel of Königsberg and Struve of Dorpat. Bessel selected 61 *Cygni* for observation, in August, 1837. The result of two or three years of observation was that this star had a parallax of 0″.35, or about one third of a second. This would make its distance from the sun nearly 600,000 astronomical units. The reality of this parallax has been well-established by subsequent investigators, only it has been shown to be a little larger, and therefore the star a little nearer than Bessel supposed. The most probable parallax is now found to be 0″.51, corresponding to a distance of 400,000 radii of the earth's orbit.

The distances of the stars are sometimes expressed by the time required for light to pass from them to our system. The velocity of light is, it will be remembered, about 300,000 kilometres per second, or such as to pass from the sun to the earth in 8 minutes 18 seconds.

The time required for light to reach the earth from some of the stars, of which the parallax has been measured, is as follows :

STAR.	Years.	STAR.	Years.
α *Centauri*	3·5	70 *Ophiuchi*	19·1
61 *Cygni*	6·7	ι *Ursæ Majoris*	24·3
21,185 Lelande	6·3	*Arcturus*	25·4
β *Centauri*	6·9	γ *Draconis*	35·1
μ *Cassiopeiæ*	9·4	1830 Groombridge	35·9
34 Groombridge	10·5	*Polaris*	42·4
21,258 Lelande	11·9	3077 Bradley	46·1
17,415 Oeltzen	13·1	85 *Pegasi*	64·5
Sirius	16·7	α *Aurigæ*	70·1
α *Lyræ*	17·9	σ *Draconis*	129·1

CHAPTER VI.

CONSTRUCTION OF THE HEAVENS.

THE visible universe, as revealed to us by the telescope, is a collection of many millions of stars and of several thousand nebulæ. It is sometimes called the stellar or sidereal system, and sometimes, as already remarked, the stellar universe. The most far-reaching question with which astronomy has to deal is that of the form and magnitude of this system, and the arrangement of the stars which compose it.

It was once supposed that the stars were arranged on the same general plan as the bodies of the solar system, being divided up into great numbers of groups or clusters, while all the stars of each group revolved in regular orbits round the centre of the group. All the groups were supposed to revolve around some great common centre, which was therefore the centre of the visible universe.

But there is no proof that this view is correct. We have already seen that a great many stars are collected into clusters, but there is no evidence that the stars of these clusters revolve in regular orbits, or that the clusters themselves have any regular motion around a common centre.

The first astronomer to make a careful study of the arrangement of the stars with a view to learn the structure of the heavens was Sir WILLIAM HERSCHEL.

HERSCHEL'S method of study was founded on a mode of observation which he called *star-gauging.* It consisted in pointing a powerful telescope toward various parts of the heavens and ascertaining by actual count how thick the stars were in each region. His 20-foot reflector was provided with such an eye piece that, in looking into it, he would see a portion of the heavens about 15′ in diameter. A circle of this size on the celestial sphere has about one quarter the apparent surface of the sun, or of the full moon. On pointing the telescope in any direction, a greater or less number of stars were nearly always visible. These were counted, and the direction in which the telescope pointed was noted. Gauges of this kind were made in all parts of the sky at which he could point his instrument, and the results were tabulated in the order of right ascension.

The following is an extract from the gauges, and gives the average number of stars in each field at the points noted in right ascension and north-polar distance:

R. A.		N. P. D. 92° to 94°. No. of Stars.	R. A.		N. P. D. 78° to 80°. No. of Stars.
h.	m.		h.	m.	
15	10	9.4	11	6	3.1
15	47	10.6	12	44	4.6
16	25	13.6	12	49	3.9
16	37	18.6	14	30	3.6

In this small table, it is plain that a different law of clustering or of distribution obtains in the two regions.

The number of these stars in certain portions is very great. For example, in the Milky Way this number was as great as 116,000 stars in a quarter of an hour in some cases.

Herschel supposed at first that he completely resolved the whole Milky Way into small stars. This conclusion he subsequently modified. He says:

"It is very probable that the great stratum called the Milky Way is that in which the sun is placed, though perhaps not in the very centre of its thickness.

