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TEN YEARS' WORK OF A MOUNTAIN OBSERVATORY

by

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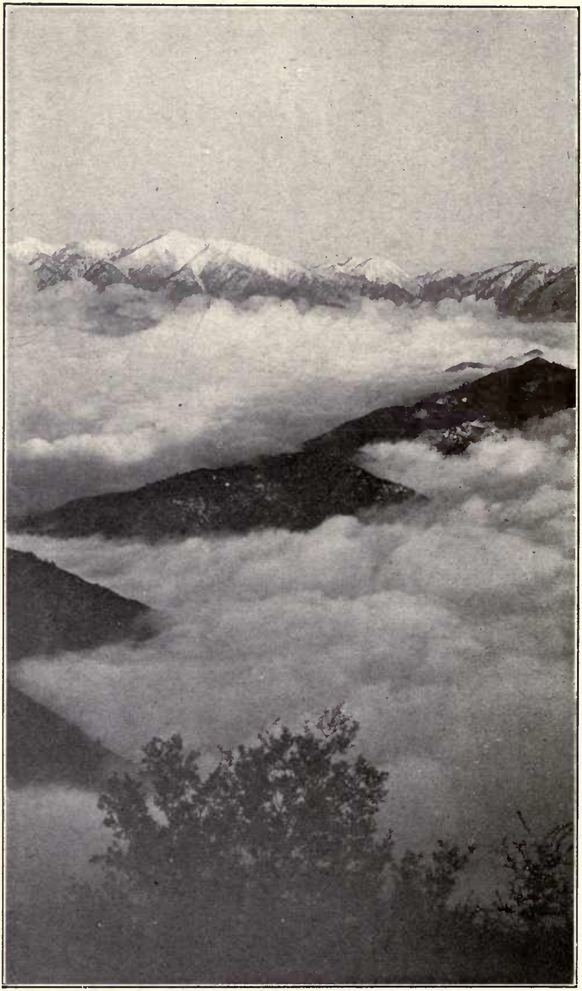

Mount San Antonio from Mount Wilson.

TEN YEARS' WORK
OF A
MOUNTAIN OBSERVATORY

A brief account of the Mount
Wilson Solar Observatory of the
Carnegie Institution of Washington

BY

GEORGE ELLERY HALE

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NOTE.

The eleven departments of research of the Carnegie Institution of Washington, of which the Mount Wilson Solar Observatory is one, are located in various places selected because of their suitability for the several purposes in view. Information regarding the work of the Institution may be obtained on application to the Office of Administration, Washington D. C.

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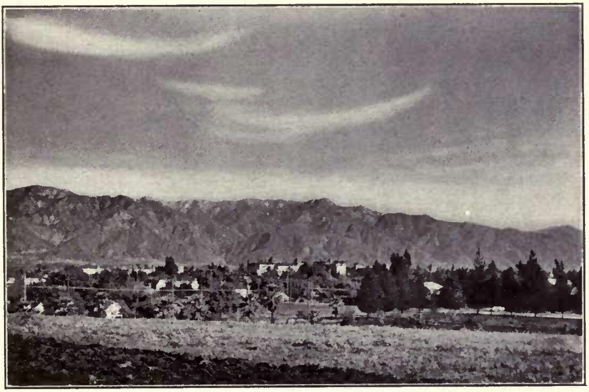


FIG. 1.—Mount Wilson from Pasadena

TEN YEARS' WORK OF A MOUNTAIN OBSERVATORY

Ten years have elapsed since the inception of the Mount Wilson Observatory, and the time is opportune for a general survey of the work of the past and the possibilities of the future. An extensive equipment of buildings and instruments, involving heavy initial cost and large annual expenditure for operation and maintenance, has been provided on a 6,000-foot mountain summit and in the valley near its base. Activities of many kinds, including the preparation of new plans of research, the invention, design, and construction of instruments, the building of a mountain road, the transportation of many hundreds of tons of materials, the erection of brick, steel, and concrete structures, the execution of an observational program, the measurement and reduction of thousands of photographs, and the imitation of celestial phenomena by laboratory experiments, have taxed the capacity of a large staff of workers. The equipment is now so nearly complete and the plan of investigation so definitely outlined that a brief description of some typical methods and results may be of service to the visitor and to the general reader interested in the progress of astrophysical research.

OLD METHODS AND NEW.

An observatory, like any other laboratory of research, may concentrate its attention upon either one of two widely different objects: the accumulation of great stores of data in existing departments of knowledge, or the opening up and exploration of new fields of investigation. In both cases extensive series of routine observations are required, but the point of view and the mode of attack are essentially different. In known fields, long since efficiently occupied, standard methods of observation and instruments obtainable from skilled makers are available for use. With the aid of such instruments and methods, perhaps modified and perfected in various details, observations of great precision and importance can be obtained. Moreover, by the preparation of a suitable scheme, well exemplified in Kapteyn's work on the structure of the universe, these observations can be made to serve, not merely for the tabulation of accurate data, but for the solution of the greatest problems of astronomy.

Results of the highest importance are therefore within the reach of the investigator equipped with standard instruments. His studies may develop new points of view or new data which will lead into new fields of research, but his position and needs are very different from those of the man whose researches force him to leave the familiar path. Discarding, perhaps, the instruments which have proved their strength and weakness by many years of use, he replaces them with others possessing new advantages and defects. In departing from accepted standards and in preparing to overcome difficulties, the initiator of new methods almost necessarily becomes an instrument-maker, and hence a machine-shop may be his first requirement. He can not afford to intrust construction to instrument-makers thousands of miles away, with whom he is unable to discuss details of the design, necessarily subject to frequent modification in the light of newly acquired ideas. To be most efficient, he must be his own designer and builder, ready to take immediate advantage of those new points of view and new possibilities of attack which his investigations are certain to disclose.

A laboratory or observatory like that of Mount Wilson, planned for the exploration of unfamiliar fields, can thus possess no fixed and standard equipment. Its mode of attack and its means of progress must grow with its work and develop with the disclosure of new and unexpected possibilities.

ADVANTAGES OF A MOUNTAIN SITE.

It was Newton who first pointed out the importance of making astronomical observations from a mountain top: "For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd stars. . . . The only remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds." (*Opticks*, third edition, p. 98.)

But height is not the only essential; indeed, very great altitudes are to be avoided. The summit of the Rocky Mountains is a notoriously bad place for astronomical work, because of the unstable atmospheric conditions and the frequent storms. Long periods of unbroken weather, free from rain and with little cloud, are associated with that tranquillity and steadiness of the atmosphere which Newton so much desired. These are to be found on the mountains of the Sierra Madre range, in the semi-tropical climate of Southern California. Mount Wilson, selected by Hussey after many tests of other elevated points in the northern and southern hemispheres, was accordingly chosen as the observation station. Rising abruptly from the San Gabriel Valley to a height of nearly 6,000 feet, and lying some 30 miles from the Pacific Ocean, it offered more advantages than any other site known. One of these was the possibility of establishing the shops, laboratories, and offices in the city of Pasadena, within easy reach of large foundries, supply houses, sources of electric light and power, and other facilities demanded by the nature of the work. Throughout the dry season, day after day is clear and tranquil and the wind velocity is remarkably low. The broad and diversified mountain summit, protected from the sun's heat by spruces, pines, and undergrowth, affords numerous locations perfectly adapted for the various instruments; the water-supply is abundant, and the completion of the mountain road makes the distance to the Pasadena office only 16 miles, covered in $2\frac{1}{4}$ hours (ascending) by auto-stage.

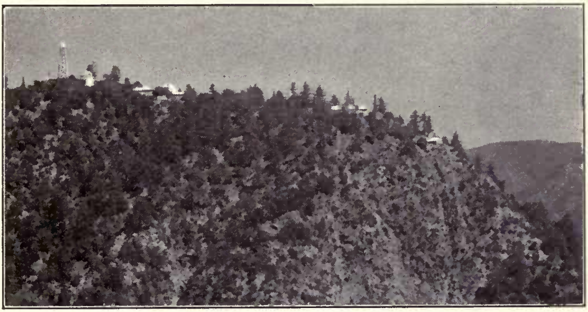


FIG. 2.—Mount Wilson from Mount Harvard.

But the scheme of research is the prime consideration. Let us suppose, as in the case of the Mount Wilson Observatory, that the chief object is to contribute, in the highest degree possible, to the solution of the problem of stellar evolution. What was the origin of this earth on which we live? We know that it is a member of a solar system, one of several planets moving harmoniously about a great central sun, on which they depend for light and heat. But how was the earth formed? Through what successive stages did it pass in its early life? How were its constituent parts separated from that great vaporous mass which, as most astronomers believe, once united the planets and the sun? By what process, extending over millions of years, have the intensely hot solar gases condensed toward a center, leaving behind those rotating and revolving spheres, the planets and their satellites? Or must this Laplacian view give

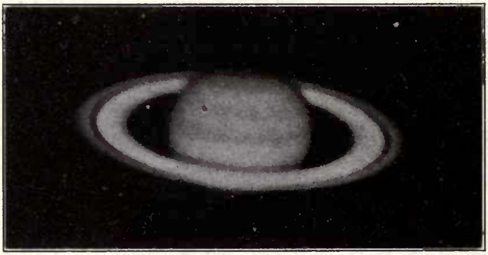


FIG. 3.—Saturn.

way to the radically different conceptions of the planetesimal hypothesis? What is the nature of the central sun, on which our lives depend? What is its relationship to other stars, and what part does it play in the universe? How is this universe organized, what bodies does it comprise, what is its structure, and what are its bounds? If the processes of creation and evolution are still at work within it, may we not expect to find existing examples of the various stages through which our own solar system has passed? And may we not hope, by learning the relationship of stars in moving groups, and by tracing these groups back to their former positions in space, to reconstruct a picture of the universe as it was long before the solar system had taken form?

Fig. 4.—Nebula N. G. C. 7217.

A large project, it may be said, too ambitious for the ideal of any institution. But while no single observatory may hope to cover the ground completely, it may reasonably expect to contribute toward the solution of the problem and thus to aid in attaining a clearer comprehension of that great process of evolution which has produced the earth and its inhabitants. It is evident, from the nature of the case, that the plan of attack must be broad and elastic, utilizing a variety of powerful methods toward a common end. But in the presence of innumerable interesting objects for study, there is danger of a scattering of effort and a mere multiplication of observations. Every possible astronomical observation might have a bearing on our problem and thus seem to justify its making; but unless it were made as an element in some general plan, an indefinite amount of energy might be spent without avail. A common scheme should tie together many diverse investigations, multiplying the intrinsic importance of each because of its bearing on all the others.

THE SUN.

Let us begin with the sun. Its prime interest and importance, as the source of the light and heat on which we all depend, would be sufficient reason for its special consideration. But equally significant is the fact that the sun is the only one of all the stars which lies near enough to the earth to be studied in detail; each of the others is reduced by distance to an infinitesimal point of light, which the most powerful of telescopes can not magnify into an appreciable disk. We may safely infer, from many observations of recent years, that thousands of the stars are almost identical in character with the sun, though some are much larger or smaller and some are in earlier or later stages of development. But if we wish to know what a star really is we must approach it closely, and this is possible only in the case of the sun. Indeed, because the sun was regarded as so important, offering so many opportunities to increase our knowledge of its nature, the observatory was conceived primarily

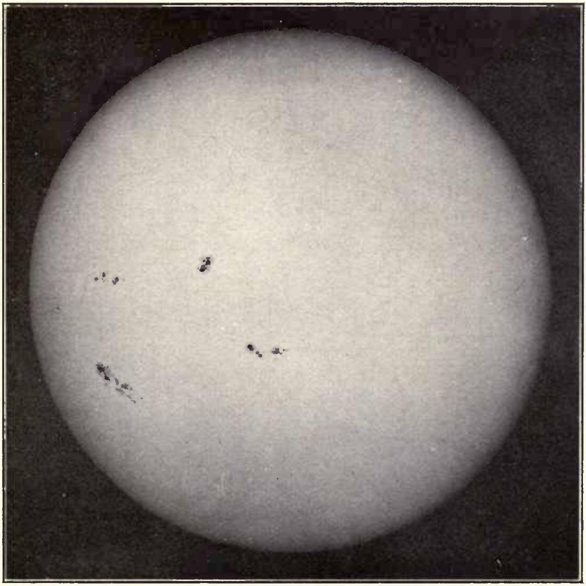


FIG. 5.—Direct photograph of the Sun.

for solar research. But the necessity for seeking, among the stars and nebulæ, for evidence as to the past and future stages of solar and stellar life, rendered a broadening of scope advisable from the outset. Much attention is therefore devoted to the sun as the chief among the stars, but the essential means of attacking the more distant objects of the universe have also been provided.

