Chapter 19

A COSMIC PERSPECTIVE [9]

Modern cosmology, the study of the universe as a whole, has developed detailed theories about the origin, evolution, large-scale structure, and future of the cosmos. It owes its origins to Einstein's Theory of General Relativity, and to the discovery made in 1927 by the American astronomer Edwin P. Hubble (1889-1953) that the galaxies are receding from our Milky Way, and that the farther they are, the faster they are receding.

The fact that galaxies are moving away from our own galaxy in all directions suggested that, the further back in time we go, the closer together they must have been in the past, all the way back to some "primeval atom" containing the total mass of the universe. Cosmology accounts for the origin of the universe with the widely accepted "Big Bang" theory, according to which, about 10 to 20 billion years ago, the universe was born in a sudden outburst of energy of inconceivable intensity. Starting from a minuscule, immensely dense lump of energy-matter, the universe has been expanding ever since.

One would be easily tempted to imagine a gigantic explosion occurring at a particular place in a pre-existing empty space. The theory, however, tells us that the Big Bang gave birth not only to matter, but also to space and time. Galaxies today are receding from one another, not because they are rushing *through* space, but because the space between them is expanding. As an analogy, consider a balloon with many spots painted on it. As the balloon is inflated, all the spots are seen to move away from one another. From the viewpoint of any one spot, however, all the others appear to be receding from it.

A BRIEF HISTORY OF THE UNIVERSE

The First 100,000 Years (or so): The Age of Radiation [1]

Cosmologists believe that, from mathematical models, they can retrace the early history of the universe, but only (!) back to time $t = 10^{-43}$ of a second after the cosmic "explosion". At this moment in time, known as the "Planck time", the density of matter is an unimaginable 10^{94} grams per cubic inch, and the universe is only 10^{-33} of a centimeter across. The temperature has a staggering value of 10^{32} degrees K, ten trillion trillion times hotter than the core of an average star.

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[9] More recent estimates may supersede some of the numbers used in this chapter. The grand panoramic view across time and space presented here, however, is likely to remain valid in its broad outlines.

As sketchily outlined below, the early history of the universe can be divided into a number of eras. Although their durations progressively increase from tiny fractions of a second to seconds to minutes to 100,000 years, each represents a major phase of cosmic evolution.

The GUT Era

This era lasted only about 10 billion-billion-billion-billionths (10^{-35}) of a second! The acronym GUT stands for "Grand Unification Theory". As proposed by a number of such theories, the three fundamental forces other than gravity were still unified (indistinguishable) during this era. Gravity is believed to have separated from the other three forces at the beginning of the GUT Era at time t = 10^{-43} of a second.

During this era, the universe is a "chaotic soup of energy-matter". In a fireball of radiation, pairs of matter and antimatter particles of various types spring into existence from extremely energetic photons, but are immediately annihilated in violent collisions that give birth to more particles and antiparticles.

The fundamental particles that make up the infant universe include photons, leptons, quarks, and their antiparticles.

The Inflation Era

The duration of this era is about 1000 billion-billion-billion-billionths (10^{-33}) of a second. As the universe expands, its temperature drops. When the cosmic temperature falls below a critical value of about 10^{27} degrees K, the universe undergoes a period of inflation (expansion) at a skyrocketing rate. By the end of this era, the volume of space has increased more than a trillion trillion times.

The strong nuclear force becomes differentiated from the electromagnetic and weak nuclear forces, which remain unified as the so-called "electroweak" force.

A break in the matter-antimatter symmetry results in about one billion and one particles of matter being produced for every billion particles of antimatter.

The Electroweak Era

The duration of this era is about one millionth of a second. The pull of gravity begins to slow down the expansion of the universe. The temperature drops to 10^{26} degrees K. The electroweak force divides into the electromagnetic force and the weak nuclear force. The separation of the four fundamental forces of the universe is now complete.

Leptons and antileptons evolve into variants such as electrons, positrons (or anti-electrons), neutrinos and anti-neutrinos.

The Quark Confinement Era

The duration of this era is about 2 seconds. The temperature is down to 10^{13} degrees K (more than a million times hotter than the core of the Sun).

Photons of very high energy are continually colliding with particles of various types, but they no longer have enough energy to prevent quarks from combining together to form protons and neutrons, the building blocks of future atomic nuclei. Photons, however, have still enough energy to smash any bonds between protons and electrons, thus preventing the formation of even the simplest atoms.

