

ASTRONOMY

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CHAPTER 1 — SCIENCE AND THE UNIVERSE: A BRIEF TOUR

Astronomy is defined as the study of the objects that lie beyond our planet Earth and the processes by which these objects interact with one another. We will see, though, that it is much more. It is also humanity's attempt to organize what we learn into a clear history of the universe, from the instant of its birth in the Big Bang to the present moment. Throughout this book, we emphasize that science is a progress report—one that changes constantly as new techniques and instruments allow us to probe the universe more deeply.

CHAPTER 2 — OBSERVING THE SKY: THE BIRTH OF ASTRONOMY

2.1 The Sky Above

The direct evidence of our senses supports a geocentric perspective, with the celestial sphere pivoting on the celestial poles and rotating about a stationary Earth. We see only half of this sphere at one time, limited by the horizon; the point directly overhead is our zenith. The Sun's annual path on the celestial sphere is the ecliptic—a line that runs through the center of the zodiac, which is the 18-degree-wide strip of the sky within which we always find the Moon and planets. The celestial sphere is organized into 88 constellations, or sectors.

2.2 Ancient Astronomy

Ancient Greeks such as Aristotle recognized that Earth and the Moon are spheres, and understood the phases of the Moon, but because of their inability to detect stellar parallax, they rejected the idea that Earth moves. Eratosthenes measured the size of Earth with surprising precision. Hipparchus carried out many astronomical observations, making a star catalog, defining the system of stellar magnitudes, and discovering precession from the apparent shift in the position of the north celestial pole. Ptolemy of Alexandria summarized classic astronomy in his *Almagest*; he explained planetary motions, including retrograde motion, with remarkably good accuracy using a model centered on Earth. This geocentric model, based on combinations of uniform circular motion using epicycles, was accepted as authority for more than a thousand years.

2.3 Astrology and Astronomy

The ancient religion of astrology, with its main contribution to civilization a heightened interest in the heavens, began in Babylonia. It reached its peak in the Greco-Roman world, especially as recorded in the *Tetrabiblos* of Ptolemy. Natal astrology is based on the assumption that the positions of the planets at the time of our birth, as described by a horoscope, determine our future. However, modern tests clearly show that there is no evidence for this, even in a broad statistical sense, and there is no verifiable theory to explain what might cause such an astrological influence.

2.4 The Birth of Modern Astronomy

Nicolaus Copernicus introduced the heliocentric cosmology to Renaissance Europe in his book *De Revolutionibus*. Although he retained the Aristotelian idea of uniform circular motion, Copernicus suggested that Earth is a planet and that the planets all circle about the Sun, dethroning Earth from its position at the center of the universe. Galileo was the father of both modern experimental physics and telescopic astronomy. He studied the acceleration of moving objects and, in 1610, began telescopic

observations, discovering the nature of the Milky Way, the large-scale features of the Moon, the phases of Venus, and four moons of Jupiter. Although he was accused of heresy for his support of heliocentric cosmology, Galileo is credited with observations and brilliant writings that convinced most of his scientific contemporaries of the reality of the Copernican theory.

CHAPTER 3 — ORBITS AND GRAVITY

3.1 The Laws of Planetary Motion

Tycho Brahe's accurate observations of planetary positions provided the data used by Johannes Kepler to derive his three fundamental laws of planetary motion. Kepler's laws describe the behavior of planets in their orbits as follows: (1) planetary orbits are ellipses with the Sun at one focus; (2) in equal intervals, a planet's orbit sweeps out equal areas; and (3) the relationship between the orbital period (P) and the semimajor axis (a) of an orbit is given by $P^2 = a^3$ (when a is in units of AU and P is in units of Earth years).

3.2 Newton's Great Synthesis

In his *Principia*, Isaac Newton established the three laws that govern the motion of objects: (1) objects continue to be at rest or move with a constant velocity unless acted upon by an outside force; (2) an outside force causes an acceleration (and changes the momentum) for an object; and (3) for every action there is an equal and opposite reaction. Momentum is a measure of the motion of an object and depends on both its mass and its velocity. Angular momentum is a measure of the motion of a spinning or revolving object and depends on its mass, velocity, and distance from the point around which it revolves. The density of an object is its mass divided by its volume.

3.3 Newton's Universal Law of Gravitation

Gravity, the attractive force between all masses, is what keeps the planets in orbit. Newton's universal law of gravitation relates the gravitational force to mass and distance: $F_{\text{gravity}} = G \times M_1 \times M_2 \div R^2$. The force of gravity is what gives us our sense of weight. Unlike mass, which is constant, weight can vary depending on the force of gravity (or acceleration) you feel. When Kepler's laws are reexamined in the light of Newton's gravitational law, it becomes clear that the masses of both objects are important for the third law, which becomes $a^3 = (M_1 + M_2) \times P^2$. Mutual gravitational effects permit us to calculate the masses of astronomical objects, from comets to galaxies.

3.4 Orbits in the Solar System

The closest point in a satellite orbit around Earth is its perigee, and the farthest point is its apogee (corresponding to perihelion and aphelion for an orbit around the Sun). The planets follow orbits around the Sun that are nearly circular and in the same plane. Most asteroids are found between Mars and Jupiter in the asteroid belt, whereas comets generally follow orbits of high eccentricity.

3.5 Motions of Satellites and Spacecraft

The orbit of an artificial satellite depends on the circumstances of its launch. The circular satellite velocity needed to orbit Earth's surface is 8 kilometers per second, and the escape speed from our planet is 11 kilometers per second. There are many possible interplanetary trajectories, including those that use

gravity-assisted flybys of one object to redirect the spacecraft toward its next target.

3.6 Gravity with More Than Two Bodies

Calculating the gravitational interaction of more than two objects is complicated and requires large computers. If one object (like the Sun in our solar system) dominates gravitationally, it is possible to calculate the effects of a second object in terms of small perturbations. This approach was used by John Couch Adams and Urbain Le Verrier to predict the position of Neptune from its perturbations of the orbit of Uranus and thus discover a new planet mathematically.

CHAPTER 4 — EARTH, MOON AND SKY

4.1 Earth and Sky

The terrestrial system of latitude and longitude makes use of the great circles called meridians. Longitude is arbitrarily set to 0° at the Royal Observatory at Greenwich, England. An analogous celestial coordinate system is called right ascension (RA) and declination, with 0° of declination starting at the vernal equinox. These coordinate systems help us locate any object on the celestial sphere. The Foucault pendulum is a way to demonstrate that Earth is turning.

4.2 The Seasons

The familiar cycle of the seasons results from the 23.5° tilt of Earth's axis of rotation. At the summer solstice, the Sun is higher in the sky and its rays strike Earth more directly. The Sun is in the sky for more than half of the day and can heat Earth longer. At the winter solstice, the Sun is low in the sky and its rays come in at more of an angle; in addition, it is up for fewer than 12 hours, so those rays have less time to heat. At the vernal and autumnal equinoxes, the Sun is on the celestial equator and we get about 12 hours of day and night. The seasons are different at different latitudes.

4.3 Keeping Time

The basic unit of astronomical time is the day—either the solar day (reckoned by the Sun) or the sidereal day (reckoned by the stars). Apparent solar time is based on the position of the Sun in the sky, and mean solar time is based on the average value of a solar day during the year. By international agreement, we define 24 time zones around the world, each with its own standard time. The convention of the International Date Line is necessary to reconcile times on different parts of Earth.