"We gather this from the appearance of the Galaxy, which seems to encompass the whole heavens, as it certainly must do if the sun is within it. For, suppose a number of stars arranged between two parallel planes, indefinitely extended every way, but at a given considerable distance from each other, and calling this a sidereal stratum, an eye placed somewhere within it will see all the stars in the direction of the planes of the stratum projected into a great circle, which will appear lucid on account of the accumulation of the stars, while

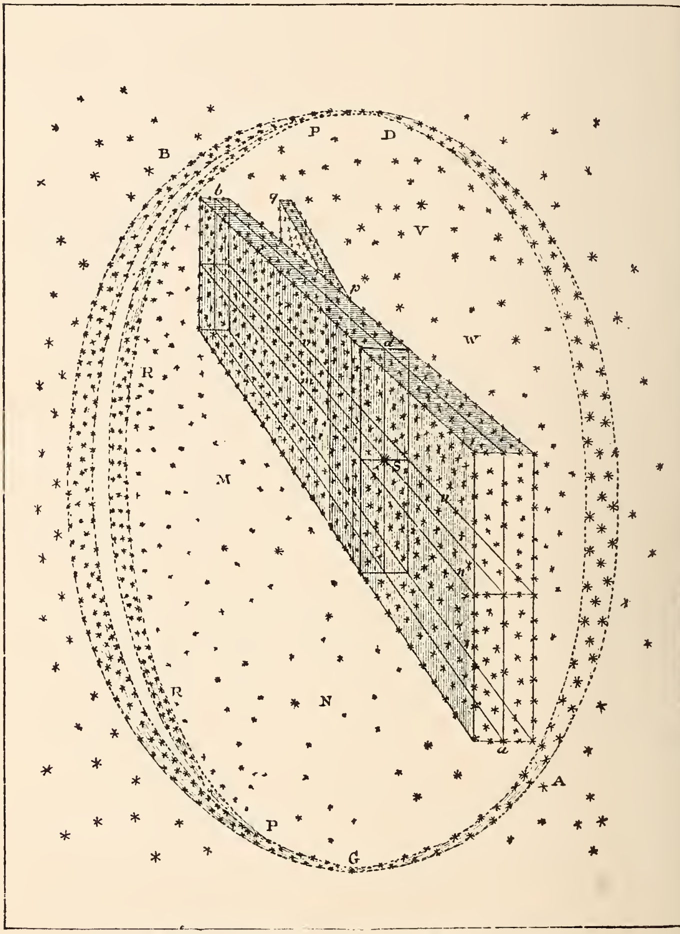

FIG. 93.—HERSCHEL'S THEORY OF THE STELLAR SYSTEM.

the rest of the heavens, at the sides, will only seem to be scattered over with constellations, more or less crowded, according to the distance of the planes, or number of stars contained in the thickness or sides of the stratum."

Thus in HERSCHEL'S figure an eye at S within the stratum $a\,b$ will see the stars in the direction of its length $a\,b$, or height $c\,d$, with all those in the intermediate situations, projected into the lucid circle $A\ C\,B\,D$, while those in the sides $m\,v$, $n\,w$, will be seen scattered over the remaining part of the heavens $M\ V\,N\ W$.

"If the eye were placed somewhere without the stratum, at no very great distance, the appearance of the stars within it would assume the form of one of the smaller circles of the sphere, which would be more or less contracted according to the distance of the eye; and if this distance were exceedingly increased, the whole stratum might at last be drawn together into a lucid spot of any shape, according to the length, breadth, and height of the stratum.

"Suppose that a smaller stratum $p\,q$ should branch out from the former in a certain direction, and that it also is contained between two parallel planes, so that the eye is contained within the great stratum somewhere before the separation, and not far from the place where the strata are still united. Then this second stratum will not be projected into a bright circle like the former, but it will be seen as a lucid branch proceeding from the first, and returning into it again at a distance less than a semicircle.

"In the figure the stars in the small stratum $p\,q$ will be projected into a bright arc $P\,R\,R\,P$, which, after its separation from the circle $C\,B\,D$, unites with it again at P.

"If the bounding surfaces are not parallel planes, but irregularly curved surfaces, analogous appearances must result."

The Milky Way, as we see it with the naked eye, presents the aspect which has been just accounted for, in its general appearance of a girdle around the heavens and in its bifurcation at a certain point, and HERSCHEL'S explanation of this appearance, as just given, has never been seriously questioned. One doubtful point remains: are the stars in Fig. 93 scattered all through the space S—$a\,b\,p\,d$? or are they near its bounding planes, or clustered in any way within this space so as to produce the same result to the eye as if uniformly distributed?