AUXILIARIES OF THE TELESCOPE.

Ten years ago the possibilities of the spectroheliograph, as a means of increasing our knowledge of the invisible atmosphere of the sun, had become apparent. This instrument, which was clearly susceptible of further improvement and development, was accordingly chosen as one of our chief auxiliaries for the study of the sun. Of still wider range of application was the solar spectroscope, previously used almost exclusively as a visual instrument of small dimensions attached to a moving telescope tube. Rowland had invented

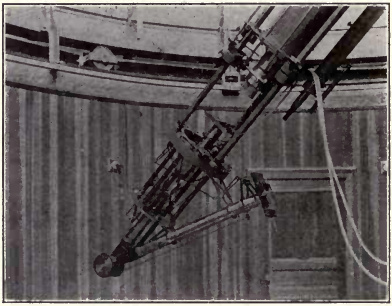


FIG. 6.—The Kenwood Spectroheliograph.

the concave grating, and used it for his epoch-making photographic studies of laboratory spectra and the spectrum of sunlight. But his solar image was small and unsteady and there remained a most promising opportunity to apply a powerful photographic spectroscope to the investigation of sun-spots, the chromosphere, and other details of a large solar image. Solar spectroscopy was far behind laboratory spectroscopy and new types of instruments were clearly demanded. It was evident that for efficient use in photography the spectroscope of the day must be greatly lengthened, thus making it too long to serve as an attachment to a moving telescope. Accordingly it became necessary to develop a suitable form of fixed telescope, capable of forming a large and sharply defined image of the sun on the slit of a long fixed spectrograph.

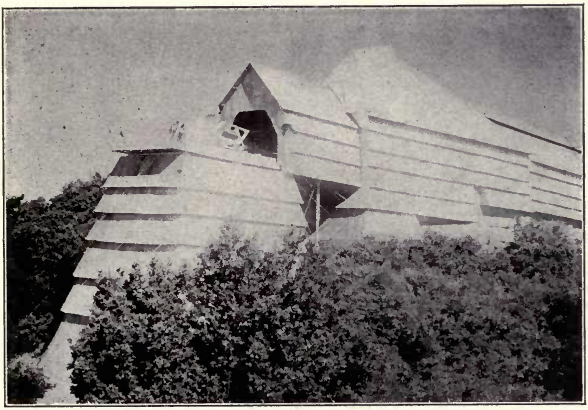


FIG. 7.—The Snow Telescope.

A step in this direction was the horizontal telescope, which the late Miss Snow had presented to the Yerkes Observatory through the kind interest and assistance of Dr. George S. Isham. It consists of a cœlostat, with a plane mirror 30 inches in diameter, rotated by clockwork at such a rate as to keep the beam of sunlight, reflected from its silvered (front) surface, in a fixed position on a second plane mirror standing above and south of it. From this mirror the beam is reflected nearly horizontally to a point 100 feet north, where it falls on a 24-inch concave mirror of 60 feet focal length, which forms a solar image about 6½ inches

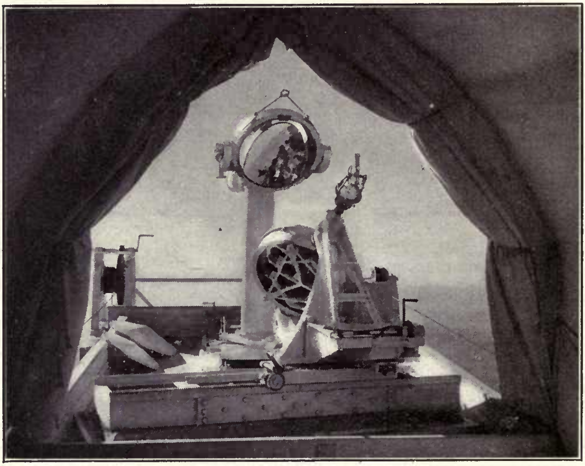


FIG. 8.—Cœlostat and second mirror of Snow Telescope.

in diameter on the slit of the spectrograph or spectroheliograph.

Loaned by the University of Chicago, and set up on Mount Wilson at a time when the Solar Observatory was at work as an expedition from the Yerkes Observatory, the Snow telescope was found to have advantages and defects characteristic of a new instrument. Currents of warm air, rising from the hot soil of the mountain summit and carried across the entering beam of light, decreased the sharpness of the image during the hotter hours of the day. The sun's direct rays warped the telescope mirrors, changing the focus and blurring the details of the image after a few minutes of exposure. But the worst of these difficulties were soon overcome by observing in the early morning or late afternoon, shielding the mirrors from the sun between exposures and cooling them with blasts from electric fans. Thus controlled, the Snow telescope yielded excellent photographs of the solar atmosphere and justified the hopes we had entertained of its performance.

WHAT IS A SUN-SPOT?

Sun-spots, though known and studied for 300 years, offered most promising opportunities for research. Evidently there was much to be learned from an investigation of their spectra, which had never been attempted with adequate instrumental means. To produce these spectra, the light of a sun-spot was passed through a narrow slit, and thence to a lens of 18 feet focal length, which rendered the rays parallel; they then met a grating of polished metal, ruled with some 15,000 lines to the inch; this analyzed the composite light into its constituent parts and returned the rays through the lens, which formed an image of the long spectrum band on a photographic plate below the slit.

With this spectrograph, constructed in our shop in Pasadena and mounted for use with the Snow telescope, it soon became an easy matter to photograph sun-spot spectra. The curious widened lines, the much debated bands, and the strengthened and weakened lines were thus accurately recorded for study. What is the cause of these peculiarities? The first step was to test by laboratory experiments the hypothesis that some of them are due to reduced temperature of the spot vapors. In studying such phenomena the spectroscopist is in a position much like that of an

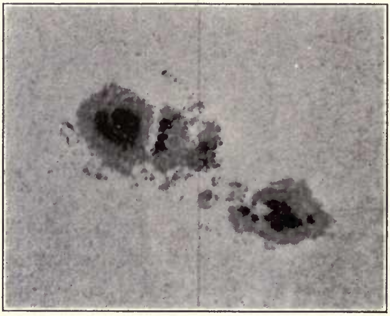


Fig. 9.—Direct photograph of Sun-spot.

archeologist endeavoring to translate an unknown language. A bilingual inscription, containing an expression of the same fact in both celestial and terrestrial characters, is what he requires, and this a suitably equipped physical laboratory is often capable of supplying.

In the solar spectrum we can photograph about 20,000 lines, distributed irregularly from the red to the violet, and throughout the invisible regions beyond. Perhaps some of these are due to iron.

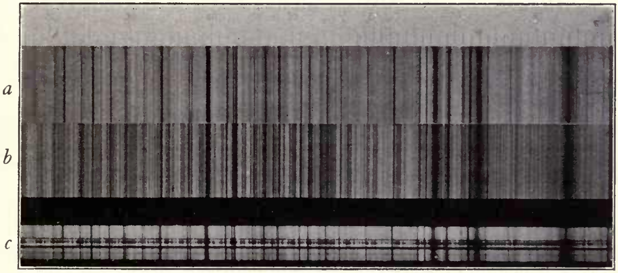


Fig. 10.—Sun-spot Spectrum. *a* Solar and *b* Spot Spectrum widened; *c* from original negative, Spot Spectrum in middle.

To settle this it is only necessary to vaporize some iron between the poles of an electric arc and photograph its spectrum beside that of the sun (Fig. 11). Some 2,000 solar lines are found to coincide in position with lines of iron. As these lines are given only by iron, we may conclude at once that this element exists in the solar atmosphere.

So much for the chemical identification of lines. We may next interpret their peculiarities. In the case of sun-spots we suspected that certain changes in the relative intensities of the lines were due to a reduced temperature of the spot vapors. To test this, the spectrum of iron vapor in an electric arc was photographed at different temperatures. Some of the lines were found to strengthen, others to weaken relatively, as the temperature was reduced. When compared with the iron lines in sun-spots the changes were seen to be of the same kind. The same test, applied to the vapors of chromium, nickel, manganese, titanium, and other metallic elements, previously identified in spots,

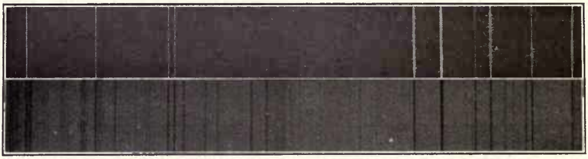


FIG. 11.—Iron (above) and Solar Spectrum (below).

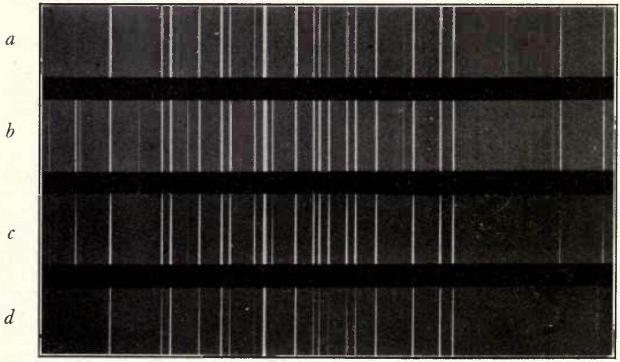


FIG. 12.—Effect of temperature on Spectrum of Vanadium: *a* In Carbon Arc; *b*, *c*, and *d* in Electric Furnace at temperatures of 2600°, 2350°, and 2150° C., respectively.

gave the same result. It thus became clear that sun-spots actually are regions of reduced temperature in the solar atmosphere.

The next step bore out this conclusion. If the solar vapors are cooler in spots than in the general atmosphere of the sun, then it may be possible for some of them to unite chemically. Thousands of faint lines in the spot spectra were measured and identified as band lines due to chemical compounds. Fowler, who had also worked with success on the strengthened and weakened lines, found magnesium hydride. Titanium oxide and calcium hydride were identified in our laboratory. Thus we began to form a new picture of these regions of the solar atmosphere and to recognize the chemical changes at work in the spot vapors.

SOLAR METEOROLOGY.

Meanwhile systematic work was in progress with the spectroheliograph, which gives images of the sun in monochromatic light, showing the distribution of some one vapor in its atmosphere. In the favorable California climate it is possible to photograph the sun on about 300 days of the year (in one season on 113 successive days). Every clear morning, and frequently in the afternoon, the instrument was at work, making pictures of the great gaseous clouds in the solar atmosphere. These were first observed many years ago as solar prominences, rising high above the sun's limb at total eclipses, when the bright light of the disk was cut off by the moon. The spectroheliograph not only permits the prominences to be photographed on any clear day, but discloses extensive clouds of calcium, hydrogen, iron, and other vapors, which do not rise high enough to be observed in elevation at the limb, but are recorded (as flocculi) in projection against the bright disk. To the eye at the telescope, or in direct photographs of the ordinary kind, these flocculi are wholly invisible. The spectroheliograph brings them to view by excluding from the photographic plate all light except that due to calcium or hydrogen, as the case may be.

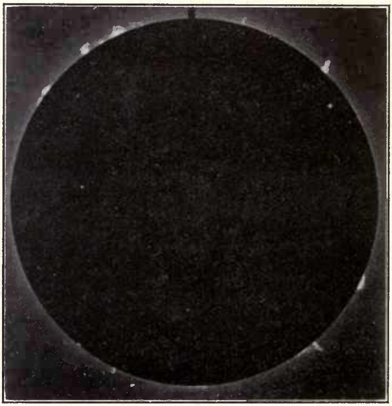


Fig. 13.—The Chromosphere photographed without an Eclipse.

The measurement of these plates with the heliomicrometer (Fig. 55), an instrument devised and constructed in our instrument-shop, gave directly the latitudes and longitudes of the flocculi, without the extensive computations required when the ordinary type of measuring machine is used. Their change of position from day to day yielded a new determination of the law of the solar rotation, which was found to differ at the calcium and hydrogen levels. At the lower level of the calcium flocculi the period of rotation at the sun's equator is 24.8 days, increasing gradually to 26.8 days at 45° latitude. In other words, the gaseous sun does not rotate like the solid earth, on which points in all latitudes complete a rotation in 24 hours. It turns more and more slowly as the poles are approached, points in high latitudes lagging behind those nearer the equator. If this could happen on the earth, Jacksonville, which is almost due south of Cleveland, would be far to the east of it 24 hours hence. In the higher levels of the solar

FIG. 14.—Solar Prominence 80,000 miles high.

atmosphere, where the hydrogen flocculi float, the period of rotation for any latitude is less than for the levels below, but the difference in rotation time between pole and equator is less marked than in the lower atmosphere.