4.4 The Calendar

The fundamental problem of the calendar is to reconcile the incommensurable lengths of the day, month, and year. Most modern calendars, beginning with the Roman (Julian) calendar of the first century BCE, neglect the problem of the month and concentrate on achieving the correct number of days in a year by using such conventions as the leap year. Today, most of the world has adopted the Gregorian calendar established in 1582 while finding ways to coexist with the older lunar calendars' system of months.

4.5 Phases and Motions of the Moon

The Moon's monthly cycle of phases results from the changing angle of its illumination by the Sun. The

full moon is visible in the sky only during the night; other phases are visible during the day as well. Because its period of revolution is the same as its period of rotation, the Moon always keeps the same face toward Earth.

4.6 Ocean Tides and the Moon

The twice-daily ocean tides are primarily the result of the Moon's differential force on the material of Earth's crust and ocean. These tidal forces cause ocean water to flow into two tidal bulges on opposite sides of Earth; each day, Earth rotates through these bulges. Actual ocean tides are complicated by the additional effects of the Sun and by the shape of the coasts and ocean basins.

4.7 Eclipses of the Sun and Moon

The Sun and Moon have nearly the same angular size (about $\frac{1}{2}^\circ$). A solar eclipse occurs when the Moon moves between the Sun and Earth, casting its shadow on a part of Earth's surface. If the eclipse is total, the light from the bright disk of the Sun is completely blocked, and the solar atmosphere (the corona) comes into view. Solar eclipses take place rarely in any one location, but they are among the most spectacular sights in nature. A lunar eclipse takes place when the Moon moves into Earth's shadow; it is visible (weather permitting) from the entire night hemisphere of Earth.

CHAPTER 5 — RADIATION AND SPECTRA

5.1 The Behavior of Light

James Clerk Maxwell showed that whenever charged particles change their motion, as they do in every atom and molecule, they give off waves of energy. Light is one form of this electromagnetic radiation. The wavelength of light determines the color of visible radiation. Wavelength (λ) is related to frequency (f) and the speed of light (c) by the equation $c = \lambda f$. Electromagnetic radiation sometimes behaves like waves, but at other times, it behaves as if it were a particle—a little packet of energy, called a photon. The apparent brightness of a source of electromagnetic energy decreases with increasing distance from that source in proportion to the square of the distance—a relationship known as the inverse square law.

5.2 The Electromagnetic Spectrum

The electromagnetic spectrum consists of gamma rays, X-rays, ultraviolet radiation, visible light, infrared, and radio radiation. Many of these wavelengths cannot penetrate the layers of Earth's atmosphere and must be observed from space, whereas others—such as visible light, FM radio and TV—can penetrate to Earth's surface. The emission of electromagnetic radiation is intimately connected to the temperature of the source. The higher the temperature of an idealized emitter of electromagnetic radiation, the shorter is the wavelength at which the maximum amount of radiation is emitted. The mathematical equation describing this relationship is known as Wien's law: $\lambda_{\text{max}} = (3 \times 10^6) \div T$. The total power emitted per square meter increases with increasing temperature. The relationship between emitted energy flux and temperature is known as the Stefan-Boltzmann law: $F = \sigma T^4$.

5.3 Spectroscopy in Astronomy

A spectrometer is a device that forms a spectrum, often utilizing the phenomenon of dispersion. The light from an astronomical source can consist of a continuous spectrum, an emission (bright line)

spectrum, or an absorption (dark line) spectrum. Because each element leaves its spectral signature in the pattern of lines we observe, spectral analyses reveal the composition of the Sun and stars.

5.4 The Structure of the Atom

Atoms consist of a nucleus containing one or more positively charged protons. All atoms except hydrogen can also contain one or more neutrons in the nucleus. Negatively charged electrons orbit the nucleus. The number of protons defines an element (hydrogen has one proton, helium has two, and so on) of the atom. Nuclei with the same number of protons but different numbers of neutrons are different isotopes of the same element. In the Bohr model of the atom, electrons on permitted orbits (or energy levels) don't give off any electromagnetic radiation. But when electrons go from lower levels to higher ones, they must absorb a photon of just the right energy, and when they go from higher levels to lower ones, they give off a photon of just the right energy. The energy of a photon is connected to the frequency of the electromagnetic wave it represents by Planck's formula, $E = hf$.

5.5 Formation of Spectral Lines

When electrons move from a higher energy level to a lower one, photons are emitted, and an emission line can be seen in the spectrum. Absorption lines are seen when electrons absorb photons and move to higher energy levels. Since each atom has its own characteristic set of energy levels, each is associated with a unique pattern of spectral lines. This allows astronomers to determine what elements are present in the stars and in the clouds of gas and dust among the stars. An atom in its lowest energy level is in the ground state. If an electron is in an orbit other than the least energetic one possible, the atom is said to be excited. If an atom has lost one or more electrons, it is called an ion and is said to be ionized. The spectra of different ions look different and can tell astronomers about the temperatures of the sources they are observing.

5.6 The Doppler Effect

If an atom is moving toward us when an electron changes orbits and produces a spectral line, we see that line shifted slightly toward the blue of its normal wavelength in a spectrum. If the atom is moving away, we see the line shifted toward the red. This shift is known as the Doppler effect and can be used to measure the radial velocities of distant objects.

CHAPTER 6 — ASTRONOMICAL INSTRUMENTS

6.1 Telescopes

A telescope collects the faint light from astronomical sources and brings it to a focus, where an instrument can sort the light according to wavelength. Light is then directed to a detector, where a permanent record is made. The light-gathering power of a telescope is determined by the diameter of its aperture, or opening—that is, by the area of its largest or primary lens or mirror. The primary optical element in a telescope is either a convex lens (in a refracting telescope) or a concave mirror (in a reflector) that brings the light to a focus. Most large telescopes are reflectors; it is easier to manufacture and support large mirrors because the light does not have to pass through glass.

6.2 Telescopes Today

New technologies for creating and supporting lightweight mirrors have led to the construction of a number of large telescopes since 1990. The site for an astronomical observatory must be carefully chosen for clear weather, dark skies, low water vapor, and excellent atmospheric seeing (low atmospheric turbulence). The resolution of a visible-light or infrared telescope is degraded by turbulence in Earth's atmosphere. The technique of adaptive optics, however, can make corrections for this turbulence in real time and produce exquisitely detailed images.

6.3 Visible-Light Detectors and Instruments

Visible-light detectors include the human eye, photographic film, and charge-coupled devices (CCDs). Detectors that are sensitive to infrared radiation must be cooled to very low temperatures since everything in and near the telescope gives off infrared waves. A spectrometer disperses the light into a spectrum to be recorded for detailed analysis.

6.4 Radio Telescopes

In the 1930s, radio astronomy was pioneered by Karl G. Jansky and Grote Reber. A radio telescope is basically a radio antenna (often a large, curved dish) connected to a receiver. Significantly enhanced resolution can be obtained with interferometers, including interferometer arrays like the 27-element VLA and the 66-element ALMA. Expanding to very long baseline interferometers, radio astronomers can achieve resolutions as precise as 0.0001 arcsecond. Radar astronomy involves transmitting as well as receiving. The largest radar telescope currently in operation is a 305-meter bowl at Arecibo.