The cosmic fireball is dominated by photons, electrons, positrons, neutrinos and anti-neutrinos. Protons and neutrons represent a tiny minority. An anti-neutrino colliding with a proton produces a positron and a neutron. A neutrino colliding with a neutron produces an electron and a proton. Constantly bombarded, individual protons repeatedly change into neutrons and back to protons, while neutrons change into protons and back to neutrons.

Matter and antimatter continue to collide, mutually annihilating one another. Many of these events, however, produce photons that are no longer strong enough to create new particle-antiparticle pairs. Eventually, practically all antimatter disappears. In spite of the one-to-one annihilation of matter and antimatter particles, the slight excess of matter over antimatter produced during the Inflationary Era survives as the matter that constitutes the present universe.

The Neutrino Era

The duration of this era is 58 seconds. The temperature, which is now down to 10 billion (10^{10}) degrees K, continues to fall. By the time it drops to 3 billion degrees, no more electron-positron pairs are being generated, and the remaining ones are being annihilated. Positrons, like most other antimatter, gradually disappear. The antineutrino becomes the only antiparticle left.

No longer interacting with other particles of matter, neutrinos and antineutrinos form an almost undetectable "sea" that still fills the universe. Having no charge and nearly no mass, they can pass through matter as if it did not exist at all.

The Nucleosynthesis Era

The duration of this era is 4 minutes. The temperature is now 1,300 million degrees K; by the end of this era, it will be down to 600 million degrees. Photons can no longer prevent protons and neutrons from fusing into atomic nuclei under the pull of the strong nuclear force. They still have, however, enough energy to prevent the bonding of nuclei and electrons into atoms.

The most common combinations of protons and neutrons are the nuclei of hydrogen-2 (one proton and one neutron), helium-3 (two protons and one neutron) and helium-4 (two protons and two neutrons). The temperature of the expanding universe is dropping too quickly to allow more complex nuclei to form.

The Radiation Era

The duration of this era is about 100,000 years. At five minutes after the Big Bang, cosmic evolution slows down dramatically. The universe continues to expand and cool down. It is still too hot, however, for any stable atoms to form. As soon as a positive nucleus captures a negative electron, the electron is knocked out by an energetic photon. The universe is still dominated by radiation (photons).

When the temperature is down to 3,000 degrees K about 100,000 years after the Big Bang, photons have become weak enough that they can no longer prevent or disrupt the bonding of electrons with the simple nuclei of hydrogen and helium generated during the Nucleosynthesis Era.

At this point, the universe is a vast expanding cloud of gas consisting of approximately 75% hydrogen, 25% helium and traces of lithium. (As we will see, atoms of heavier elements will be formed only eons later in the blazing cores of stars.)

Practically all the electrons are now bound up in stable atoms. Since photons are no longer scattered by random encounters with electrons, they can finally burst free of matter. Space becomes transparent for the first time, and photons can travel unimpeded through the thin gas of the early universe.

From now on, photons and matter will rarely interact on a cosmic scale. As the universe continues to expand, the energy of photons continues to decline. Like the neutrinos before them, the primordial photons recede into a cosmic background. The universe has entered a new age no longer dominated by photons but by matter and gravity.

The Next 10-20 Billion Years: The Age of Matter

Galaxies

There is evidence that the cloud of hydrogen and helium that constituted the universe about 100,000 years after the Big Bang was extremely smooth and uniform in density. Yet, today the universe shows a very lumpy large-scale structure consisting of billions of stars grouped into "galaxies", which in turn form "clusters" grouped into "superclusters". How this large-scale structure of the universe came about is still an unsolved mystery.

It was only in the mid-1920s that most astronomers fully accepted the existence of galaxies beyond our Milky Way, which had been believed to constitute the entire universe. Before they could recognize the large-scale structure of the cosmos, astronomers had to develop ways of determining what was far and what was near, what was large and what was small - an exceedingly difficult task that was accomplished very gradually.

Galaxies typically contain from millions to hundreds of billions of stars. Their diameters range from 5,000 to more than 3 million light-years (a light-year is the distance traveled by light in one year, or about 6 million million miles).

The majority of known galaxies are either rapidly rotating "spirals" shaped like pinwheels, or slowly turning "ellipticals" with spherical or spheroidal shapes. Roughly 70% of the bright galaxies in the sky are of the spiral type, including our Milky Way.