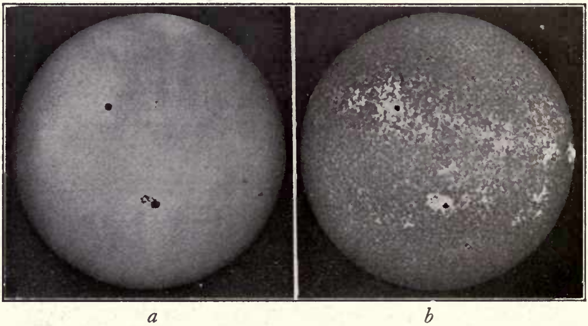


FIG. 15.—*a*, Direct photograph of Sun, August 31, 1906; *b*. Calcium (H_2) Flocculi at same hour.

SOLAR AND STELLAR SPECTROSCOPY.

Since the flocculi are constantly changing in form, they are not very satisfactory objects for rotation measurements. Much more accurate results can be obtained by measuring, with a powerful spectrograph, the velocity of approach and recession of the east and west edges of the sun. The east edge is moving toward the earth on account of the sun's rotation; this causes a displacement of the spectrum lines toward the violet (Fig.16). At the west edge, which is moving away, the lines are equally displaced toward the red. The double displacement, measured at different latitudes, gives the velocity of approach and recession in kilometers per second. An investigation of this kind threw much new light on the peculiar law of the solar rotation, giving with high precision the rotation period at different levels and the change in its value from equator to pole.

The Snow telescope thus proved its usefulness for a wide variety of observations, most of which we could not have made with moving telescopes of the standard type. In addition to the work already mentioned, the 18-foot spectrograph yielded excellent photographs of spectra of various parts of the solar disk, revealing numerous peculiarities in the spectrum near the edge of the sun. Although not designed for stellar work, the Snow telescope also permitted photographs of the spectrum of Arcturus to be taken with a powerful grating spectrograph. When compared with the spectra of sun-spots, the relative intensities of the lines were found to be similar, indicating that Arcturus is cooler than the sun, a fact of importance in its bearing on the question of stellar evolution.

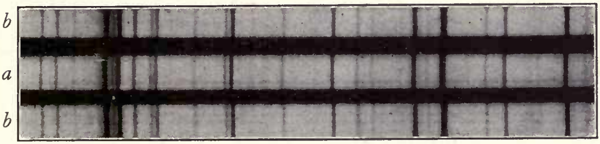


FIG. 16.—Spectra of east (*a*) and west (*b*) edges of Sun, showing displacement caused by solar rotation.

THE 60-FOOT TOWER TELESCOPE.

But the Snow telescope was not free from limitations. During long exposures its mirrors were seriously distorted by the sun's heat and the effect of heated air from the earth was plainly shown by a blurring of the solar image. To obviate or reduce these difficulties the vertical or tower telescope was devised, and constructed in an inexpensive form. After reflection from two plane mirrors at the summit, the sun's rays pass through a 12-inch objective of 60 feet focal length, which forms an image of the sun on the slit of the spectrograph in the observing-room at the foot of the tower. The

FIG. 17.—60-foot Tower Telescope.

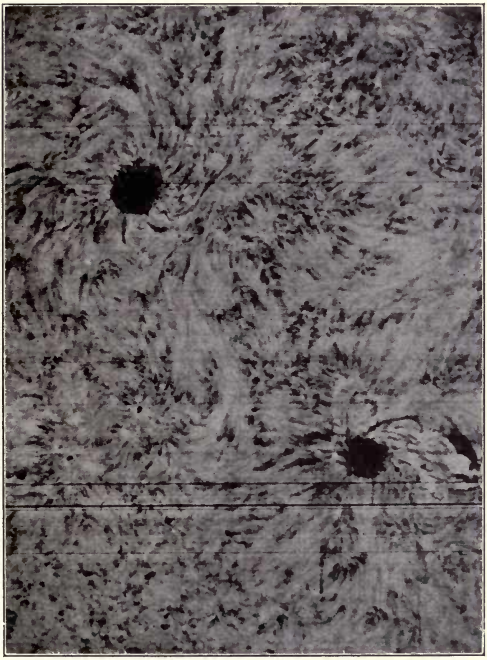
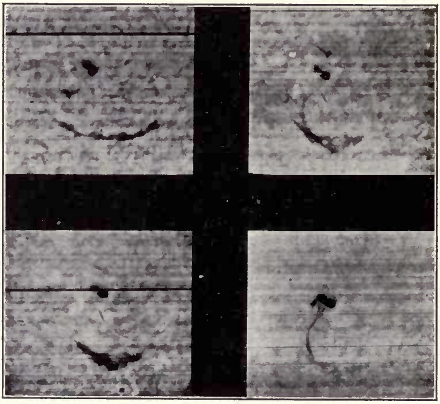


Fig. 18.—Hydrogen Flocculi surrounding Sun-spots, showing right- and left-handed Vortices, September 9, 1908.

mirrors, much thicker than those of the Snow telescope, are but little affected by the sun's heat. Elevated 60 feet in the air, they also escape some of the warm currents rising from the hot soil. The results are a decided improvement in the sharpness of the image and a prolongation of the period during which good observations are possible. Another advantage, quite as important, follows from the use of an underground chamber to contain the spectrograph, now increased in length from 18 to 30 feet. The gain resulting from its greater stability and from the constancy of temperature of the grating at the bottom of the well was plainly apparent in the new photographs of spot spectra, which brought out details previously unrecognized.

SOLAR VORTICES AND MAGNETIC FIELDS.

The development of the spectroheliograph had also advanced another step. The dark hydrogen flocculi, first photographed at the Yerkes Observatory in 1903, had hitherto been recorded only with the blue hydrogen lines. In 1908 the new red-sensitive plates of Wallace, applied to the photography of the sun's disk with the red ($H\alpha$) line of hydrogen, gave results of great interest. In the


June 2 $6^h\,10^m$ A.M.

June 3 $5^h\,14^m$ P.M.

June 3 $4^h\,58^m$ P.M.

June 3 $5^h\,22^m$ P.M.

FIG. 19.—Hydrogen Flocculus sucked into Sun-spot, June 3, 1908.

higher part of the hydrogen atmosphere, thus revealed in projection against the disk, immense vortices were found surrounding sun-spots (Fig. 18). This led to the hypothesis that a sun-spot is a solar storm, resembling a terrestrial tornado, in which the hot vapors, whirling at high velocity, are cooled by expansion, thus accounting for the observed intensity changes of the spectrum lines and the presence of chemical compounds.

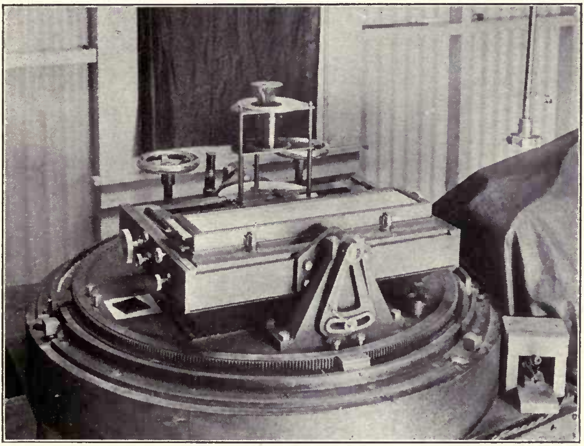


Fig. 20.—30-foot Spectrograph, with Polarizing Apparatus above Slit.

But the observed widening of many spot lines and the doubling or trebling of some of them remained inexplicable until the vortex hypothesis suggested an explanation. Thomson and others had shown that electrons are emitted by hot bodies; hence they must be present in great numbers in the sun. If positive or negative electrons were caught and whirled in a vortex they would produce a magnetic field, such as we obtain by passing an electric current through a coil of wire. Zeeman had discovered in 1896 that the lines in the spectrum of a luminous vapor in a magnetic field are widened or (if the field is strong enough) split into several components (Fig. 21). Moreover, the light of these components is polarized in so characteristic a way that there can be no uncertainty in identifying the effect. Could this be the condition of things in sun-spots?

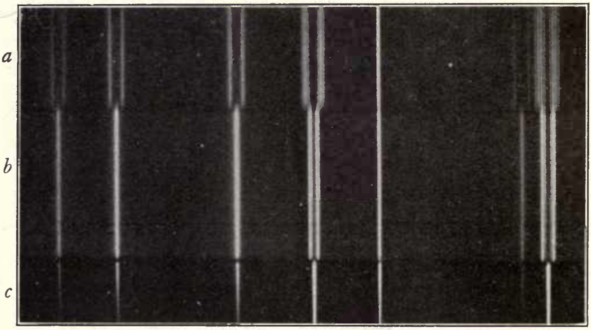


Fig. 21.—Effect of Magnetic Field upon Lines of Iron Spectrum. In *a* the middle component and in *b* the outer components are cut out by a Nicol Prism; *c*, Spectrum without Magnetic Field.

The 30-foot spectrograph of the tower telescope permitted the test to be made at once. The characteristic polarization phenomena appeared and one by one all of the distinctive peculiarities of the Zeeman effect were made out. Thus direct evidence, open to only one interpretation, proved the existence of magnetic fields in sun-spots, and strengthened the view that these are caused by electric vortices. This conclusion, in common with many others regarding the nature of sun-spots, could not have been obtained without the aid of the physical laboratory.

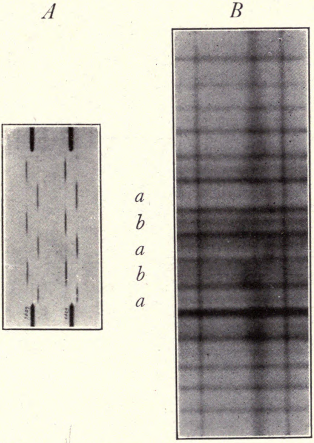


FIG. 22.—Effect of Nicol and Compound Quarter-wave Plate upon (*A*) Lines of Spark in Magnetic Field and (*B*) Solar Line in Spectrum of Sun-spot. *a* Red Components; *b* Violet Components; middle line of Triplet shows in *B* but not in *A*.

Let us see how the effect of magnetism on light is studied. We place our iron arc or spark between the poles of a powerful magnet (Fig. 29) and photograph its spectrum. The lines behave in the most diverse way, some splitting into triplets, others into quadruplets, quintuplets, sextuplets, etc. One chromium line is resolved by the magnet into 21 components. If a magnetic field is really at work in sun-spots we should anticipate a close correspondence between the behavior of each solar line and its laboratory equivalent. And this is exactly what we find (Fig. 22). Furthermore, the distance between the components of a line is directly proportional to the strength of the magnetic field. Thus, by determining the separation corresponding to a magnetic field whose strength can be measured in the laboratory, we may easily derive the strength of the field in sun-spots.

Fig. 23.—Waterspout off the Coast of Sicily.

SUN-SPOTS AND FLOCCULI.

We can not enter here into the various applications of this conclusion to the explanation of solar phenomena. If we could see a single sun-spot from a point beneath the solar surface, it would probably resemble a terrestrial water-spout or tornado, though its cross-section, instead of being a few hundred feet, would be hundreds of miles. The strength of the magnetic field produced, which is measured by the degree of separation of the triple lines, increases with the diameter of the spot. The field is strongest near the center of the spot, where the lines of the triplet are most widely separated, and decreases to very low intensity at points just outside the edge of the penumbra. The spectrograph, when equipped with suitable polarizing apparatus, serves as an extraordinarily delicate means of measuring these fields, which can be observed in regions where they are not much more intense than the magnetic field of the earth. In this way it became possible, as described below (p. 43), to detect the comparatively weak magnetic field of the entire sun.

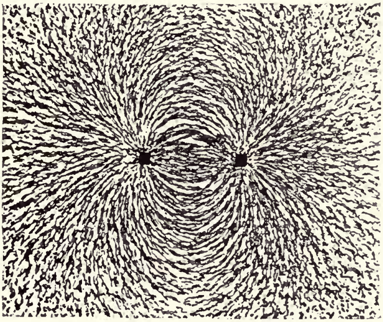


Fig. 24.—Lines of Force about + and − Poles of a Magnet.