6.5 Observations outside Earth's Atmosphere

Infrared observations are made with telescopes aboard aircraft and in space, as well as from ground-based facilities on dry mountain peaks. Ultraviolet, X-ray, and gamma-ray observations must be made from above the atmosphere. Many orbiting observatories have been flown to observe in these bands of the spectrum in the last few decades. The largest-aperture telescope in space is the Hubble Space telescope (HST), the most significant infrared telescope is Spitzer, and Chandra and Fermi are the premier X-ray and gamma-ray observatories, respectively.

6.6 The Future of Large Telescopes

New and even larger telescopes are on the drawing boards. The James Webb Space Telescope, a 6-meter successor to Hubble, is currently scheduled for launch in 2018. Gamma-ray astronomers are planning to build the CTA to measure very energetic gamma rays. Astronomers are building the LSST to observe with an unprecedented field of view and a new generation of visible-light/infrared telescopes with apertures of 24.5 to 39 meters in diameter.

CHAPTER 7 — OTHER WORLDS: AN INTRODUCTION TO THE SOLAR SYSTEM

7.1 Overview of Our Planetary System

Our solar system currently consists of the Sun, eight planets, five dwarf planets, nearly 200 known moons, and a host of smaller objects. The planets can be divided into two groups: the inner terrestrial planets and the outer giant planets. Pluto, Eris, Haumea, and Makemake do not fit into either category; as icy dwarf planets, they exist in an ice realm on the fringes of the main planetary system. The giant

planets are composed mostly of liquids and gases. Smaller members of the solar system include asteroids (including the dwarf planet Ceres), which are rocky and metallic objects found mostly between Mars and Jupiter; comets, which are made mostly of frozen gases and generally orbit far from the Sun; and countless smaller grains of cosmic dust. When a meteor survives its passage through our atmosphere and falls to Earth, we call it a meteorite.

7.2 Composition and Structure of Planets

The giant planets have dense cores roughly 10 times the mass of Earth, surrounded by layers of hydrogen and helium. The terrestrial planets consist mostly of rocks and metals. They were once molten, which allowed their structures to differentiate (that is, their denser materials sank to the center). The Moon resembles the terrestrial planets in composition, but most of the other moons—which orbit the giant planets—have larger quantities of frozen ice within them. In general, worlds closer to the Sun have higher surface temperatures. The surfaces of terrestrial planets have been modified by impacts from space and by varying degrees of geological activity.

7.3 Dating Planetary Surfaces

The ages of the surfaces of objects in the solar system can be estimated by counting craters: on a given world, a more heavily cratered region will generally be older than one that is less cratered. We can also use samples of rocks with radioactive elements in them to obtain the time since the layer in which the rock formed last solidified. The half-life of a radioactive element is the time it takes for half the sample to decay; we determine how many half-lives have passed by how much of a sample remains the radioactive element and how much has become the decay product. In this way, we have estimated the age of the Moon and Earth to be roughly 4.5 billion years.

7.4 Origin of the Solar System

Regularities among the planets have led astronomers to hypothesize that the Sun and the planets formed together in a giant, spinning cloud of gas and dust called the solar nebula. Astronomical observations show tantalizingly similar circumstellar disks around other stars. Within the solar nebula, material first coalesced into planetesimals; many of these gathered together to make the planets and moons. The remainder can still be seen as comets and asteroids. Probably all planetary systems have formed in similar ways, but many exoplanet systems have evolved along quite different paths, as we will see in chapter 14, *Cosmic Samples and the Origin of the Solar System*.

CHAPTER 8 — EARTH AS A PLANET

8.1 The Global Perspective

Earth is the prototype terrestrial planet. Its interior composition and structure are probed using seismic waves. Such studies reveal that Earth has a metal core and a silicate mantle. The outer layer, or crust, consists primarily of oceanic basalt and continental granite. A global magnetic field, generated in the core, produces Earth's magnetosphere, which can trap charged atomic particles.

8.2 Earth's Crust

Terrestrial rocks can be classified as igneous, sedimentary, or metamorphic. A fourth type, primitive

rock, is not found on Earth. Our planet's geology is dominated by plate tectonics, in which crustal plates move slowly in response to mantle convection. The surface expression of plate tectonics includes continental drift, recycling of the ocean floor, mountain building, rift zones, subduction zones, faults, earthquakes, and volcanic eruptions of lava from the interior.

8.3 Earth's Atmosphere

The atmosphere has a surface pressure of 1 bar and is composed primarily of N₂ and O₂, plus such important trace gases as H₂O, CO₂, and O₃. Its structure consists of the troposphere, stratosphere, mesosphere, and ionosphere. Changing the composition of the atmosphere also influences the temperature. Atmospheric circulation (weather) is driven by seasonally changing deposition of sunlight. Many longer term climate variations, such as the ice ages, are related to changes in the planet's orbit and axial tilt.

8.4 Life, Chemical Evolution, and Climate Change

Life originated on Earth at a time when the atmosphere lacked O₂ and consisted mostly of CO₂. Later, photosynthesis gave rise to free oxygen and ozone. Modern genomic analysis lets us see how the wide diversity of species on the planet are related to each other. CO₂ and methane in the atmosphere heat the surface through the greenhouse effect; today, increasing amounts of atmospheric CO₂ are leading to the global warming of our planet.

8.5 Cosmic Influences on the Evolution of Earth

Earth, like the Moon and other planets, has been influenced by the impacts of cosmic debris, including such recent examples as Meteor Crater and the Tunguska explosion. Larger past impacts are implicated in some mass extinctions, including the large impact 65 million years ago at the end of the Cretaceous period that wiped out the dinosaurs and many other species. Today, astronomers are working to predict the next impact in advance, while other scientists are coming to grips with the effect of impacts on the evolution and diversity of life on Earth.

CHAPTER 9 — CRATERED WORLDS

9.1 General Properties of the Moon

Most of what we know about the Moon derives from the Apollo program, including 400 kilograms of lunar samples still being intensively studied. The Moon has one-eightieth the mass of Earth and is severely depleted in both metals and volatile materials. It is made almost entirely of silicates like those in Earth's mantle and crust. However, more recent spacecraft have found evidence of a small amount of water near the lunar poles, most likely deposited by comet and asteroid impacts.

9.2 The Lunar Surface

The Moon, like Earth, was formed about 4.5 billion year ago. The Moon's heavily cratered highlands are made of rocks more than 4 billion years old. The darker volcanic plains of the maria were erupted primarily between 3.3 and 3.8 billion years ago. Generally, the surface is dominated by impacts, including continuing small impacts that produce its fine-grained soil.

9.3 Impact Craters

A century ago, Grove Gilbert suggested that the lunar craters were caused by impacts, but the cratering process was not well understood until more recently. High-speed impacts produce explosions and excavate craters 10 to 15 times the size of the impactor with raised rims, ejecta blankets, and often central peaks. Cratering rates have been roughly constant for the past 3 billion years but earlier were much greater. Crater counts can be used to derive approximate ages for geological features on the Moon and other worlds with solid surfaces.

9.4 The Origin of the Moon

The three standard hypotheses for the origin of the Moon were the fission hypothesis, the sister hypothesis, and the capture hypothesis. All have problems, and they have been supplanted by the giant impact hypothesis, which ascribes the origin of the Moon to the impact of a Mars-sized projectile with Earth 4.5 billion years ago. The debris from the impact made a ring around Earth which condensed and formed the Moon.

9.5 Mercury

Mercury is the nearest planet to the Sun and the fastest moving. Mercury is similar to the Moon in having a heavily cratered surface and no atmosphere, but it differs in having a very large metal core. Early in its evolution, it apparently lost part of its silicate mantle, probably due to one or more giant impacts. Long scarps on its surface testify to a global compression of Mercury's crust during the past 4 billion years.