HERSCHEL assumed that they were nearly equably arranged all through the space in question. He only examined one other arrangement—viz., that of a ring of stars surrounding the sun—and he pronounced against such an arrangement, for the reason that there is absolutely nothing in the size or brilliancy of the sun to cause us to suppose it to be the centre of such a gigantic system. No reason except its importance to us personally can be alleged for such a supposition. By the assumptions of Fig. 93, each star will have its own appearance of a galaxy or milky way, which will vary according to the situation of the star.

Such an explanation will account for the general appearances of the Milky Way and of the rest of the sky, supposing the stars equally or nearly equally distributed in space. On this supposition, the system must be deeper where the stars appear more numerous.

CHAPTER VII.

COSMOGONY.

A THEORY of the operations by which the universe received its present form and arrangement is called *Cosmogony.* This subject does not treat of the origin of matter, but only of its transformations.

Three systems of Cosmogony have prevailed among thinking men at different times:

(1) That the universe had no origin, but existed from eternity in the form in which we now see it. This was the view of the ancient philosophers.

(2) That it was created in its present shape in a moment, out of nothing. This view is based on the literal sense of the words of the Old Testament.

(3) That it came into its present form through an arrangement of materials which were before "without form and void." This may be called the evolution theory. It is to be noticed that no attempt is made to explain the origin of the primitive matter.

The last is the idea which has prevailed, and it receives many striking confirmations from the scientific discoveries of modern times. The latter seem to show beyond all reasonable doubt that the universe could not always have existed in its present form and under its present conditions; that there was a time when the materials composing it were masses of glowing vapor, and that there will be a time when the present state of things will cease. The explanation of the processes through which this occurs is sometimes called the *nebular hypothesis.* It was first propounded by the philosophers Swedenborg, Kant, and Laplace, and, although since greatly modified in detail, their views have in the main been retained until the present time.

We shall begin its consideration by a statement of the various facts which appear to show that the earth and planets, as well as the sun, were once a fiery mass.

The first of these facts is the gradual but uniform increase of temperature as we descend into the interior of the earth. Wherever mines have been dug or wells sunk to a great depth, the temperature increases as we go downward at the rate of about one degree centigrade to every 30 metres, or one degree Fahrenheit to every 50 feet. The rate differs in different places, but the general average is near this. The conclusion which we draw from this may not at first sight be obvious, because it may seem that the earth might always have shown this same increase of temperature. But there are several results which a little thought will make clear, although their complete establishment requires the use of the higher mathematics.

The first result is that the increase of temperature cannot be merely superficial, but must extend to a great depth, probably even to the centre of the earth. If it did not so extend, the heat would have all been lost long ages ago by conduction to the interior and by radiation from the surface. It is certain that the earth has not received any great supply of heat from outside since the earliest geological ages, because such an accession of heat at the earth's surface would have destroyed all life, and even melted all the rocks. Therefore, whatever heat there is in the *interior* of the earth must have been there from before the commencement of life on the globe, and remained through all geological ages.

The interior of the earth being hotter than its surface, and hotter than the space around it, must be losing heat. We know by the most familiar observation that if any object is hot inside, the heat will work its way through to the surface by the process of conduction. Therefore, since the earth is a great deal hotter at the depth of 30 metres than it is at the surface, heat must be continually coming to the surface. On reaching the surface, it must be radiated off into space, else the surface would have long ago become as hot as the interior. Moreover, this loss of heat must have been going on since the beginning, or at least since a time when the surface was as hot as the interior. Thus, if we reckon backward in time, we find that there must have been more and more heat in the earth the further back we go, so that we must finally reach back to a time when it was so hot as to be molten, and then again to a time when it was so hot as to be a mass of fiery vapor.

The second fact is that we find the sun to be cooling off like the earth, only at an incomparably more rapid rate. The sun is constantly radiating heat into space, and, so far as we can ascertain, receiving none back again. A small portion of this heat reaches the earth, and on this portion depends the existence of life and motion on the earth's surface. The quantity of heat which strikes the earth is only about $\frac{1}{2000000000}$ of that which the sun radiates. This fraction expresses the ratio of the apparent surface of the earth, as seen from the sun, to that of the whole celestial sphere.