It has long been known that sun-spots usually occur in pairs, and our study of the Zeeman effect indicates that the two principal spots in such a group are almost invariably of opposite polarity. The natural inference is that we are here dealing with a semi-circular vortex (like half a smoke ring) the two ends of which, coming to the sun's surface from below, appear to whirl in opposite directions. But this hypothesis is still under investigation. Störmer of Christiania has developed for us the mathematical theory of the motions in the solar atmosphere of vapors within the influence of such magnetic fields, with results of great interest.

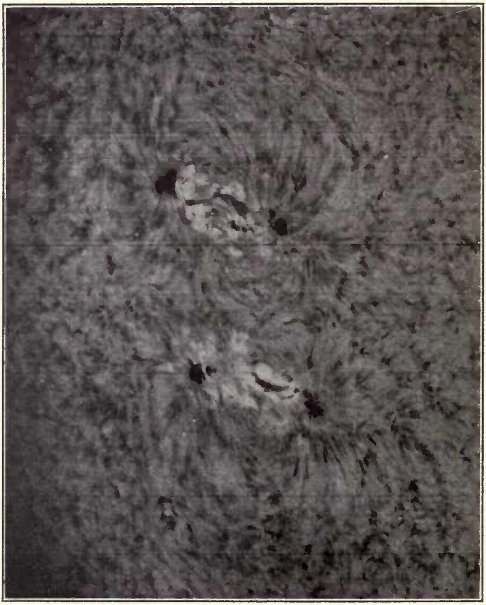


FIG. 25.—Two Bipolar Sun-spot Groups.

The illustration (Fig. 25) shows that the hydrogen flocculi about a bipolar spot-group resemble the lines of force between two magnets of opposite polarity (Fig. 24). But similar structure might be produced by the direct hydrodynamical influence of the spot vortices upon the solar atmosphere above them, and it is still a question whether this or the electromagnetic influence is predominant.

The existence of electric vortices in sun-spots is indirectly shown by the presence of the magnetic fields, which presumably could not be produced in the sun by any other means. But direct proof of the existence of these vortices was subsequently found by Evershed, of Kodaikanal, who measured the outflow of gases close to the solar surface and their inflow at higher levels. This work has been repeated and extended on Mount Wilson with highly significant results, affording not only an accurate picture of the conditions existing above a sun-spot, but also the means of assigning to each line of the solar spectrum a definite level in the sun's atmosphere.

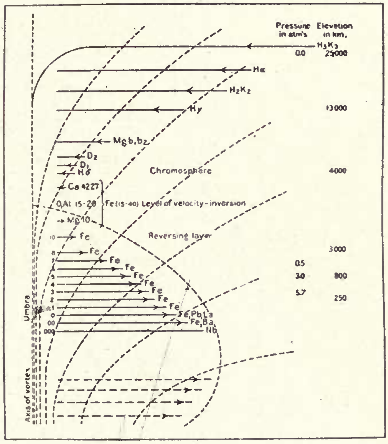


FIG. 26.—Inflow at High Levels and Outflow at Low Levels above Spots.

WORK OF THE PASADENA LABORATORY.

The value of laboratory work in the interpretation of solar phenomena has already been illustrated. Magnetic fields are detected by the splitting and polarization of spectrum lines, differences of temperature by changes in their relative intensities, differences of pressure by shifts in their positions, etc. By producing such effects artificially, with the aid of powerful electric furnaces, pressure pumps, and other physical instruments, we can imitate a great variety of celestial phenomena and interpret complex and obscure peculiarities. It is thus plainly apparent that a physical laboratory is a necessary adjunct of an astrophysical observatory. Our experience has shown

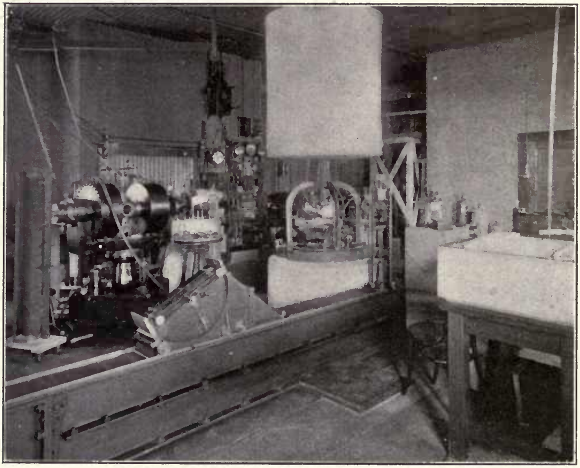


FIG. 27.—Pasadena Laboratory.

that the literature of spectroscopy almost never contains the information we require. The only way to obtain sufficient data is to produce them ourselves, under conditions within our own control and adapted to meet the manifold requirements of the observed astronomical phenomena. Moreover, the performace of a few experiments never suffices. It becomes necessary, not only to imitate an effect for a given line, or for a limited region of the spectrum, but to extend the observations over the whole range of spectrum available.

It is easy to see that heavy tasks devolve upon our laboratory staff, both in observing and in the extensive work of measurement and reduction. It is a comparatively simple matter to show that a change of furnace temperature will modify the relative intensities of certain lines; but to measure the changes for the thousands of lines of iron, chromium, nickel, vanadium, and many other elements recognized in celestial objects is a task requiring years of continuous work. So with all of the other effects of pressure, magnetic field, change of potential of the electric discharge, etc. It is evident why the simple beginnings of this laboratory on Mount Wilson have led to larger developments in Pasadena, where heavy electric currents and other facilities are available.

The intrinsic value of the laboratory results, as distinguished from their usefulness for the interpretation of astronomical observations, should not be overlooked. Each investigation is equally applicable to the interpretation of fundamental problems of physics, particularly those concerned with the nature of radiation. The changes of intensity of spectrum lines produced by raising and lowering the temperature of the electric furnace help to indicate how the shock of molecular collisions may influence the motions of the electrons within the atom. The phenomena of the "tube arc" throw new light on radiation processes hitherto associated mainly with high electric potentials. The complex phenomena of the Zeeman effect (as revealed in a comparative study, with powerful spectrographs and an intense magnetic field, of the lines of a long list of elements) furnish material available for wide generalizations, important in their bearing on theories of radiation and atomic structure. Thus the maintenance of this laboratory would be highly advantageous from the standpoint of the physicist, even if it had no

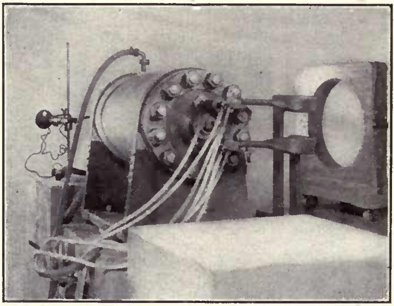


Fig. 28.—Electric Furnace.

connection with the Observatory. The doubled efficiency resulting from the combination of the two is of the same character as that which follows from the joint prosecution of the solar and stellar work.

PRESSURES AND MOTIONS IN THE SOLAR ATMOSPHERE.

I have mentioned the displacement of lines by pressure as a laboratory problem. The application of the results to the interpretation of line displacements observed in various parts of the solar atmosphere has yielded much new information. If the vapors in question are moving toward or away from the observer, displacements due to motion must be distinguished from those caused by pressure; this can be done with certainty by

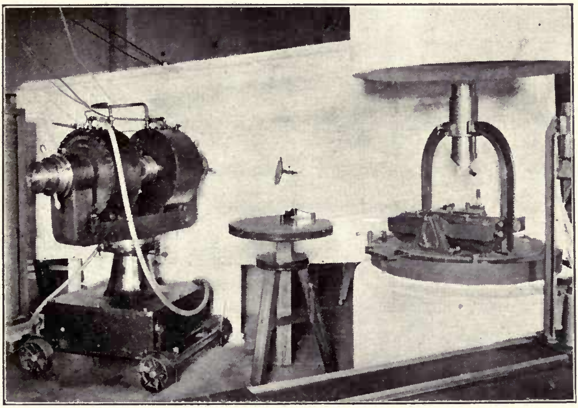


Fig. 29.—Magnet for Zeeman Effect.

using the laboratory data, some lines being shifted by pressure to the red and others to the violet. It is found that some of the solar gases are rising, while others are falling. The pressure at different heights is then determined, and found to range from about an atmosphere close to the solar surface to exceedingly low values, such as we know in vacuum tubes, at elevations of several thousand miles. The delicacy of this method is illustrated by the fact that the spectrographs on Mount Wilson and in Pasadena show a distinct difference in the position of certain lines in the electric-arc spectrum, caused by the difference in atmospheric pressure between mountain and valley. Thus we are enabled to sound the solar atmosphere through all its depths and to learn of its phenomena at different levels. The same method, when applied to stars, has given us a preliminary determination of the pressure in stellar atmospheres.

THE "FLASH" SPECTRUM WITHOUT AN ECLIPSE.

In designing the first tower telescope, one of the objects in view was to provide a means of photographing the "flash" spectrum without the aid of a total eclipse. When the moon passes between the earth and the sun it cuts off the brilliant light of the solar disk and permits the spectrum of its gaseous atmosphere to be photographed. The narrow arc of light, coming from this luminous atmosphere at the moment when the sun's disk is completely covered by the dark body of the moon, is passed through a prism, and the resulting series of bright lines is recorded upon a sensitive plate. But the study of this "flash" spectrum has been seriously hampered by its momentary visibility, occurring only at intervals of years. With the 60-foot tower telescope the numerous bright lines of the "flash" can be photographed on any day of good definition, with a spectrograph more powerful than those used in eclipse observations. In this way we not only get a marked increase in the accuracy of measuring these lines and their displacements, but we also find it possible to study the phenomena of levels lower than are attainable at eclipses. Some remarkable modifications of the dark-line solar spectrum at the sun's limb have also been found on these photographs.

THE 150-FOOT TOWER TELESCOPE.

The success of the first tower telescope indicated that the construction of a more powerful instrument, giving a larger image of the sun (16 inches in diameter), would be fully warranted. To secure the necessary steadiness of mirrors and lenses mounted 160 feet above the ground, the plan was adopted of incasing each steel member (leg or cross-bracing) of a skeleton tower within the corresponding hollow member of another skeleton tower, with sufficient clearance to prevent contact. The inner tower thus carries the instruments; the outer tower carries the dome to cover them, while its members serve as an efficient

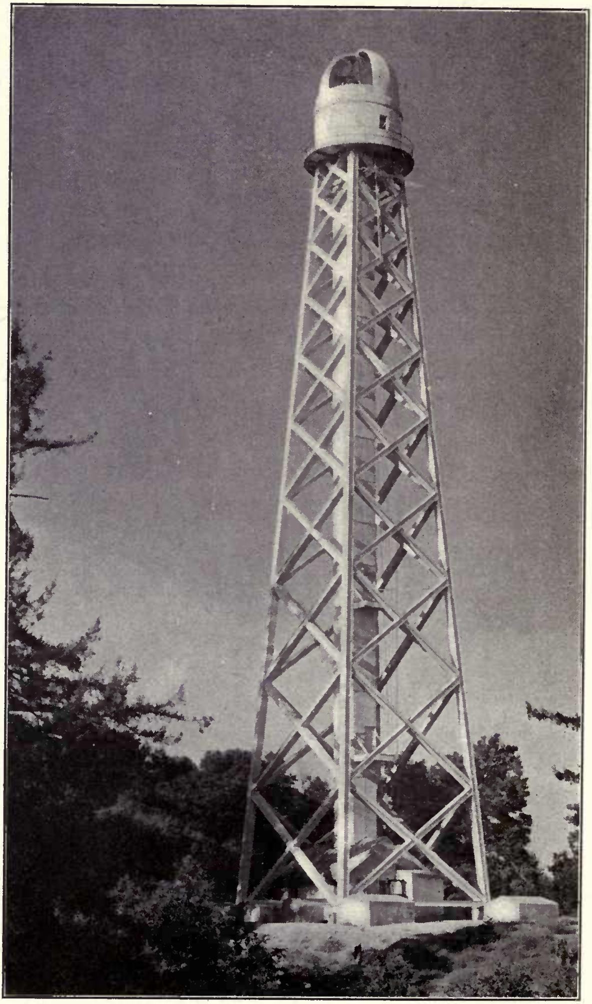


FIG. 30.—150-foot Tower Telescope.

wind-shield. Thus the requisite steadiness has been secured, in spite of the great height of the structure. In other respects the new tower is also a decided improvement, adding still further to the sharpness of the solar image during the warmer hours and thus increasing the duration of the period of observation, which with this telescope lasts throughout the day. The opening up of the various new fields of solar research taxes the capacity of all three telescopes, each of which is devoted to the work for which it is best adapted.