CHAPTER 10 — EARTHLIKE PLANETS: VENUS AND MARS

10.1 The Nearest Planets: An Overview

Venus, the nearest planet, is a great disappointment through the telescope because of its impenetrable cloud cover. Mars is more tantalizing, with dark markings and polar caps. Early in the twentieth century, it was widely believed that the "canals" of Mars indicated intelligent life there. Mars has only 11% the mass of Earth, but Venus is nearly our twin in size and mass. Mars rotates in 24 hours and has seasons like Earth; Venus has a retrograde rotation period of 243 days. Both planets have been extensively explored by spacecraft.

10.2 The Geology of Venus

Venus has been mapped by radar, especially with the Magellan spacecraft. Its crust consists of 75% lowland lava plains, numerous volcanic features, and many large coronae, which are the expression of subsurface volcanism. The planet has been modified by widespread tectonics driven by mantle convection, forming complex patterns of ridges and cracks and building high continental regions such as Ishtar. The surface is extraordinarily inhospitable, with pressure of 90 bars and temperature of 730 K, but several Russian Venera landers investigated it successfully.

10.3 The Massive Atmosphere of Venus

The atmosphere of Venus is 96% CO₂. Thick clouds at altitudes of 30 to 60 kilometers are made of

sulfuric acid, and a CO₂ greenhouse effect maintains the high surface temperature. Venus presumably reached its current state from more earthlike initial conditions as a result of a runaway greenhouse effect, which included the loss of large quantities of water.

10.4 The Geology of Mars

Most of what we know about Mars is derived from spacecraft: highly successful orbiters, landers, and rovers. We have also been able to study a few martian rocks that reached Earth as meteorites. Mars has heavily cratered highlands in its southern hemisphere, but younger, lower volcanic plains over much of its northern half. The Tharsis bulge, as big as North America, includes several huge volcanoes; Olympus Mons is more than 20 kilometers high and 500 kilometers in diameter. The Valles Marineris canyons are tectonic features widened by erosion. Early landers revealed only barren, windswept plains, but later missions have visited places with more geological (and scenic) variety. Landing sites have been selected in part to search for evidence of past water.

10.5 Water and Life on Mars

The martian atmosphere has a surface pressure of less than 0.01 bar and is 95% CO₂. It has dust clouds, water clouds, and carbon dioxide (dry ice) clouds. Liquid water on the surface is not possible today, but there is subsurface permafrost at high latitudes. Seasonal polar caps are made of dry ice; the northern residual cap is water ice, whereas the southern permanent ice cap is made predominantly of water ice with a covering of carbon dioxide ice. Evidence of a very different climate in the past is found in water erosion features: both runoff channels and outflow channels, the latter carved by catastrophic floods. Our rovers, exploring ancient lakebeds and places where sedimentary rock has formed, have found evidence for extensive surface water in the past. Even more exciting are the gullies that seem to show the presence of flowing salty water on the surface today, hinting at near-surface aquifers. The Viking landers searched for martian life in 1976, with negative results, but life might have flourished long ago. We have found evidence of water on Mars, but following the water has not yet led us to life on that planet.

10.6 Divergent Planetary Evolution

Earth, Venus, and Mars have diverged in their evolution from what may have been similar beginnings. We need to understand why if we are to protect the environment of Earth.

CHAPTER 11 — THE GIANT PLANETS

11.1 Exploring the Outer Planets

The outer solar system contains the four giant planets: Jupiter, Saturn, Uranus, and Neptune. The gas giants Jupiter and Saturn have overall compositions similar to that of the Sun. These planets have been explored by the Pioneer, Voyager, Galileo, and Cassini spacecraft. Voyager 2, perhaps the most successful of all space-science missions, explored Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989)—a grand tour of the giant planets—and these flybys have been the only explorations to date of the ice giants Uranus and Neptune. The Galileo and Cassini missions were long-lived orbiters, and each also deployed an entry probe, one into Jupiter and one into Saturn's moon Titan.

11.2 The Giant Planets

Jupiter is 318 times more massive than Earth. Saturn is about 25% as massive as Jupiter, and Uranus and Neptune are only 5% as massive. All four have deep atmospheres and opaque clouds, and all rotate quickly with periods from 10 to 17 hours. Jupiter and Saturn have extensive mantles of liquid hydrogen. Uranus and Neptune are depleted in hydrogen and helium relative to Jupiter and Saturn (and the Sun). Each giant planet has a core of “ice” and “rock” of about 10 Earth masses. Jupiter, Saturn, and Neptune have major internal heat sources, obtaining as much (or more) energy from their interiors as by radiation from the Sun. Uranus has no measurable internal heat. Jupiter has the strongest magnetic field and largest magnetosphere of any planet, first discovered by radio astronomers from observations of synchrotron radiation.

11.3 Atmospheres of the Giant Planets

The four giant planets have generally similar atmospheres, composed mostly of hydrogen and helium. Their atmospheres contain small quantities of methane and ammonia gas, both of which also condense to form clouds. Deeper (invisible) cloud layers consist of water and possibly ammonium hydrosulfide (Jupiter and Saturn) and hydrogen sulfide (Neptune). In the upper atmospheres, hydrocarbons and other trace compounds are produced by photochemistry. We do not know exactly what causes the colors in the clouds of Jupiter. Atmospheric motions on the giant planets are dominated by east-west circulation. Jupiter displays the most active cloud patterns, with Neptune second. Saturn is generally bland, in spite of its extremely high wind speeds, and Uranus is featureless (perhaps due to its lack of an internal heat source). Large storms (oval-shaped high-pressure systems such as the Great Red Spot on Jupiter and the Great Dark Spot on Neptune) can be found in some of the planet atmospheres.

CHAPTER 12 — RINGS, MOONS AND PLUTO

12.1 Ring and Moon Systems Introduced

The four jovian planets are accompanied by impressive systems of moons and rings. Nearly 200 moons have been discovered in the outer solar system. Of the four ring systems, Saturn’s is the largest and is composed primarily of water ice; in contrast, Uranus and Neptune have narrow rings of dark material, and Jupiter has a tenuous ring of dust.

12.2 The Galilean Moons of Jupiter

Jupiter’s largest moons are Ganymede and Callisto, both low-density objects that are composed of more than half water ice. Callisto has an ancient cratered surface, while Ganymede shows evidence of extensive tectonic and volcanic activity, persisting until perhaps a billion years ago. Io and Europa are denser and smaller, each about the size of our Moon. Io is the most volcanically active object in the solar system. Various lines of evidence indicate that Europa has a global ocean of liquid water under a thick ice crust. Many scientists think that Europa may offer the most favorable environment in the solar system to search for life.

12.3 Titan and Triton

Saturn’s moon Titan has an atmosphere that is thicker than that of Earth. There are lakes and rivers of liquid hydrocarbons, and evidence of a cycle of evaporation, condensation, and return to the surface that is similar to the water cycle on Earth (but with liquid methane and ethane). The Cassini-Huygens lander

set down on Titan and showed a scene with boulders, made of water ice, frozen harder than rock. Neptune's cold moon Triton has a very thin atmosphere and nitrogen gas geysers.