Galaxies usually exist in clusters, which contain from a few to 10,000 galaxies, and have diameters of up to 50 million light-years. The distance between galaxies within a cluster averages 1-2 million light-years.

Clusters are frequently grouped with other clusters, forming giant superclusters, which may consist of 3 to 10 clusters, and span up to 200 million light-years.

Basically, the process that will lead to the lumpy large-scale structure of the universe starts when, within the primordial gas, the density of matter in some regions becomes somewhat higher than in others. Under the action of gravity, a region of higher-than-average density starts attracting the surrounding matter. This increases the density of the region, causing more matter to be drawn in, and so on. In time, huge separate clouds of gas are formed that begin to break up into countless stars by the same process that formed the clouds themselves.

Stars [10]

Stars are brilliant because they are nuclear furnaces that release huge amounts of energy by converting hydrogen into helium. They all start as "protostars", which are concentrations of gas within much larger and less dense clouds of dust and gas. Once formed, a protostar steadily shrinks for a very long time until it reaches the levels of density and temperature needed to ignite the nuclear fusion of hydrogen into helium.

At the raging temperatures inside the core of a star, atoms are stripped of their electrons into bare nuclei. Under ordinary conditions, these nuclei, which contain positively charged protons, would never fuse because of the strong electrical repulsion between them.

In the intense heat inside the core of a star, however, some nuclei acquire enough energy to come within a tenth of a trillionth of an inch from other nuclei. The strong nuclear force, which has a very short range, is now able to overcome the electrical repulsion, and cause the fusion of nuclei into more complex ones.

During the hydrogen fusion stage, a star consumes its hydrogen fuel at a steady rate, and changes only slightly in brightness and temperature.

[10] This and the following sections are based on “Voyage Through the Universe – Stars (Time-Life Books, 1989)

Throughout this period, the inward gravitational pull is balanced by an outward pressure created by the thermonuclear conversion of hydrogen into helium.

"Dwarf stars" with a few tenths of the mass of the Sun have a relatively weak gravitational pull. This allows them to fuse hydrogen very slowly. A star with half the Sun's mass, for instance, could go on for 200 billion years, well beyond the present age of the universe.

Giant stars with at least three times the mass of the Sun have a much stronger gravitational pull and much faster nuclear reactions. Even though they have a greater supply of hydrogen, they consume it within only a few tens of millions of years.

Once a star depletes its hydrogen supply, what happens next depends on its mass. Dwarf stars will simply fade out, a yet-to-be-observed phenomenon. Of much greater interest - particularly because of its effect on the later evolution of the universe - is the life cycle of giant stars. Their short life span makes them rare, since only some of those formed in the last 30 million years still exist.

Life and death of a giant star

We will follow now the various stages in the life of a giant star with a mass twenty times that of the Sun. Such a star fuses some 20 trillion tons of hydrogen per second, at a core temperature of 40 million degrees K! Inside the core, the process of fusing hydrogen into helium is completed in about 9-10 million years.

The star is now about one million years from its end. Its helium core is surrounded by a much larger hydrogen shell. When hydrogen fusion is completed, nuclear reactions momentarily stop. The core becomes slightly less able to resist the pull of gravity, and its atoms are consequently squeezed closer together. The temperature climbs to 170 million degrees K, starting a new series of nuclear reactions, which result mainly in the fusion of helium into carbon and oxygen. The core stops shrinking, and the star remains stable for about one million years. The inner part of the star consists of a shell of helium surrounding a hotter and denser core of carbon and oxygen.

With about one thousand years to go, once most of the helium in the inner core has been fused, the core begins to shrink again. The temperature rises to 700 million degrees K, starting a new round of nuclear reactions, which hold the star stable and convert carbon into neon and magnesium. In layers surrounding the core, at lower temperatures, fusion continues to convert helium into carbon and, further out, hydrogen into helium.