A feature of the new tower telescope, which is quite as important as the enlarged solar image, is the spectrograph, now extended to a focal length of 75 feet and mounted in a deep well

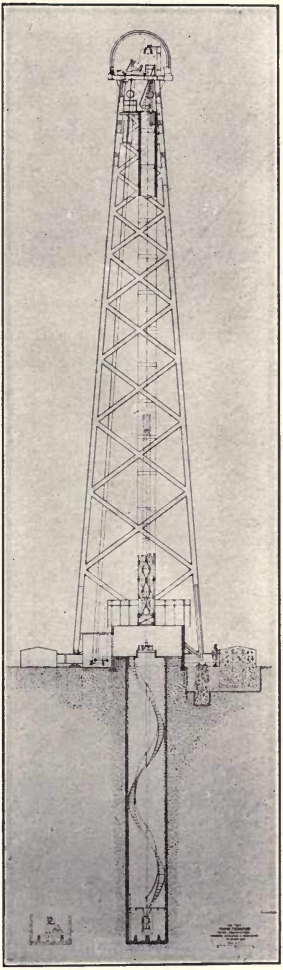


Fig. 31.—Section of 150-foot Tower Telescope.

beneath the tower. With this powerful instrument the D lines of sodium, which are barely separated with the standard one-prism spectroscope of the chemist, are about 1.2 inches apart in the third-order spectrum. A photograph of the solar spectrum on this scale, including the ultra-violet but excluding the infra-red, would be 70 feet long. With the aid of Koch's recording microphotometer, the gain in precision of measurement is directly proportional to the length of the spectrograph. Thus, as compared with the 3.5 foot Kenwood spectro-

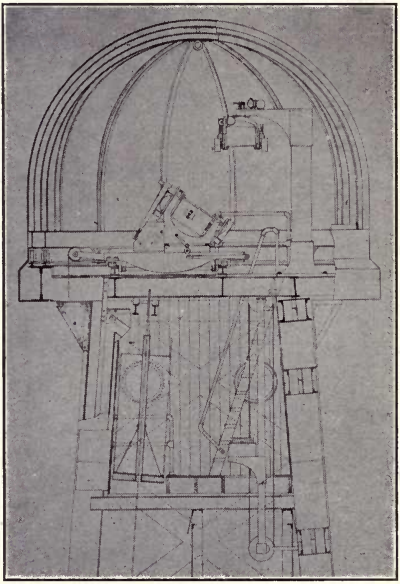


FIG. 32.—Summit of 150-foot Tower Telescope.

graph, of which it is the direct successor, the 75-foot spectrograph gives results fully 20 times as accurate.

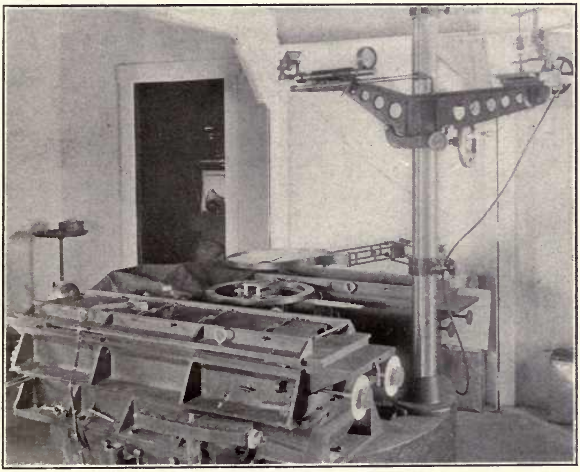


Fig. 33.—Observing Room and 75-foot Spectrograph.

THE SUN AS A MAGNET.

What this means in practice is illustrated by a recent investigation. As already explained, many of the spectrum lines are split into two or more components by a magnetic field. A Nicol prism and quarter-wave mica plate, placed over the slit of the spectrograph, permit us in the laboratory to cut off either component at will. The use of a compound quarter-wave plate, made of narrow strips, gives the serrated appearance of the lines shown in Fig. 22. If the lines in the solar spectrum are similarly affected, and if the degree of their displacement varies from pole to equator as calculation shows it should do on a magnetized sphere, we may conclude that the whole sun is a magnet. An extended investigation (rendered difficult by the very minute displacements of the solar lines, far too small to appear to the eye in the photographs) has led us to the conclusion that the sun is a magnet, with its poles lying at or near the poles of rotation.

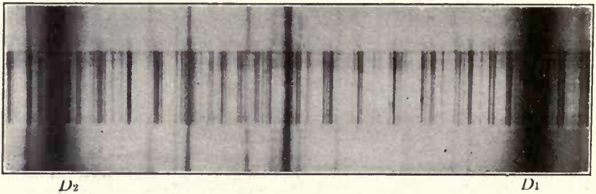


FIG. 34.—D Lines of Solar Spectrum, with Iodine Absorption Spectrum superposed.

The sun in this respect resembles the earth, which has long been known to be a magnet. The general magnetic field of the sun, although about 80 times as intense as that of the earth, is so weak compared with the magnetic fields in sun-spots that the full power of the 75-foot spectrograph was required to reveal it. As the sun rotates on its axis, it permits the magnetic phenomena of all parts of its surface to be studied. Photographs of the spectra over a wide range of latitude are therefore made daily, in order to provide material for charts which will show the exact position of the magnetic poles and the intensity of the field at different levels in the solar atmosphere.

Our interest in the sun's magnetism is not confined to the field of solar physics; its study should aid in explaining the source and fluctuations of the earth's magnetism and in the interpretation of certain stellar phenomena. It is not improbable, as Schuster has suggested, that every star, and perhaps every rotating body of whatever nature, becomes a magnet through the fact of its rotation. It is hoped that the 100-inch reflector will enable this test for magnetism to be applied to certain stars.

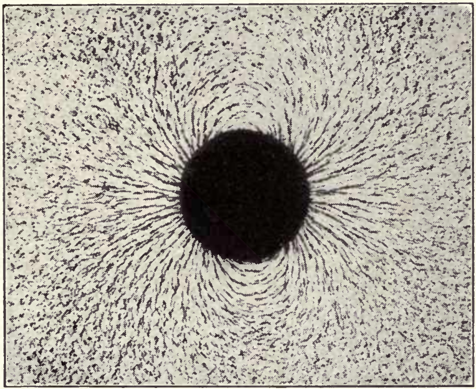


Fig. 35.—Lines of Force about a Magnetized Sphere.

It may be well to add that at the distance of the earth the solar magnetic field can not be directly appreciable, since the effect of one pole counteracts the equal and opposite effect of the other pole.

These examples will suffice to illustrate the character of the solar work in progress on Mount Wilson. Let us now consider for a moment the broader bearing of these results, each of which has a wide range of application. Thousands of stars, in the same stage of evolution as the sun, doubtless exhibit similar phenomena, which are hidden from us by distance. No possible increase in the power of our telescopes, so far as can be judged from present knowledge, will ever render star images comparable in size with the solar image. But the knowledge derived from the study of the sun prepares us to solve problems otherwise much more difficult. For example, the results of the work on sun-spot spectra, in harmony with other phenomena, render it safe to attribute to reduced temperature the bands and the weakened and strengthened lines in the spectra of Arcturus and other stars. This conclusion will assist in arranging the stars on a temperature basis, showing the gradual changes they have passed through in the different periods of their existence. Again, the peculiar behavior of certain lines in the sun has recently led to the detection of an interesting relationship between a star's spectrum and its absolute magnitude, which provides a new and very effective way of determining stellar distances and throws much new light on the evolution problem.

Fig. 36.—The Great Nebula in Andromeda.

We are thus prepared to appreciate the intimate relationship which unites all phases of the Observatory's work and determines its plan of operation. But how shall we enter the vast sphere of the sidereal world, where hundreds of millions of objects, exhibiting phenomena of inconceivable magnitude and infinite variety, vie with one another in their appeal to the observer and tend to scatter and exhaust his efforts? The simplest and most obvious step would be to make just such a study of the physical phenomena of selected stars, representing different phases of evolution, as we are now making of the sun. In spite of the necessity, because of their feeble brightness, of basing our conclusions on spectra a few inches long, representing the combined light from all parts of the stellar disks, material progress could be made in this way. But the importance of making the most effective use of our instrumental equipment and of accomplishing the greatest possible advance within a limited period of years led to the postponement of most of this work and the immediate adoption of a different plan.

THE STRUCTURE OF THE UNIVERSE.

A great Dutch astronomer, gifted with a powerful scientific imagination, had been engaged for many years in the study of the structure of the universe. The fact that he had no telescope or other observatory equipment did not hamper in the least his ambitions or his successes. On the contrary, it led to his coöperation with astronomers in various parts of the world, who gladly contributed toward the realization of his far-reaching projects. Kapteyn's first ally was the late Sir David Gill, Astronomer Royal at the Cape of Good Hope, who had photographed the whole of the southern heavens. After twelve years of patient labor in measuring the positions of 454,875 stars on these photographs, Kapteyn turned his attention to the study of stellar motions. He found, in brief, that all the stars whose motions were known belonged in one or the other of two great intersecting streams, which have been moving through space since time immemorial. Projected back into the positions which they occupied in the remote past, these stars represent two great systems, which drew toward one another, interpenetrated, and now continue toward their unknown goals.

This impressive result, with its strong appeal to imaginations curious as to the past or the future, was but a single step in Kapteyn's progress. His plans involved the study of great numbers of stars, uniformly distributed over the heavens and embracing questions of brightness, of distance, and of motion. Through the coöperation of many astronomers the necessary measurements to solve these questions will ultimately be obtained. But the great light-collecting power of our 60-inch reflector and the facilities provided for its use indicated that it might prove of special service in the realization of Kapteyn's hopes. Could this help be given without loss to our own enterprise?

STELLAR EVOLUTION.

For it will be observed that Kapteyn's project differed materially from our own. He was occupied with such questions as the limits of the universe, the number of the stars, their distribution in space, their association in groups, and their common motions. He was not directly concerned with those studies of physical condition and of evolutional progress in which we hoped to aid in tracing the life-history of stars and stellar systems from their birth to their decay. Could we afford to postpone some of our own investigations, at first sight very different from his, even for the very important purpose of advancing his great undertaking?


FIG. 37.—The Milky Way near θ Ophiuchi.

It appeared on reflection that the surest way to accomplish our own special object was to coöperate in the closest possible way with Kapteyn, even to the extent of devoting a large share of the working-time of our instruments to the study of his problems. The physical development of stars may depend upon just such association in systems as the discovery of star-streams has disclosed, and many questions might long escape answer if attacked only from a single viewpoint. In short, close coöperation should prove mutually advantageous, contributing in material measure toward the solution of what, after all, is but a single great problem. How manifestly the annual visits of Kapteyn to Mount Wilson have aided progress toward our original goal will appear in the sequel.

INSTRUMENTAL POSSIBILITIES.

And now a word as to instrumental means. Here we may advance in two ways: (1) as we have seen, by the use of methods and the adaptation of principles, borrowed in the main from the physicist, and (2) by increase in telescopic power, derived from greater optical aperture and greater perfection of optical and mechanical construction. Mere size is of no moment, unless supported by corresponding precision of parts. Lord Rosse's 6-foot reflector, built before the development of modern machine tools, was less efficient than a 12-inch telescope of the present day. It is true that photography is mainly responsible for the gain in observational method, but the design and construction of Lord Rosse's instrument would have precluded his use of the sensitive plate. The types of telescopes adopted for our solar studies have already been described. Let us now consider the very different needs of stellar observations, where the first requirement in many classes of work is the collection of the greatest possible amount of light.

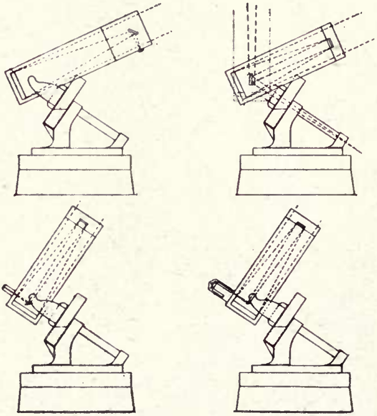


Fig. 38.—Mirror Combinations in 60-inch Reflector.