12.4 Pluto and Charon

Pluto and Charon have been revealed by the New Horizons spacecraft to be two of the most fascinating objects in the outer solar system. Pluto is small (a dwarf planet) but also surprisingly active, with contrasting areas of dark cratered terrain, light-colored basins of nitrogen ice, and mountains of frozen water that may be floating in the nitrogen ice. Even Pluto's largest moon Charon shows evidence of geological activity. Both Pluto and Charon turn out to be far more dynamic and interesting than could have been imagined before the New Horizons mission.

12.5 Planetary Rings

Rings are composed of vast numbers of individual particles orbiting so close to a planet that its gravitational forces could have broken larger pieces apart or kept small pieces from gathering together. Saturn's rings are broad, flat, and nearly continuous, except for a handful of gaps. The particles are mostly water ice, with typical dimensions of a few centimeters. One Saturn moon, Enceladus, is today erupting geysers of water to maintain the tenuous E Ring, which is composed of very small ice crystals. The rings of Uranus are narrow ribbons separated by wide gaps and contain much less mass. Neptune's rings are similar but contain even less material. Much of the complex structure of the rings is due to waves and resonances induced by moons within the rings or orbiting outside them. The origin and age of each of these ring systems is still a mystery.

CHAPTER 13 — COMETS AND ASTEROIDS: DEBRIS OF THE SOLAR SYSTEM

13.1 Asteroids

The solar system includes many objects that are much smaller than the planets and their larger moons. The rocky ones are generally called asteroids. Ceres is the largest asteroid; about 15 are larger than 250 kilometers and about 100,000 are larger than 1 kilometer. Most are in the asteroid belt between Mars and Jupiter. The presence of asteroid families in the belt indicates that many asteroids are the remnants of ancient collisions and fragmentation. The asteroids include both primitive and differentiated objects. Most asteroids are classed as C-type, meaning they are composed of carbonaceous materials. Dominating the inner belt are S-type (stony) asteroids, with a few M-type (metallic) ones. We have spacecraft images of several asteroids and returned samples from asteroid Itokawa. Recent observations have detected a number of asteroid moons, making it possible to measure the masses and densities of the asteroids they orbit. The two largest asteroids, Ceres and Vesta, have been extensively studied from orbit by the Dawn spacecraft.

13.2 Asteroids and Planetary Defense

Near-Earth asteroids (NEAs), and near-Earth objects (NEOs) in general, are of interest in part because of their potential to hit Earth. They are on unstable orbits, and on timescales of 100 million years, they will either impact one of the terrestrial planets or the Sun, or be ejected. Most of them probably come from the asteroid belt, but some may be dead comets. NASA's Spaceguard Survey has found 90% of the NEAs larger than 1 kilometer, and none of the ones found so far are on a collision course with Earth. Scientists are actively working on possible technologies for planetary defense in case any NEOs are

found on a collision course with Earth years in advance. For now, the most important task is to continue our surveys, so we can find the next Earth impactor before it finds us.

13.3 The “Long-Haired” Comets

Halley first showed that some comets are on closed orbits and return periodically to swing around the Sun. The heart of a comet is its nucleus, a few kilometers in diameter and composed of volatiles (primarily frozen H₂O) and solids (including both silicates and carbonaceous materials). Whipple first suggested this “dirty snowball” model in 1950; it has been confirmed by spacecraft studies of several comets. As the nucleus approaches the Sun, its volatiles evaporate (perhaps in localized jets or explosions) to form the comet’s head or atmosphere, which escapes at about 1 kilometer per second. The atmosphere streams away from the Sun to form a long tail. The ESA Rosetta mission to Comet P67 (Churyumov-Gerasimenko) has greatly increased our knowledge of the nature of the nucleus and of the process by which comets release water and other volatiles when heated by sunlight.

13.4 The Origin and Fate of Comets and Related Objects

Oort proposed in 1950 that long-period comets are derived from what we now call the Oort cloud, which surrounds the Sun out to about 50,000 AU (near the limit of the Sun’s gravitational sphere of influence) and contains between 10^{12} and 10^{13} comets. Comets also come from the Kuiper belt, a disk-shaped region beyond the orbit of Neptune, extending to 50 AU from the Sun. Comets are primitive bodies left over from the formation of the outer solar system. Once a comet is diverted into the inner solar system, it typically survives no more than a few thousand perihelion passages before losing all its volatiles. Some comets die spectacular deaths: Shoemaker-Levy 9, for example, broke into 20 pieces before colliding with Jupiter in 1994.

CHAPTER 14 — COSMIC SAMPLES AND THE ORIGIN OF THE SOLAR SYSTEM

14.1 Meteors

When a fragment of interplanetary dust strikes Earth’s atmosphere, it burns up to create a meteor. Streams of dust particles traveling through space together produce meteor showers, in which we see meteors diverging from a spot in the sky called the radiant of the shower. Many meteor showers recur each year and are associated with particular comets that have left dust behind as they come close to the Sun and their ices evaporate (or have broken up into smaller pieces).

14.2 Meteorites: Stones from Heaven

Meteorites are the debris from space (mostly asteroid fragments) that survive to reach the surface of Earth. Meteorites are called finds or falls according to how they are discovered; the most productive source today is the Antarctic ice cap. Meteorites are classified as irons, stony-irons, or stones accordingly to their composition. Most stones are primitive objects, dated to the origin of the solar system 4.5 billion years ago. The most primitive are the carbonaceous meteorites, such as Murchison and Allende. These can contain a number of organic (carbon-rich) molecules.

14.3 Formation of the Solar System

A viable theory of solar system formation must take into account motion constraints, chemical

constraints, and age constraints. Meteorites, comets, and asteroids are survivors of the solar nebula out of which the solar system formed. This nebula was the result of the collapse of an interstellar cloud of gas and dust, which contracted (conserving its angular momentum) to form our star, the Sun, surrounded by a thin, spinning disk of dust and vapor. Condensation in the disk led to the formation of planetesimals, which became the building blocks of the planets. Accretion of infalling materials heated the planets, leading to their differentiation. The giant planets were also able to attract and hold gas from the solar nebula. After a few million years of violent impacts, most of the debris was swept up or ejected, leaving only the asteroids and cometary remnants surviving to the present.

14.4 Comparison with Other Planetary Systems

The first planet circling a distant solar-type star was announced in 1995. Twenty years later, thousands of exoplanets have been identified, including planets with sizes and masses between Earth's and Neptune's, which we don't have in our own solar system. A few percent of exoplanet systems have "hot Jupiters," massive planets that orbit close to their stars, and many exoplanets are also in eccentric orbits. These two characteristics are fundamentally different from the attributes of gas giant planets in our own solar system and suggest that giant planets can migrate inward from their place of formation where it is cold enough for ice to form. Current data indicate that small (terrestrial type) rocky planets are common in our Galaxy; indeed, there must be tens of billions of such earthlike planets.

14.5 Planetary Evolution

After their common beginning, each of the planets evolved on its own path. Different possible outcomes are illustrated by comparison of the terrestrial planets (Earth, Venus, Mars, Mercury, and the Moon). All are rocky, differentiated objects. The level of geological activity is proportional to mass: greatest for Earth and Venus, less for Mars, and absent for the Moon and Mercury. However, tides from another nearby world can also generate heat to drive geological activity, as shown by Io, Europa, and Enceladus. Pluto is also active, to the surprise of planetary scientists. On the surfaces of solid worlds, mountains can result from impacts, volcanism, or uplift. Whatever their origin, higher mountains can be supported on smaller planets that have less surface gravity. The atmospheres of the terrestrial planets may have acquired volatile materials from comet impacts. The Moon and Mercury lost their atmospheres; most volatiles on Mars are frozen due to its greater distance from the Sun and its thinner atmosphere; and Venus retained CO₂ but lost H₂O when it developed a massive greenhouse effect. Only Earth still has liquid water on its surface and hence can support life.