As this process continues at an accelerated rate, the star's core begins to look more and more like an onion, with concentric layers of elements whose density increases as we move toward the center. When there are only a few days to go, the temperature skyrockets above 3 billion degrees. The star has now concentric shells of hydrogen, helium, carbon, neon and oxygen. Inside the shrinking core, nuclear reactions convert silicon and sulfur into iron. Once these are completed, no further nuclear reactions can take place inside the core, because the nuclear structure of iron does not allow fusion into heavier elements,

When fusion reactions stop in the innermost core, with only tenths of a second to go, the star begins its final collapse. The core's temperature rises to 100 billion degrees K. Iron nuclei are so compressed that they melt together. The repulsive force between the nuclei overcomes the force of gravity and, like an overwound spring, the inner part of the iron core snaps back with explosive force.

As a powerful shock wave rushes outwardly through the various layers, new elements continue to be created. The shock wave spews matter into space, and ultimately all that will remain is a "neutron star", a superdense sphere composed almost entirely of neutrons, perhaps 10 miles in diameter.

The spectacular explosion that marks the end of a giant star is called a "supernova". Only seven supernovas are known to have been recorded. The most recent one occurred in 1987. The preceding one was observed by Kepler in 1604.

The material ejected in the final explosions of early giant stars was eventually incorporated into a second and then a third generation of stars, including the Sun. The debris provided also the material out of which planets, moons, complex molecules and, eventually, living things were formed. The atoms in our bodies were once part of some giant star.

Black Holes

A neutron star represents the final relic of the cataclysmic death of a massive star. This is the expected outcome when the final mass of the dead star is between 1.4 and 3 times the mass of the Sun. If the final mass of the dead star is more than three solar masses, the outcome, instead, is the birth of a "black hole". Because of the larger mass, the crush of gravity is unstoppable. The dead star is compressed down to a point of zero volume and infinite density, what is called a "singularity".

Within some radius from the singularity, the pull of gravity is so powerful that all matter is sucked in and not even light can escape. This radius would be 37 miles for a black hole of 10 solar masses.

The Emergence of Life and Intelligence on Earth

It is widely accepted today that the solar system was formed about 4.6 billion years ago, and that there has been life on Earth since at least 3.5 billion years ago.

For a period of over 2 billion years, the only forms of life were one-celled "procaryotes". A procaryotic cell has no nucleus. Its genetic material is organized into a single chromosome.

One-cell "eukaryotes" appeared about 1.2 to 1.4 billion years ago. A eukaryotic cell contains a nucleus whose membrane encloses the gene-bearing chromosomes. Eukaryotic cells are found today in all forms of life other than blue-green algae and bacteria, which have procaryotic cells.

The first multicellular organisms may date back to 900 million years ago. The oldest animal fossils, about 700 million years old, come from small wormlike creatures with soft bodies. The last 600 million years, when hard parts such as shells and bones became available for making fossils, are much better documented.

The story of the evolution of higher forms of life need not be repeated here in any detail. In the approximate outline shown below, the last 570 million years have been broken down into major periods, which are listed together with their major life forms (MYA = Million Years Ago):

- 570 to 435 MYA: primitive vegetation, marine invertebrates.
- 435 to 345 MYA: first land plants, fern-like plants, fishes.
- 345 to 230 MYA: moss, ferns, insects, amphibians.
- 230 to 65 MYA: tree ferns, palms and broad-leaf plants, reptiles, birds.
- 65 to 1.8 MYA: modern plants, mammals.
- 1.8 MYA to now: mankind.

If the entire life of the universe so far - say, 15,000 million years - were compressed into a single year, the appearance of mankind would not occur until 63 minutes before the very end of the year; the last two millennia would not start until 4 seconds before the end!

THE FUTURE OF THE UNIVERSE [11]

According to present theories, the ultimate fate of the universe depends on how much matter is available to rein in the cosmic expansion with the pull of gravity.

This fate will be determined by how the average mass density of the universe compares with a "critical density", which is equivalent to one hydrogen atom in a cube about 7 feet long on each side. If the universe has an average mass density smaller than or equal to the critical density, it will go on expanding forever. Over many billions of years, its average temperature will drop ever closer to absolute zero until a lifeless universe will have reached what has been called the "Big Chill".

On the other hand, if the average mass density is larger than the critical

[11] Based on “The Shadows of Creation” by Michael Riordan & David Schramm (W.H. Freeman and Company, 1990)

density, the pull of gravity will eventually bring the cosmic expansion to a halt. In a reverse Big Bang, the universe will start shrinking back toward an ultimate "Big Crunch".

A JOURNEY INTO SPACE

Having retraced the history of the universe from its very beginning and speculated about its future, let's embark now on an imaginary journey to our "neighbors" in the great vastness of space.