Most of the astronomical telescopes in use are refractors, consisting of a lens, through which the rays from a star pass, to be united in an image at the lower end of the telescope tube. A reflecting telescope, on the other hand, consists of a silvered concave mirror, lying at the lower end of a tube, the upper end of which is open. The parallel rays of light, after falling on the mirror, converge to the focal point, which in this case is at the upper end of the tube (Fig. 38). The photographic plate may be fixed in the axis of the tube or placed at one side, where it receives the image after reflection from a plane mirror mounted diagonally. In another arrangement a convex mirror takes the place of the diagonal plane and sends the rays back toward the base of the tube, where they are again reflected by a plane mirror, either to a point on one side of the tube or down through the hollow polar axis, to unite in an image on the slit of a powerful spectrograph mounted in a constant-temperature chamber.

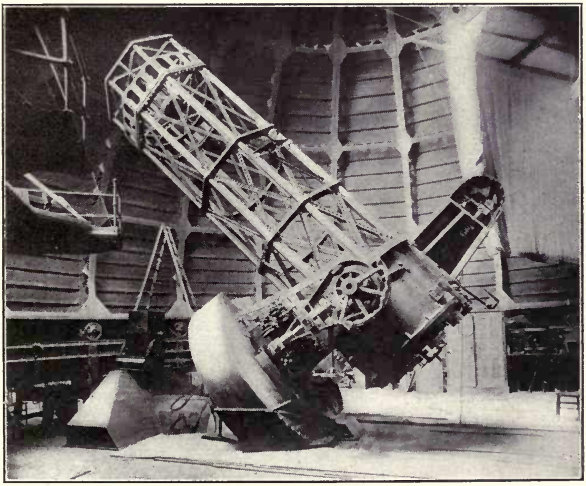


Fig. 39.—60-inch Reflector, showing Stellar Spectrograph on Tube.

THE 60-INCH REFLECTOR.

In modern astrophysical research the eye has given place to the photographic plate, which in almost all cases records much more than the eye can perceive. As the reflector is especially adapted for celestial photography, this form of telescope was chosen for our stellar work, for which the Snow and tower telescopes are not suitable. A 5-foot mirror, already ground and partly polished at the Yerkes Observatory, was acquired for use on Mount Wilson and brought to a perfect figure in our optical shop in Pasadena. The heavy parts of the mounting, some of which weigh 5 tons each, were made at the Union Iron Works in San Francisco; while all of the more exacting work, requiring greater precision, including the assembling of the instrument, the cutting of the teeth of the 10-foot

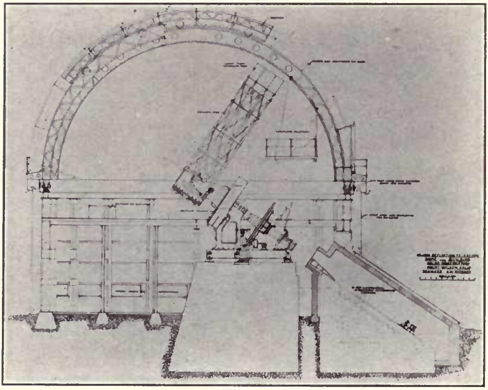


Fig. 40.—Sectional Drawing of 60-inch Reflector and Dome.

worm-gear (when mounted in place on the polar axis), and the construction of the driving-clock, was done by our own mechanicians. A necessary part of the undertaking was the building of a mountain road over 9 miles long, the transportation of the telescope and the steel building with its revolving dome to the summit, and their erection by our construction corps.

FIG. 41.—Great Cluster in Hercules.

Five years of work with this telescope have brought out all of its admirable qualities and provided a rich store of photographs for the study of stellar evolution. These are of the most varied character, including star clusters (showing in one case some 30,000 stars), nebulæ, stellar spectra, and occasionally the moon, planets, and comets, though the three latter classes of objects are not included in our present scheme of research.

FIG. 42.—Spiral Nebula M 81 Ursæ Majoris.

THE NEBULÆ.

Hypotheses of stellar evolution usually assume that the stars and stellar systems originate in the nebulæ, of which many excellent photographs, showing much new and remarkable structure, have been obtained on Mount Wilson. These cloud-like objects, many of which are shown by the spectroscope to consist of glowing gases, occur in the widest variety of form. The vast majority, however, are of definite spiral structure. Several nights of each month are devoted to a systematic photographic survey of the

Fig. 43.—Spiral Nebula M 101 Ursæ Majoris.

small nebulæ, which have been catalogued in great numbers by Herschel and others, but never studied, except in a moderate number of cases, under adequate telescopic power; in fact, in most instances the existing (visual) records give no conception whatever of the true form of these curious objects. At the same time the spectra of many of these nebulæ are being photographed.

Keeler's discovery, that there are at least 100,000 spiral nebulæ, left no doubt of their fundamental importance in the scheme of stellar evolution. The development represented by their spiral forms is

FIG. 44.—Spiral Nebula M 33 Trianguli.

on an incomparably greater scale than that of our own solar system, which would shrink to the dimensions of a pin-point if seen at the same distance. This distance is so great that in spite of the realistic appearance of motion in these spirals, no evidence of change in form has yet been detected.

But Slipher has found displacements of their spectral lines indicating rotational motion, and the planetesimal hypothesis offers a possible means of accounting for their origin and development. We are fortunate in being able to coöperate with Chamberlin and Moulton, the authors of this hypothesis, in a study of the structure of spiral nebulæ. The small spirals are of peculiar interest, and here the 100-inch telescope should be of service in extending our knowledge of the structural details of objects now barely recognizable as spiral in form.

MAGNITUDE OF THE UNIVERSE.

In our study of the sun as a typical star and in this investigation of nebulæ as the probable source of stellar existence, we are thus engaged on two phases of the evolution problem. Let us now see how the use of the 60-inch reflector in coöperation with Kapteyn has contributed in the same direction. A question of prime importance in astronomy is the magnitude of the universe. As our telescopes increase in power we reach farther and farther into space. As the sphere of vision enlarges, each increase in its diameter must mean the addition of a larger number of stars than the previous equal increase produced, because it involves the addition of a larger volume of space. This reasoning is based on the assumption that the stars are distributed nearly uniformly through space, at least as far as we can penetrate it, and that no light is lost in transmission.

In practice we find that each successive advance into a region of more distant, and therefore (on

Fig. 45.—Spiral Nebula HV 24 Comæ Berenices.

the average) fainter, stars does mean the addition of a greater number; but toward the outer boundaries of the known sphere the increase is less rapid than would be anticipated. Kapteyn pointed out that this might be due, at least in part, not to an actual thinning out of the stars near the outer boundary of the sphere, but to scattering of light by minute particles distributed at wide intervals through space. What would be the result? We know that the sun appears red at sunset, or when seen through smoke, because the blue light is intercepted and scattered by the minute floating

FIG. 46.—Milky Way, showing Nebula surrounding ρ Ophiuchi.

particles more than the red light. For the same reason the very distant stars should appear redder than the nearer ones, if there is similar scattering in space. It is therefore necessary to determine, by several independent methods, the proportion of red and blue light sent us by near and distant stars.

THE BRIGHTNESS OF THE STARS.

A knowledge of the relative intensity of the light of the different stars, from brightest to faintest, is essential in statistical investigations of their distances, luminosities, and distribution in space.

FIG. 47.—Spiral Nebula N. G. C. 4736.

The brightness is expressed in quantities called magnitudes, ranging from about 1 for the brightest stars to about 20 for the faintest objects registered in 4 hours' exposure with the 60-inch reflector. A star 1 magnitude brighter than another gives

FIG. 48.—Spiral Nebula M 51 Canum Venaticorum.

light about 2.5 times as intense. Thus an interval of 5 magnitudes corresponds to an intensity ratio of 1 to 100, while the most brilliant stars are about 100,000,000 times as intense as the faintest photographed with the 60-inch telescope.

This great range of intensity seriously complicates the determination of the magnitude scale, but photographic methods have been developed with the 60-inch reflector, and applied to a determination of standard magnitudes for all the stars of Pickering's North Polar Sequence and numerous other faint stars near the Pole. The scale thus established, over a range of about 17½ magnitudes, probably represents satisfactorily the degree of homogeneity attainable by the use of uniform methods employed with a single instrument.

For the ready determination of stellar magnitudes over the whole sky, standard magnitudes on an absolute scale, of a considerable number of uniformly distributed stars, must be measured. To this end observations of such standard stars to the seventeenth magnitude in each of Kapteyn's 115 Selected Areas on and north of the celestial equator are now in progress.

Magnitudes measured on ordinary photographic plates give the intensity of the blue and violet light of the stars. By using plates sensitive to red or yellow, behind a yellow glass filter, the resulting "photovisual" magnitudes furnish a measure of the intensity of the red or yellow light. As the relative intensity of the blue and red light for any object depends upon its color, a comparison of the photographic and photovisual magnitudes gives at once a measure of the color. The method is of importance, as it can be applied to the faintest stars that can be photographed.

A comparison of this kind, made for about 300 faint stars near the pole and about 300 additional stars in two other regions, shows clearly that there is a gradual change in color with brightness. The fainter stars, on the average, are redder than the brighter ones.

But while this result is just what would be expected on the basis of Kapteyn's reasoning, other possible explanations must not be overlooked. The increased redness of the fainter stars may be due to a gradually increasing preponderance of late spectral types (old stars) with decreasing brightness; it may be (as Kapteyn pointed out in his papers) a consequence of absolute luminosity, which for the faint stars is less, on the average, than for the brighter objects; or it may be due to scattering of light in space. Perhaps all of these possibilities enter in some degree. We shall soon see how the study of stellar spectra bears upon this problem.

STELLAR MOTIONS.

The extension of Kapteyn's study of star-streaming involves the measurement of the velocity, toward or away from the earth, of a great number of stars. These velocities are determined by means of the spectrograph shown attached to the telescope tube (Fig. 39). Side by side on the photographic plate, the spectrum of a star and the standard lines in the spectrum of iron or titanium are recorded. If the titanium or iron lines in the star are shifted toward the red, with reference to the corresponding lines of the comparison spectrum, we know that the star is moving away from the earth at a velocity proportional to the amount of the shift. Displacement toward the violet means motion toward the earth. This method, first applied on a large and comprehensive plan by Campbell, of the Lick Observatory, gave the velocities of 1,500 stars and yielded many conclusions of great importance. The 60-inch reflector has enabled us to extend such measures to many fainter stars. A discussion of the resulting velocities shows that Kapteyn's two star-streams extend into space much farther than the original data (for nearer stars) permitted them to be traced. Thus the view that the main body of the universe is constituted of these streams receives added support.

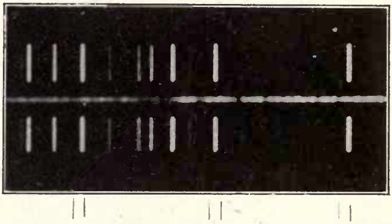


FIG. 49.—Spectrum of Lalande 1966, showing velocity of 325 km. per second toward the Earth. Position of lines in stellar spectrum and of corresponding lines in comparison spectrum indicated at bottom.

STARS OF HIGH VELOCITY.

Kapteyn and Campbell independently found that the radial velocities of the stars, corrected for the sun's motion, range from about 6 kilometers per second for the early type (young) stars to about 20 kilometers per second for the late type (old) stars. Boss, whose meridian-circle observations in the northern and southern hemispheres have determined the positions of numerous stars with the highest precision, deduced a similar conclusion from his studies of stellar motions perpendicular to the line of sight. The meaning of this remarkable variation of velocity with type is not yet understood and it will remain for future researches on the fainter stars to develop its full significance.

Although the average velocities of stars are thus found to be moderate, notable exceptions are frequently encountered in the work with the 60-inch reflector. Among the high velocities in space thus far found on Mount Wilson, cases of 141, 150, 179, 233, 316, and 320 kilometers per second may be mentioned. The last-named is the highest velocity of translation yet found for any star. At these speeds the attraction of the entire known stellar system would be wholly insufficient to check the star in its flight into unknown regions of space.

SPECTROSCOPIC BINARIES.