CHAPTER 15 — THE SUN: A GARDEN-VARIETY STAR

15.1 The Structure and Composition of the Sun

The Sun, our star, has several layers beneath the visible surface: the core, radiative zone, and convective zone. These, in turn, are surrounded by a number of layers that make up the solar atmosphere. In order of increasing distance from the center of the Sun, they are the photosphere, with a temperature that ranges from 4500 K to about 6800 K; the chromosphere, with a typical temperature of 10⁴ K; the transition region, a zone that may be only a few kilometers thick, where the temperature increases rapidly from 10⁴ K to 10⁶ K; and the corona, with temperatures of a few million K. The Sun's surface is mottled with upwelling convection currents seen as hot, bright granules. Solar wind particles stream out into the solar system through coronal holes. When such particles reach the vicinity of Earth, they produce auroras, which are strongest near Earth's magnetic poles. Hydrogen and helium together make

up 98% of the mass of the Sun, whose composition is much more characteristic of the universe at large than is the composition of Earth.

15.2 The Solar Cycle

Sunspots are dark regions where the temperature is up to 2000 K cooler than the surrounding photosphere. Their motion across the Sun's disk allows us to calculate how fast the Sun turns on its axis. The Sun rotates more rapidly at its equator, where the rotation period is about 25 days, than near the poles, where the period is slightly longer than 36 days. The number of visible sunspots varies according to a sunspot cycle that averages 11 years in length. Spots frequently occur in pairs. During a given 11-year cycle, all leading spots in the Northern Hemisphere have the same magnetic polarity, whereas all leading spots in the Southern Hemisphere have the opposite polarity. In the subsequent 11-year cycle, the polarity reverses. For this reason, the magnetic activity cycle of the Sun is understood to last for 22 years. This activity cycle is connected with the behavior of the Sun's magnetic field, but the exact mechanism is not yet understood.

15.3 Solar Activity above the Photosphere

Signs of more intense solar activity, an increase in the number of sunspots, as well as prominences, plagues, solar flares, and coronal mass ejections, all tend to occur in active regions—that is, in places on the Sun with the same latitude and longitude but at different heights in the atmosphere. Active regions vary with the solar cycle, just like sunspots do.

15.4 Space Weather

Space weather is the effect of solar activity on our own planet, both in our magnetosphere and on Earth's surface. Coronal holes allow more of the Sun's material to flow out into space. Solar flares and coronal mass ejections can cause auroras, disrupt communications, damage satellites, and cause power outages on Earth.

CHAPTER 16 — THE SUN: A NUCLEAR POWERHOUSE

16.1 Sources of Sunshine: Thermal and Gravitational Energy

The Sun produces an enormous amount of energy every second. Since Earth and the solar system are roughly 4.5 billion years old, this means that the Sun has been producing vast amounts for energy for a very, very long time. Neither chemical burning nor gravitational contraction can account for the total amount of energy radiated by the Sun during all this time.

16.2 Mass, Energy, and the Theory of Relativity

Solar energy is produced by interactions of particles—that is, protons, neutrons, electrons, positrons, and neutrinos. Specifically, the source of the Sun's energy is the fusion of hydrogen to form helium. The series of reactions required to convert hydrogen to helium is called the proton-proton chain. A helium atom is about 0.71% less massive than the four hydrogen atoms that combine to form it, and that lost mass is converted to energy (with the amount of energy given by the formula $E = mc^2$).

16.3 The Solar Interior: Theory

Even though we cannot see inside the Sun, it is possible to calculate what its interior must be like. As input for these calculations, we use what we know about the Sun. It is made entirely of hot gas. Apart from some very tiny changes, the Sun is neither expanding nor contracting (it is in hydrostatic equilibrium) and puts out energy at a constant rate. Fusion of hydrogen occurs in the center of the Sun, and the energy generated is carried to the surface by radiation and then convection. A solar model describes the structure of the Sun's interior. Specifically, it describes how pressure, temperature, mass, and luminosity depend on the distance from the center of the Sun.

16.4 The Solar Interior: Observations

Studies of solar oscillations (helioseismology) and neutrinos can provide observational data about the Sun's interior. The technique of helioseismology has so far shown that the composition of the interior is much like that of the surface (except in the core, where some of the original hydrogen has been converted into helium), and that the convection zone extends about 30% of the way from the Sun's surface to its center. Helioseismology can also detect active regions on the far side of the Sun and provide better predictions of solar storms that may affect Earth. Neutrinos from the Sun call tell us about what is happening in the solar interior. A recent experiment has shown that solar models do predict accurately the number of electron neutrinos produced by nuclear reactions in the core of the Sun. However, two-thirds of these neutrinos are converted into different types of neutrinos during their long journey from the Sun to Earth, a result that also indicates that neutrinos are not mass-less particles.

CHAPTER 17 — ANALYZING STARLIGHT

17.1 The Brightness of Stars

The total energy emitted per second by a star is called its luminosity. How bright a star looks from the perspective of Earth is its apparent brightness. The apparent brightness of a star depends on both its luminosity and its distance from Earth. Thus, the determination of apparent brightness and measurement of the distance to a star provide enough information to calculate its luminosity. The apparent brightnesses of stars are often expressed in terms of magnitudes, which is an old system based on how human vision interprets relative light intensity.

17.2 Colors of Stars

Stars have different colors, which are indicators of temperature. The hottest stars tend to appear blue or bluewhite, whereas the coolest stars are red. A color index of a star is the difference in the magnitudes measured at any two wavelengths and is one way that astronomers measure and express the temperature of stars.

17.3 The Spectra of Stars (and Brown Dwarfs)

The differences in the spectra of stars are principally due to differences in temperature, not composition. The spectra of stars are described in terms of spectral classes. In order of decreasing temperature, these spectral classes are O, B, A, F, G, K, M, L, T, and Y. These are further divided into subclasses numbered from 0 to 9. The classes L, T, and Y have been added recently to describe newly discovered star-like objects—mainly brown dwarfs—that are cooler than M9. Our Sun has spectral type G2.

17.4 Using Spectra to Measure Stellar Radius, Composition, and Motion

Spectra of stars of the same temperature but different atmospheric pressures have subtle differences, so spectra can be used to determine whether a star has a large radius and low atmospheric pressure (a giant star) or a small radius and high atmospheric pressure. Stellar spectra can also be used to determine the chemical composition of stars; hydrogen and helium make up most of the mass of all stars. Measurements of line shifts produced by the Doppler effect indicate the radial velocity of a star. Broadening of spectral lines by the Doppler effect is a measure of rotational velocity. A star can also show proper motion, due to the component of a star's space velocity across the line of sight.

CHAPTER 18 — THE STARS: A CELESTIAL CENSUS

18.1 A Stellar Census

To understand the properties of stars, we must make wide-ranging surveys. We find the stars that appear brightest to our eyes are bright primarily because they are intrinsically very luminous, not because they are the closest to us. Most of the nearest stars are intrinsically so faint that they can be seen only with the aid of a telescope. Stars with low mass and low luminosity are much more common than stars with high mass and high luminosity. Most of the brown dwarfs in the local neighborhood have not yet been discovered.