Since the sun is losing heat at this rate, it must have had more heat yesterday than it has to-day; more two days ago than it had yesterday, and so on. Thus calculating backward, we find that the further we go back into time the hotter the sun must have been. Since we know that heat expands all bodies, it follows that the sun must have been larger in past ages than it is now, and we can trace back this increase in size without limit. Thus we are led to the conclusion that there must have been a time when the sun filled up the space now occupied by the planets, and must have been a very rare mass of glowing vapor. The planets could not then have existed separately, but must have formed a part of this mass of vapor. The latter was therefore the material out of which the solar system was formed.

The same process may be continued into the future. Since the sun by its radiation is constantly losing heat, it must grow cooler and cooler as ages advance, and must finally radiate so little heat that life and motion can no longer exist on our globe.

The third fact is that the revolutions of all the planets around the sun take place in the same direction and in nearly the same plane. We have here a similarity amongst the different bodies of the solar system, which must have had an adequate cause, and the only cause which has ever been assigned is found in the nebular hypothesis. This hypothesis supposes that the sun and planets were once a great mass of vapor, as large as or larger than the present solar system, revolving on its axis in the same plane in which the planets now revolve.

The fourth fact is seen in the existence of nebulæ. The spectroscope shows these bodies to be masses of glowing vapor. We thus actually see matter in the celestial spaces under the very form in which the nebular hypothesis supposes the matter of our solar system to have once existed. Since these masses of vapor are so hot as to radiate light and heat through the immense distance which separates us from them, they must be gradually cooling off. This cooling must at length reach a point when they will cease to be vaporous and condense into objects like stars and planets. We know that every star in the heavens radiates heat as our sun does. In the case of the brighter stars the heat radiated has been made sensible in the foci of our telescopes by means of the thermo-multiplier. All the stars must, like the sun, be radiating heat into space.

A fifth fact is afforded by the physical constitution of the planets *Jupiter* and *Saturn*. The telescopic examination of these planets shows that changes on their surfaces are constantly going on with a rapidity and violence to which nothing on the surface of our earth can compare. Such operations can be kept up only through the agency of heat or some equivalent form of energy. But at the distance of *Jupiter* and *Saturn* the rays of the sun are entirely insufficient to produce changes so violent. We are therefore led to infer that *Jupiter* and *Saturn* must be hot bodies, and must therefore be cooling off like the sun, stars, and earth.

We are thus led to the general conclusion that, so far as our knowledge extends, nearly all the bodies of the universe are hot, and are cooling off by radiating their heat into space.

The idea that the heat radiated by the sun and stars may in some way be collected and returned to them by the operation of known natural laws is equally untenable. It is a fundamental principle of the laws of heat that "the latter can never pass from a cooler to a warmer body," and that a body can never grow warm or acquire heat in a space that is cooler than the body is itself. All differences of temperature tend to equalize themselves, and the only state of things to which the universe can tend, under its present laws, is one in which all space and all the bodies contained in space are at a uniform temperature, and then all motion and change of temperature, and hence the conditions of vitality, must cease. And then all such life as ours must cease also unless sustained by entirely new methods.

The general result drawn from all these laws and facts is, that there was once a time when all the bodies of the universe formed either a single mass or a number of masses of fiery vapor, having slight motions in various parts, and different degrees of density in different regions. A gradual condensation around the centres of greatest density then went on in consequence of the cooling and the mutual attraction of the parts, and thus arose a great number of nebulous masses. One of these masses formed the material out of which the sun and planets are supposed to have been formed. It was probably at first nearly globular, of nearly equal density throughout, and endowed with a very slow rotation in the direction in which the planets now move. As it cooled off, it grew smaller and smaller, and its velocity of rotation increased in rapidity.