Pickering was the first to discover a to-and-fro shift, in a definite period, of the lines in the spectra of certain stars. He attributed it to orbital motion, and thus the possibility of detecting "spectroscopic binaries" was shown. These are double stars lying too close together to be separately distinguished with any telescope, but betraying their existence by the effect of their motion. Usually one member of the pair is too faint to give any spectrum. The lines in the spectrum of the visible star then swing back and forth, toward the violet as the star approaches the earth, toward the red as it recedes. When both stars are nearly equal in brightness both spectra appear superposed and the lines, which are single when the two stars are moving across the line of sight, become double when one is approaching and the other receding.

Thus far 115 spectroscopic binaries have been discovered on Mount Wilson, or about 1 in 4 of all the stars whose velocities have been measured. In some interesting cases of rapid motion the relative orbital velocities of the components range from 104 to 367 kilometers per second.

TEMPORARY STARS.

Among the most remarkable phenomena of the heavens are the "new" or temporary stars, which burst out into sudden brilliancy and gradually fade into extreme faintness. With the 60-inch reflector it has been possible to photograph the spectra of some interesting "Novæ" which appeared several years ago and are now very faint. These include Nova Aurigæ, which was discovered in 1891 and is now of magnitude 13.5; Nova Persei of 1901, magnitude 12.0; Nova Lacertæ of 1910, magnitude 13; and Nova Geminorum No. 2 of 1912, magnitude 10. For such faint objects the exposures required in photographing the spectrum ranged from 2 to 16 hours.

The most plausible hypothesis of temporary stars accounts for their rapid brightening on the supposition that a faint star suddenly plunges into a gaseous nebula. After passing through a remarkable series of changes, the spectra of Novæ have usually been supposed to correspond closely, in the last visible stage of their existence, with the spectra of nebulæ. The Mount Wilson results, in harmony with an observation by Hartmann, show that after the lapse of years the characteristic lines of the nebular spectrum disappear completely, at least in some cases, as though the star had finally passed out of the nebula which caused its outburst of light. If the above hypothesis is correct, the temporary brightness of Novæ resembles that of meteorites, which are kindled into brilliancy when passing through the earth's atmosphere.

It also appears probable that at least a portion of the remarkable Wolf-Rayet stars, most of which lie in the Milky Way (where practically all Novæ occur), are temporary stars in the later stages of their existence.

VARIABLE STARS.

An interesting result is derived from a study of the color of a certain variable star, RR Draconis, one of the revolving components of which completely eclipses the other at the time of minimum brightness. It is found that the faint companion, which is the larger of the two stars, is redder than the bright central object. If we may accept, as generally valid, the result that for all systems of known mass-ratio the brighter object is invariably the more massive, it follows that the fainter and redder companion of RR Draconis is of a much lower density than the brighter object. Further, if the redder color really represents more advanced spectral type, commonly associated with a later stage of development, we should have the unexpected case of a star of low density associated with a less-developed star of higher density. As this is contrary to the usual view that a star's density increases with its age, further investigations of such systems may prove of importance in the study of stellar evolution.

LIGHT-SCATTERING IN SPACE.

The collection of nearly 4,000 photographs of stellar spectra thus far obtained on Mount Wilson is available for many classes of work. It affords Kapteyn material for the further investigation of star-streaming, which is now being studied with reference to the association in streams of stars in different stages of physical development; but it also permits many other problems to be attacked. One of these is the question of light-scattering in space. We have already seen that the fainter stars are redder than the brighter ones, but the meaning of this result is not yet certain.

One of the methods used to determine the relative colors of near and distant stars was to photograph their spectra side by side on a single plate. Since blue and violet light is weakened by scattering more than red, we should expect the violet part of the spectrum of the more distant star to be fainter than that of the nearer star. In general, this proved to be the case.

Many spectra of near and distant stars were then selected from our collection of photographs and divided into groups, each representing a different stage of evolution. That is to say, in terms of our present view of stellar ages, young, middle-aged, and old stars were placed in separate groups. It was found that in all of the groups, with one possible exception, the more distant stars are redder than the nearer ones, but that the difference in color also depends in some way upon the age of the star.

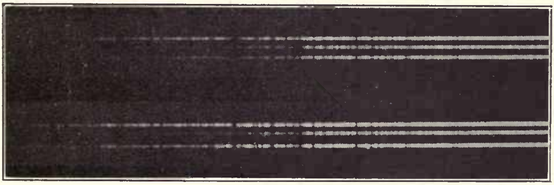


FIG. 50.—Weakness in Violet of the Spectra of Distant Stars. Compare middle spectrum of each group with those above and below.

Investigations are now in progress to explain this, but the advantage of dealing with Kapteyn's problem of distance from the astrophysical standpoint is already evident. On the one hand, an influence of physical development has been found which must be considered before any final conclusions can be drawn regarding scattering in space or its bearing on the extent of the universe. On the other hand, the study of a problem which might seem to have little to do with the question of stellar evolution has brought to light a physical phenomenon which may prove to be an important factor in the explanation of stellar development. The first application of these results has provided a new means of determining stellar distances.

A NEW MEASURE OF STELLAR DISTANCES.

We have already spoken of the apparent magnitudes of the stars. Their absolute magnitudes, on the other hand, are the magnitudes they would have if they were all at the same standard distance from the earth. To calculate these, we must know the distances of the stars. Conversely, if we can obtain the absolute magnitude of a star in some other way, we can determine its distance by comparing this with its apparent magnitude.

A knowledge of the peculiarities of certain lines in the sun's spectrum, derived from the solar investigations referred to above, suggested that their relative intensities be determined in the spectra of a list of stars of known absolute magnitude. This brought out a surprisingly close correspondence between these relative intensities and the absolute magnitudes. Hence, by determining the ratio of these intensities and the apparent magnitude for any star of this class, we can at once calculate its distance. If this method proves to be generally applicable it will give a means of finding the distances of stars too remote to be measured by other means. From a physical point of view it is also of value, because of its bearing on the constitution of stellar atmospheres.

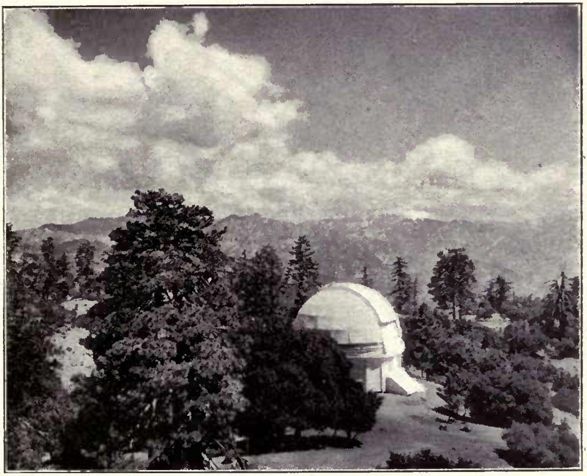


FIG. 51.—Dome of 60-inch Reflector.

OTHER RESEARCHES IN PROGRESS.

A detailed account of the investigations made or in progress would include many additional subjects, such as the measurement of the brightness of the night sky, the study of the spectra of nebulæ, star clusters, the Zodiacal Light, and the Milky Way, the determination of standards of wave-length for the use of spectroscopists, the photography of Halley's comet, statistical studies of solar prominences, sun-spots, and flocculi, etc. (See "Published Papers of the Observatory," page 92.) Enough has been said, however, to give an idea of the character of the Observatory's work and the nature of the instruments employed. In addition to the four telescopes already mentioned, a 6-inch refractor and a 10-inch photographic telescope of the portrait-lens type are soon to be provided.

THE WORK OF INTERPRETATION.

The interpretation of the varied phenomena recorded on astronomical photographs is the most important phase of the Observatory's work. At first thought it might seem that a good photograph of a celestial object would represent the chief aim of the astronomer. In fact, however, it is only a first step, since the information it contains does not often lie on the surface. It is the task of the investigator, not merely to take photographs, but to interpret them. To return to a former simile, he is in the position of Young and Champollion when attempting to read the hieroglyphic inscription of the Rosetta Stone, or, more often, in that of present-day archeologists when facing the seemingly impossible task of deciphering the unknown characters of the Minoan civilization in Crete. If, as in the latter case, the duplicate inscription in a known tongue is lacking, much searching and many failures may precede the discovery of the hidden meaning of the document.

FIG. 52.—Pasadena from Mount Wilson.

Let us suppose that we are dealing with the spectrum of a star. Side by side on the photographic plate we have the stellar spectrum and that of a spark between poles of iron or titanium. By measuring these lines with a suitable instrument, we obtain their positions within a few thousandths of a millimeter. When the positions of hundreds or, as in some cases, thousands of lines must be determined with the highest possible precision, it is evident that the measurer must be both painstaking and persistent.

Next comes the work of computation. The measured distances between the standard (spark) lines and the corresponding lines of the star must first be converted from fractions of a millimeter into fractions of an angstrom (the international unit of wave-length in spectroscopic work). When this has been done, a short computation gives the velocity of the star's motion in the direction of the observer. After computing and deducting the velocity of the observer's motion (due to the diurnal rotation of the earth and its revolution about the sun), the star's motion with respect to the sun is determined.

From this point one may go on, according to the requirements of the work in hand, to identify all of the star's lines with those of known chemical elements or compounds; to account for minute displacements of the lines from their normal places, as the result of pressure or electrical excitation or some other condition in the star's atmosphere;

FIG. 53.—Telephoto View of Pasadena from Mount Wilson, showing Observatory Buildings.

to measure their relative intensities and compare them with the known effects of temperature change, etc. Some other methods of interpretation have already been described in our account of solar phenomena.

The collection of instruments used in the Pasadena office-building for the study of the photographs includes measuring-machines of various types; visual photometers, for determining the density of the image (and hence the brightness of the object); Koch's registering microphotometer; a Zeiss stereocomparator, for the accurate comparison of two photographs of the same object; the heliomicrometer, a combined measuring and calculating machine for determining the latitude and longitude of objects on the sun; several calculating

FIG. 54.—Pasadena Office-Building.

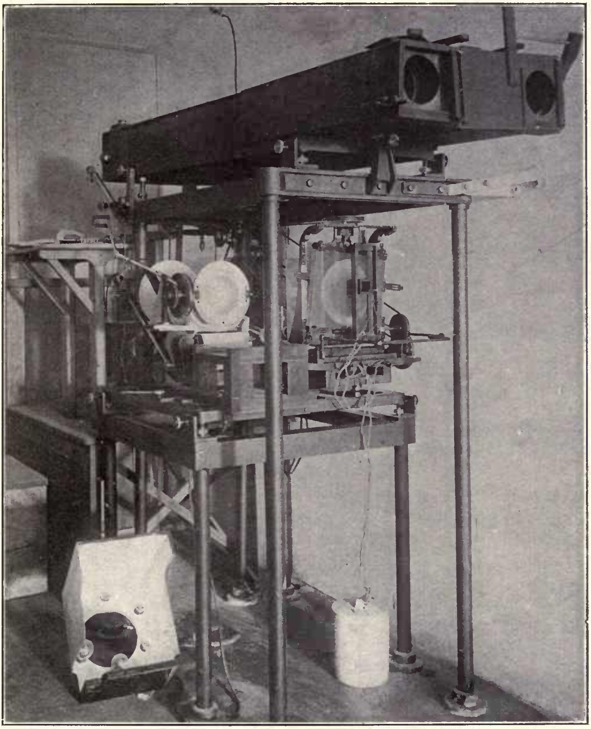


FIG. 55.—The Heliomicrometer.

machines for rapid addition, multiplication, and division; and other devices for special purposes. Most of these instruments were made in our own shop, from working drawings prepared by our draftsmen.

Beyond this process of interpretation lies the extensive work of correlation and generalization, which seeks to express a wide range of phenomena under a single mathematical law. As already indicated, the policy of the Observatory is to enlist in this endeavor the ablest mathematical astronomers and physicists, of Europe or America, whose coöperation can be secured.

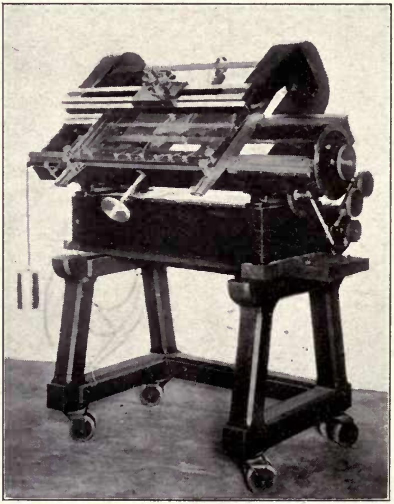


Fig. 56.—Large Measuring Machine for Solar Spectra.