18.2 Measuring Stellar Masses

The masses of stars can be determined by analysis of the orbit of binary stars—two stars that orbit a common center of mass. In visual binaries, the two stars can be seen separately in a telescope, whereas in a spectroscopic binary, only the spectrum reveals the presence of two stars. Stellar masses range from about $1/12$ to more than 100 times the mass of the Sun (in rare cases, going to 250 times the Sun's mass). Objects with masses between $1/12$ and $1/100$ that of the Sun are called brown dwarfs. Objects in which no nuclear reactions can take place are planets. The most massive stars are, in most cases, also the most luminous, and this correlation is known as the mass-luminosity relation.

18.3 Diameters of Stars

The diameters of stars can be determined by measuring the time it takes an object (the Moon, a planet, or a companion star) to pass in front of it and block its light. Diameters of members of eclipsing binary systems (where the stars pass in front of each other) can be determined through analysis of their orbital motions.

18.4 The H–R Diagram

The Hertzsprung–Russell diagram, or H–R diagram, is a plot of stellar luminosity against surface temperature. Most stars lie on the main sequence, which extends diagonally across the H–R diagram from high temperature and high luminosity to low temperature and low luminosity. The position of a star along the main sequence is determined by its mass. High-mass stars emit more energy and are hotter than low-mass stars on the main sequence. Main-sequence stars derive their energy from the fusion of protons to helium. About 90% of the stars lie on the main sequence. Only about 10% of the stars are white dwarfs, and fewer than 1% are giants or supergiants.

CHAPTER 19 — CELESTIAL DISTANCES

19.1 Fundamental Units of Distance

Early measurements of length were based on human dimensions, but today, we use worldwide standards that specify lengths in units such as the meter. Distances within the solar system are now determined by timing how long it takes radar signals to travel from Earth to the surface of a planet or other body and then return.

19.2 Surveying the Stars

For stars that are relatively nearby, we can “triangulate” the distances from a baseline created by Earth’s annual motion around the Sun. Half the shift in a nearby star’s position relative to very distant background stars, as viewed from opposite sides of Earth’s orbit, is called the parallax of that star and is a measure of its distance. The units used to measure stellar distance are the light-year, the distance light travels in 1 year, and the parsec (pc), the distance of a star with a parallax of 1 arcsecond (1 parsec = 3.26 light-years). The closest star, a red dwarf, is over 1 parsec away. The first successful measurements of stellar parallaxes were reported in 1838. Parallax measurements are a fundamental link in the chain of cosmic distances. The Hipparcos satellite has allowed us to measure accurate parallaxes for stars out to about 300 light-years, and the Gaia mission will result in parallaxes out to 30,000 light-years.

19.3 Variable Stars: One Key to Cosmic Distances

Cepheids and RR Lyrae stars are two types of pulsating variable stars. Light curves of these stars show that their luminosities vary with a regularly repeating period. RR Lyrae stars can be used as standard bulbs, and cepheid variables obey a period-luminosity relation, so measuring their periods can tell us their luminosities. Then, we can calculate their distances by comparing their luminosities with their apparent brightnesses, and this can allow us to measure distances to these stars out to over 60 million light-years.

19.4 The H–R Diagram and Cosmic Distances

Stars with identical temperatures but different pressures (and diameters) have somewhat different spectra. Spectral classification can therefore be used to estimate the luminosity class of a star as well as its temperature. As a result, a spectrum can allow us to pinpoint where the star is located on an H–R diagram and establish its luminosity. This, with the star’s apparent brightness, again yields its distance. The various distance methods can be used to check one against another and thus make a kind of distance ladder which allows us to find even larger distances.

CHAPTER 20 — BETWEEN THE STARS: GAS AND DUST IN SPACE

20.1 The Interstellar Medium

About 15% of the visible matter in the Galaxy is in the form of gas and dust, serving as the raw material for new stars. About 99% of this interstellar matter is in the form of gas—individual atoms or molecules. The most abundant elements in the interstellar gas are hydrogen and helium. About 1% of the interstellar matter is in the form of solid interstellar dust grains.

20.2 Interstellar Gas

Interstellar gas may be hot or cold. Gas found near hot stars emits light by fluorescence, that is, light is emitted when an electron is captured by an ion and cascades down to lower-energy levels. Glowing clouds (nebulae) of ionized hydrogen are called H II regions and have temperatures of about 10,000 K. Most hydrogen in interstellar space is not ionized and can best be studied by radio measurements of the 21-centimeter line. Some of the gas in interstellar space is at a temperature of a million degrees, even though it is far away in hot stars; this ultra-hot gas is probably heated when rapidly moving gas ejected in supernova explosions sweeps through space. In some places, gravity gathers interstellar gas into giant clouds, within which the gas is protected from starlight and can form molecules; more than 200 different molecules have been found in space, including the basic building blocks of proteins, which are fundamental to life as we know it here on Earth.

20.3 Cosmic Dust

Interstellar dust can be detected: (1) when it blocks the light of stars behind it, (2) when it scatters the light from nearby stars, and (3) because it makes distant stars look both redder and fainter. These effects are called reddening and interstellar extinction, respectively. Dust can also be detected in the infrared because it emits heat radiation. Dust is found throughout the plane of the Milky Way. The dust particles are about the same size as the wavelength of light and consist of rocky cores that are either sootlike (carbon-rich) or sandlike (silicates) with mantles made of ices such as water, ammonia, and methane.

20.4 Cosmic Rays

Cosmic rays are particles that travel through interstellar space at a typical speed of 90% of the speed of light. The most abundant elements in cosmic rays are the nuclei of hydrogen and helium, but electrons and positrons are also found. It is likely that many cosmic rays are produced in supernova shocks.

20.5 The Life Cycle of Cosmic Material

Interstellar matter is constantly flowing through the Galaxy and changing from one phase to another. At the same time, gas is constantly being added to the Galaxy by accretion from extragalactic space, while mass is removed from the interstellar medium by being locked in stars. Some of the mass in stars is, in turn, returned to the interstellar medium when those stars evolve and die. In particular, the heavy elements in interstellar space were all produced inside stars, while the dust grains are made in the outer regions of stars that have swelled to be giants. These elements and grains, in turn, can then be incorporated into new stars and planetary systems that form out of the interstellar medium.

20.6 Interstellar Matter around the Sun

The Sun is located at the edge of a low-density cloud called the Local Fluff. The Sun and this cloud are located within the Local Bubble, a region extending to at least 300 light-years from the Sun, within which the density of interstellar material is extremely low. Astronomers think this bubble was blown by some nearby stars that experienced a strong wind and some supernova explosions.

CHAPTER 21 — THE BIRTH OF STARS AND THE DISCOVERY OF PLANETS OUTSIDE THE SOLAR SYSTEM

21.1 Star Formation

Most stars form in giant molecular clouds with masses as large as 3×10^6 solar masses. The most well-studied molecular cloud is Orion, where star formation is currently taking place. Molecular clouds typically contain regions of higher density called clumps, which in turn contain several even-denser cores of gas and dust, each of which may become a star. A star can form inside a core if its density is high enough that gravity can overwhelm the internal pressure and cause the gas and dust to collapse. The accumulation of material halts when a protostar develops a strong stellar wind, leading to jets of material being observed coming from the star. These jets of material can collide with the material around the star and produce regions that emit light that are known as Herbig-Haro objects.

21.2 The H–R Diagram and the Study of Stellar Evolution

The evolution of a star can be described in terms of changes in its temperature and luminosity, which can best be followed by plotting them on an H–R diagram. Protostars generate energy (and internal heat) through gravitational contraction that typically continues for millions of years, until the star reaches the main sequence.