The rotating mass we have described must have had an axis around which it rotated, and therefore an equator defined as being everywhere 90° from this axis. In consequence of the increase in the velocity of rotation, the centrifugal force would also be increased as the mass grew smaller. This force varies as the radius of the circle described by any particle multiplied by the square of its angular velocity. Hence when the masses, being reduced to half the radius, rotated four times as fast, the centrifugal force at the equator would be increased $\frac{1}{2} \times 4^2$, or eight times. The gravitation of the mass at the surface, being inversely as the square of the distance from the centre, or of the radius, would be increased four times. Therefore as the masses continue to contract, the centrifugal force increases at a more rapid rate than the central attraction. A time would therefore come when they would balance each other at the equator of the mass. The mass would then cease to contract at the equator, but at the poles there would be no centrifugal force, and the gravitation of the mass would grower stronger and stronger. In consequence the mass would at length assume the form of a lens or disk very thin in proportion to its extent. The denser portions of this lens would gradually be drawn toward the centre, and there more or less solidified by the process of cooling. A point would at length be reached, when solid particles would begin to be formed throughout the whole disk. These would gradually condense around each other and form a single planet, or they might break up into small masses and form a group of planets. As the motion of rotation would not be altered by these processes of condensation, these planets would all be rotating around the central part of the mass, which is supposed to have condensed into the sun.

It is supposed that at first these planetary masses, being very hot, were composed of a central mass of those substances which condensed at a very high temperature, surrounded by the vapors of those substances which were more volatile. We know, for instance, that it takes a much higher temperature to reduce lime and platinum to vapor than it does to reduce iron, zinc, or magnesium. Therefore, in the original planets, the limes and earths would condense first, while many other metals would still be in a state of vapor. The planetary masses would each be affected by a rotation increasing in rapidity as they grew smaller, and would at length form masses of melted metals and vapors in the same way as the larger mass out of which the sun and planets were formed. These masses would then condense into a planet, with satellites revolving around it, just as the original mass condensed into sun and planets.

At first the planets would be so hot as to be in a molten condition, each of them probably shining like the sun. They would, however, slowly cool off by the radiation of heat from their surfaces. So long as they remained liquid, the surface, as fast as it grew cool, would sink into the interior on account of its greater specific gravity, and its place would be taken by hotter material rising from the interior to the surface, there to cool off in its turn. There would, in fact, be a motion something like that which occurs when a pot of cold water is set upon the fire to boil. Whenever a mass of water at the bottom of the pot is heated, it rises to the surface, and the cool water moves down to take its place. Thus, on the whole, so long as the planet remained liquid, it would cool off equally throughout its whole mass, owing to the constant motion from the centre to the circumference and back again. A time would at length arrive when many of the earths and metals would begin to solidify. At first the solid particles would be carried up and down with the liquid. A time would finally arrive when they would become so large and numerous, and the liquid part of the general mass become so viscid, that the motion would be obstructed. The planet would then begin to solidify. Two views have been entertained respecting the process of solidification.

According to one view, the whole surface of the planet would solidify into a continuous crust, as ice forms over a pond in cold weather, while the interior was still in a molten state. The interior liquid could then no longer come to the surface to cool off, and could lose no heat except what was conducted through this crust. Hence the subsequent cooling would be much slower, and the globe would long remain a mass of lava, covered over by a comparatively thin solid crust like that on which we live.

The other view is that, when the cooling attained a certain stage, the central portion of the globe would be solidified by the enormous pressure of the superincumbent portions, while the exterior was still fluid, and that thus the solidification would take place from the centre outward.

It is still an unsettled question whether the earth is now solid to its centre, or whether it is a great globe of molten matter with a comparatively thin crust. Astronomers and physicists incline to the former view; geologists to the latter one. Whichever view may be correct, it appears certain that there are great lakes of lava in the interior from which volcanoes are fed.

It must be understood that the nebular hypothesis, as we have explained it, is not a perfectly established scientific theory, but only a philosophical conclusion founded on the widest study of nature, and pointed to by many otherwise disconnected facts. The widest generalization associated with it is that, so far as we can see, the universe is not self-sustaining, but is a kind of organism which, like all other organisms we know of, must come to an end in consequence of those very laws of action which keep it going. It must have had a beginning within a certain number of years which we cannot yet calculate with certainty, but which cannot much exceed 20,000,000, and it must end in a chaos of cold, dead globes at a calculable time in the future, when the sun and stars shall have radiated away all their heat, unless it is re-created by the action of forces of which we at present know nothing.

THE END.

INDEX.

☞ This index is intended to point out the subjects treated in the work, and further, to give references to the pages where technical terms are defined or explained.

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