INSTRUMENT AND OPTICAL SHOPS.

The equipment of the instrument and optical shops has grown steadily with the demands of the work in progress. Our requirements range from the accurate cutting of the teeth of worm-gears 14 feet in diameter down to the smallest attachments of microscopes, galvanometers, and other delicate instruments. The mounting of the 100-inch reflector is making exceptional demands upon our instrument makers and their shop equipment, which has recently been enlarged to meet the needs of this telescope and the still more exacting requirements of a machine for ruling diffraction gratings.

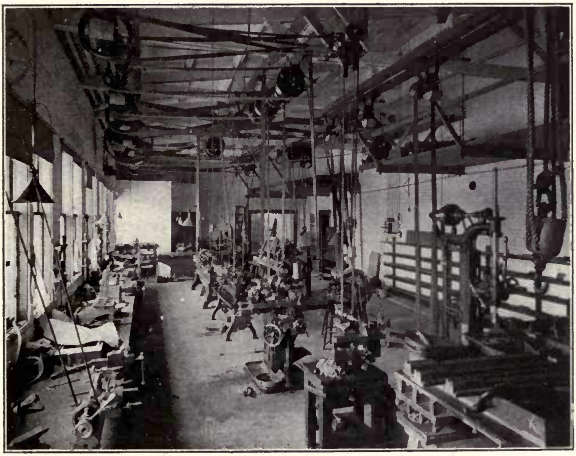


FIG. 57.—Machine Shop in Pasadena.

The success of modern spectroscopic investigation depends largely upon the size and excellence of the optical gratings available. These polished plates of speculum metal, ruled with about 15,000 lines to the inch, have reached a high degreee of perfection through the skill of Rowland, Michelson, and Anderson. But certain types of gratings required for our special work can not be obtained from existing sources, and we are accordingly attempting to overcome the peculiar difficulties involved in making them. The instrument shop and the underground constant-temperature chamber provided for this purpose are in the Pasadena office-building, where the ruling-machine is now being completed and tested.

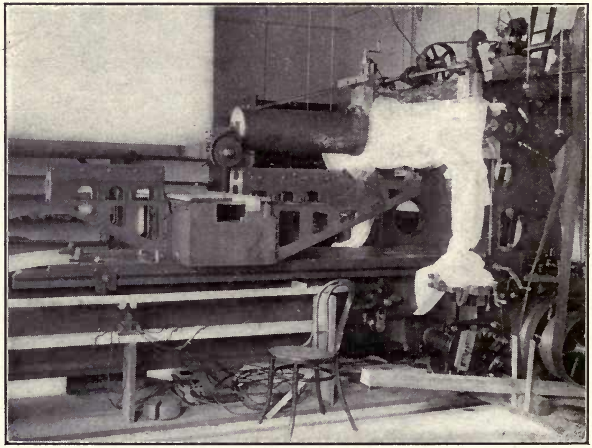


Fig. 58.—Grinding Cross Ways of Ruling Machine Bed on Large Planer.

The larger instrument-shop, in an adjoining building, contains a good collection of machine tools of the best types, and the optical shop is equipped for grinding and polishing plane and curved surfaces of various dimensions. Here the 100-inch mirror for a large reflecting telescope is now being figured.

THE 100-INCH REFLECTOR.

To the unaided vision, about 5,000 stars would be visible on a clear night in the entire sky. According to a recent estimate by Chapman and Melotte the heavens contain about 219,000,000 stars, brighter than the twentieth magnitude, which are within the range of our 60-inch reflector. If the indications afforded by Chapman's figures can be applied to fainter objects, there is reason to hope that a 100-inch telescope would add nearly 100,000,000 still fainter stars, many of them lying beyond the boundary of the universe as at present known. The inconceivably great distance of these stars makes them of peculiar interest and importance in the study of the magnitude and structure of the sidereal system.

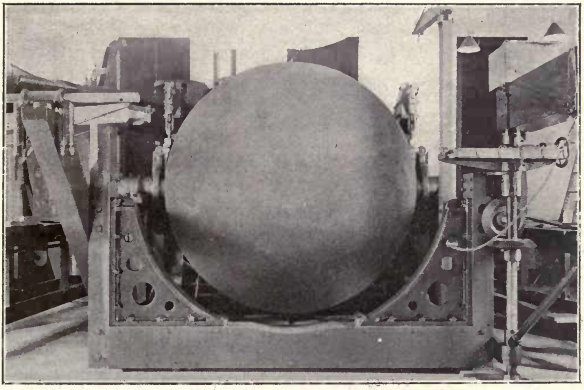


FIG. 59.—100-inch Disk on Grinding Machine turned into vertical position.

Fig. 60.—Model of 100-inch Reflector Mounting.

But in addition to its power of reaching out to such great distances, a 100-inch telescope should also contribute in large degree to the solution of other questions. It would collect more than twice as much light as the 60-inch reflector, and for all classes of work this would mean a great gain.

For example, the number of stars whose spectra could be photographed on a sufficient scale to determine their radial motions would be trebled. At present, the number of these objects is so restricted that conclusions based on their study are confined to a comparatively small region in space closely surrounding the sun.

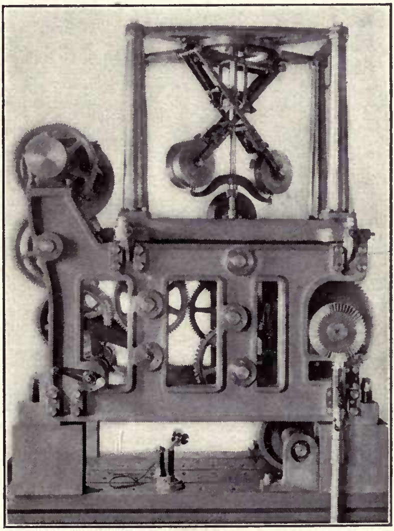


FIG. 61.—Driving Clock for 100-inch Reflector.

Quite as important would be the possibility of photographing the spectra of the brighter stars with high dispersion. For determinations of stellar motions the spectrographs now in use are very efficient. But in many other respects our present position in stellar spectroscopy is closely analogous to that which existed in the case of sun-spots before high dispersion had been applied to the analysis of their light. Many stellar lines which appear single under low dispersion are actually "blends" of several lines, and small displacements due to pressure and other physical phenomena in stellar atmospheres are beyond the reach of existing instruments. As already stated, a beginning has been made in attacking such problems with the 60-inch reflector, but the greater light-collecting power of the 100-inch telescope is required for the continuation of this investigation.

In view of certain statements in the public press, it may be remarked here that faint stars photographed for the first time with large telescopes are not regarded by astronomers as discoveries, just as the first detection of a new sun-spot is not considered in this light. But the value of a large telescope does come in part from its power of bringing such faint stars within the range of investigation, as their study may add largely to our knowledge of the universe.

The advantages of great light-gathering power were appreciated by the late Mr. John D. Hooker, of Los Angeles, who in 1906 gave to the Mount Wilson Observatory a sum of money to provide a telescope mirror of 100 inches aperture. Many difficulties have been experienced in obtaining a suitable disk of glass, on account of the great thickness (13 inches) required to prevent bending. A disk weighing 4½ tons, made by the St. Gobain

Plate Glass Company of Paris, has been thoroughly tested by the most exacting methods and is now being polished and figured in our optical shop.

To carry such a mirror with perfect freedom from flexure and with the high precision which modern photographic methods demand, a telescope mounting of exceptional size is required.

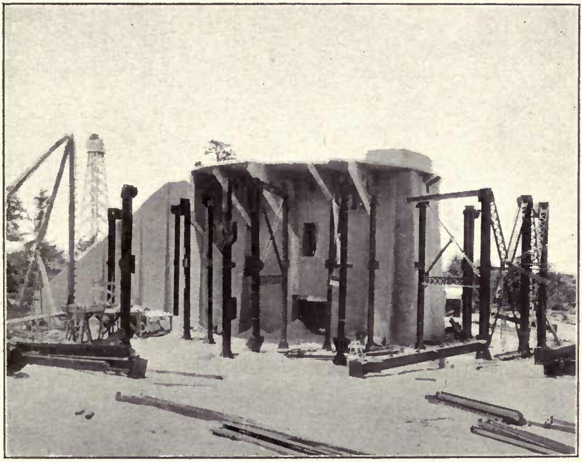


Fig. 62.—Erecting Steel Building for 100-inch Reflector.

This is now under construction at the Fore River Ship Yard in Quincy, Massachusetts, where machinery used for building the largest battleships is available. The smaller parts of the mounting, and others requiring special accuracy of fitting, are being made in our own machine-shop in Pasadena.

The concrete pier which is to support the 100-inch telescope has already been built on Mount Wilson, and the steel building, which is to be surmounted by a revolving dome 100 feet in diameter, is now being erected. It is not expected that the telescope will be ready for use before 1916.

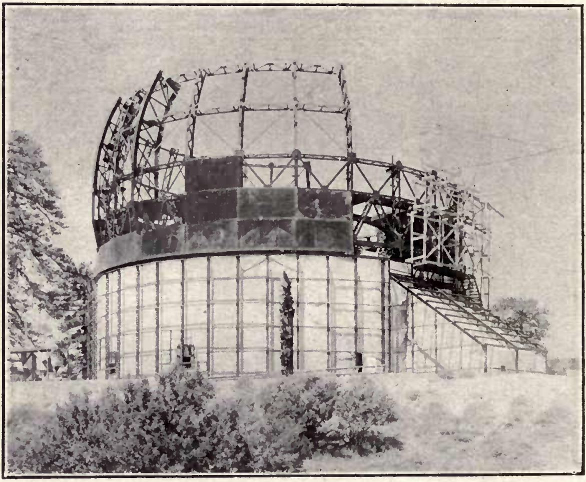


FIG. 63.—Dome for 100-inch Reflector in process of erection, June, 1915.

WORK OF THE FUTURE.

In closing this brief survey, which attempts no more than to give an idea of the Observatory's activities through certain typical examples, a word may be said regarding the future. No predictions can be made as to possible new results, as the capacities of the 100-inch reflector are still untried and the course of research in any field can never be clearly foreseen. In the study of the sun there is much to be done in continuation and extension of present work: the development, on an observational and experimental basis, of a theory of sunspots; the determination of the exact position of the sun's magnetic poles and their period of revolution about the poles of rotation; the extended investigation of the electric and magnetic phenomena, and the pressures and motions of gases at different levels in the solar atmosphere. Stellar problems are innumerable, but the work already begun demands first consideration. We must learn beyond doubt whether light is scattered in

Fig. 64.—Snow on Mount Wilson.

space, and measure the amount of scattering for unit distance if a positive conclusion is reached. This once accomplished, the determination of a star's redness, after due consideration of the scattering and absorbing effect of its own atmosphere, will afford a measure of its distance, thus providing an invaluable means of sounding the greatest depths of the universe. The closely entangled question of the dependence of a star's redness upon its physical condition, so important from the evolutional standpoint, must also be cleared up. Another capital problem is the actual extent of Kapteyn's two star-streams, which the increased light-gathering power of the 100-inch reflector should help to reveal. Then there are such fundamental phenomena as the observed increase of a star's speed with its age; the peculiar characteristics of globular star-clusters, which contain so many variable stars of short period; the significant and intricate changes of variable stars of all classes; the constitution and distribution of the nebulæ. But many pages would be needed to enumerate the problems which press for solution, and from which a selection must be made.

In the laboratory the opportunities for useful work are hardly less numerous. Tempted as we often are toward the study of purely physical questions, our chief effort must be devoted to the interpretation of astronomical phenomena. Much attention will be given to the investigation of the Zeeman effect and the phenomena of radiation at different temperatures and pressures. The recent discovery of the Stark effect affords an opportunity to determine the influence of electric fields on light, and to apply the results to the solar atmosphere. And as the prolific researches of modern physics continue to develop, much new assistance may be expected for astrophysical inquiries.

FIG. 65.—Lights of Pasadena and Los Angeles from Mount Wilson.

The outlook is thus a favorable one, from whatever standpoint it is viewed. The reappearance of numerous sun-spots, after a long period of solar calm, and the approaching completion of the 100-inch reflector, should encourage research and stimulate progress in all departments of the Observatory's work.

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