The Solar System

(Diameter = 7.4 billion miles = 0.001 light-years)
Our starting point, the Earth, is a nearly spherical planet with a diameter of 8,000 miles (approximately). At the equator, its circumference is 25,000 miles.

In our immediate "backyard" is the Moon, at an average distance of about a quarter of a million miles. It is about one-fourth the size of the Earth, with a diameter of 2,000 miles.

At a distance ranging between 91 and 94 million miles is the Sun, a sphere of luminous gas with a diameter of 870,000 miles, 110 times that of the Earth. Its mass, which is 330,000 times that of the Earth, constitutes 99% of the entire mass of the solar system.

The nine planets that orbit around the Sun are divided in two groups:

- The Near Planets (Mercury, Venus, Earth and Mars) are solid spheres with a metallic core.
- The Far Planets consist of four giants (Jupiter, Saturn, Uranus, and Neptune), and the much smaller Pluto at the outer edge of the solar system. The four giants contain 99% of the mass of the solar system outside the Sun. They are all huge spheroids of gas consisting mainly of hydrogen and helium. They have between 2 and 16 satellites each. Pluto and its satellite, which is more than half Pluto's size, are considered to be a double planet. They appear to consist of ices, such as water and methane, mixed with rock.

Between the two groups is a belt consisting of thousands of asteroids. These residues from the early solar system are fragments of rock and iron ranging in size from 600 miles to less than one mile.

For the nine planets[12], **Table II** shows their diameters and their average distances from the Sun; also listed are the approximate ratios of these values

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[12] A familiar way of remembering the names of the planets in their sequence from the Sun is to memorize the sentence: **M**y **V**ery **E**ducated **M**other **J**ust **S**erved **U**s **N**ine **P**ies (**M**ercury-**V**enus-**E**arth-**M**ars-**J**upiter-**S**aturn-**U**ranus-**N**eptune-**P**luto).

to the corresponding ones for Earth

The Milky Way
(Diameter = 100,000 light-years)
Our mighty Sun is just one of an estimated 100 billion stars that make up the Milky Way. Like other spiral galaxies, the Milky Way has at its center a dense sphere of stars, the "bulge", surrounded by a relatively thin, flat "disk" of gas and stars. These are arranged in what may be two or four spiral arms coiled around the bulge, like those of a huge pinwheel.

The entire Milky Way rotates around its center. The figures below are mostly estimates [2]:

- Age of Milky Way = 13-15 billion years
- Diameter of central bulge = 30,000 light-years
- Diameter of disk = 100,000 light-years
- Thickness of disk at the Sun = 700 light-years
- Distance of the Sun from the bulge = 27,000 light-years
- Orbital velocity of the Sun around the center = 135 miles/sec.
- Time for the Sun to complete one orbit = 250 million years

The closest star to the Sun is Alpha Centauri, 4.3 light-years away.

The Local Group
(Diameter = 2 million light-years)
Our Milky Way is part of a loosely bound cluster of some 30 galaxies, called the Local Group. Two giant spirals dominate the group: our Milky Way and the Andromeda galaxy, about two million light-years away.

The Local Supercluster
(Diameter = 200 million light-years.)
The Local Group is part of the Local Supercluster. Within this supercluster, the closest rich cluster to our Local Group is Virgo, some 50 million light-years away, near the center of the supercluster. It has thousands of galaxies.

Table II

THE SOLAR SYSTEM				
	Diameter		**Distance to Sun**	
	(Miles)	Ratio	(Millions of miles)	Ratio
Sun	870,000	110	0	0
Mercury	3,000	0.4	36	0.4
Venus	7,500	0.9	67	0.7
Earth	**7,900**	**1**	**93**	**1**
Mars	4,200	0.5	140	1.5
(Asteroid Belt)				
Jupiter	89,000	11	480	5
Saturn	75,000	9	890	10
Uranus	32,000	4	1,800	19
Neptune	30,000	3.8	2,800	30
Pluto	1,400	0.2	3,700	40

Outside the Local Supercluster, the nearest rich cluster is the Coma cluster, about seven times farther than the Virgo cluster. Its main body has a diameter of about 25 million light-years.

Astronomers believe that superclusters now fill perhaps 10% of the volume of the universe. In whatever direction we look, we can detect clusters and superclusters of galaxies.