21.3 Evidence That Planets Form around Other Stars

Observational evidence shows that most protostars are surrounded by disks with large-enough diameters and enough mass (as much as 10% that of the Sun) to form planets. After a few million years, the inner part of the disk is cleared of dust, and the disk is then shaped like a donut with the protostar centered in the hole—something that can be explained by the formation of planets in that inner zone. Around a few older stars, we see disks formed from the debris produced when small bodies (comets and asteroids) collide with each other. The distribution of material in the rings of debris disks is probably determined by shepherd planets, just as Saturn's shepherd moons affect the orbits of the material in its rings. Protoplanets that grow to be 10 times the mass of Earth or bigger while there is still considerable gas in their disk can then capture more of that gas and become giant planets like Jupiter in the solar system.

21.4 Planets beyond the Solar System: Search and Discovery

Several observational techniques have successfully detected planets orbiting other stars. These techniques fall into two general categories—direct and indirect detection. The Doppler and transit techniques are our most powerful indirect tools for finding exoplanets. Some planets are also being found by direct imaging.

21.5 Exoplanets Everywhere: What We Are Learning

Although the Kepler mission is finding thousands of new exoplanets, these are limited to orbital periods of less than 400 days and sizes larger than Mars. Still, we can use the Kepler discoveries to extrapolate the distribution of planets in our Galaxy. The data so far imply that planets like Earth are the most common type of planet, and that there may be 100 billion Earth-size planets around Sun-like stars in the Galaxy. About 2600 planetary systems have been discovered around other stars. In many of them, planets are arranged differently than in our solar system.

21.6 New Perspectives on Planet Formation

The ensemble of exoplanets is incredibly diverse and has led to a revision in our understanding of planet formation that includes the possibility of vigorous, chaotic interactions, with planet migration and scattering. It is possible that the solar system is unusual (and not representative) in how its planets are arranged. Many systems seem to have rocky planets farther inward than we do, for example, and some even have “hot Jupiters” very close to their star. Ambitious space experiments should make it possible to image earthlike planets outside the solar system and even to obtain information about their habitability as we search for life elsewhere.

CHAPTER 22 — STARS FROM ADOLESCENCE TO OLD AGE

22.1 Evolution from the Main Sequence to Red Giants

When stars first begin to fuse hydrogen to helium, they lie on the zero-age main sequence. The amount of time a star spends in the main-sequence stage depends on its mass. More massive stars complete each stage of evolution more quickly than lower-mass stars. The fusion of hydrogen to form helium changes the interior composition of a star, which in turn results in changes in its temperature, luminosity, and radius. Eventually, as stars age, they evolve away from the main sequence to become red giants or supergiants. The core of a red giant is contracting, but the outer layers are expanding as a result of hydrogen fusion in a shell outside the core. The star gets larger, redder, and more luminous as it expands and cools.

22.2 Star Clusters

Star clusters provide one of the best tests of our calculations of what happens as stars age. The stars in a given cluster were formed at about the same time and have the same composition, so they differ mainly in mass, and thus, in their life stage. There are three types of star clusters: globular, open, and associations. Globular clusters have diameters of 50–450 light-years, contain hundreds of thousands of stars, and are distributed in a halo around the Galaxy. Open clusters typically contain hundreds of stars, are located in the plane of the Galaxy, and have diameters less than 30 light-years. Associations are found in regions of gas and dust and contain extremely young stars.

22.3 Checking Out the Theory

The H–R diagram of stars in a cluster changes systematically as the cluster grows older. The most massive stars evolve most rapidly. In the youngest clusters and associations, highly luminous blue stars are on the main sequence; the stars with the lowest masses lie to the right of the main sequence and are still contracting toward it. With passing time, stars of progressively lower masses evolve away from (or turn off) the main sequence. In globular clusters, which are all at least 11 billion years old, there are no luminous blue stars at all. Astronomers can use the turnoff point from the main sequence to determine the age of a cluster.

22.4 Further Evolution of Stars

After stars become red giants, their cores eventually become hot enough to produce energy by fusing helium to form carbon (and sometimes a bit of oxygen.) The fusion of three helium nuclei produces carbon through the triple-alpha process. The rapid onset of helium fusion in the core of a low-mass star is called the helium flash. After this, the star becomes stable and reduces its luminosity and size briefly. In stars with masses about twice the mass of the Sun or less, fusion stops after the helium in the core has

been exhausted. Fusion of hydrogen and helium in shells around the contracting core makes the star a bright red giant again, but only temporarily. When the star is a red giant, it can shed its outer layers and thereby expose hot inner layers. Planetary nebulae (which have nothing to do with planets) are shells of gas ejected by such stars, set glowing by the ultraviolet radiation of the dying central star.

22.5 The Evolution of More Massive Stars

In stars with masses higher than about 8 solar masses, nuclear reactions involving carbon, oxygen, and still heavier elements can build up nuclei as heavy as iron. The creation of new chemical elements is called nucleosynthesis. The late stages of evolution occur very quickly. Ultimately, all stars must use up all of their available energy supplies. In the process of dying, most stars eject some matter, enriched in heavy elements, into interstellar space where it can be used to form new stars. Each succeeding generation of stars therefore contains a larger proportion of elements heavier than hydrogen and helium. This progressive enrichment explains why the stars in open clusters (which formed more recently) contain more heavy elements than do those in ancient globular clusters, and it tells us where most of the atoms on Earth and in our bodies come from.

CHAPTER 23 — THE DEATH OF STARS

23.1 The Death of Low-Mass Stars

During the course of their evolution, stars shed their outer layers and lose a significant fraction of their initial mass. Stars with masses of $8 M_{\text{Sun}}$ or less can lose enough mass to become white dwarfs, which have masses less than the Chandrasekhar limit (about $1.4 M_{\text{Sun}}$). The pressure exerted by degenerate electrons keeps white dwarfs from contracting to still-smaller diameters. Eventually, white dwarfs cool off to become black dwarfs, stellar remnants made mainly of carbon, oxygen, and neon.

23.2 Evolution of Massive Stars: An Explosive Finish

In a massive star, hydrogen fusion in the core is followed by several other fusion reactions involving heavier elements. Just before it exhausts all sources of energy, a massive star has an iron core surrounded by shells of silicon, sulfur, oxygen, neon, carbon, helium, and hydrogen. The fusion of iron requires energy (rather than releasing it). If the mass of a star's iron core exceeds the Chandrasekhar limit (but is less than $3 M_{\text{Sun}}$), the core collapses until its density exceeds that of an atomic nucleus, forming a neutron star with a typical diameter of 20 kilometers. The core rebounds and transfers energy outward, blowing off the outer layers of the star in a type II supernova explosion.

23.3 Supernova Observations

A supernova occurs on average once every 25 to 100 years in the Milky Way Galaxy. Despite the odds, no supernova in our Galaxy has been observed from Earth since the invention of the telescope. However, one nearby supernova (SN 1987A) has been observed in a neighboring galaxy, the Large Magellanic Cloud. The star that evolved to become SN 1987A began its life as a blue supergiant, evolved to become a red supergiant, and returned to being a blue supergiant at the time it exploded. Studies of SN 1987A have detected neutrinos from the core collapse and confirmed theoretical calculations of what happens during such explosions, including the formation of elements beyond iron. Supernovae are a main source of high-energy cosmic rays and can be dangerous for any living organisms in nearby star systems.

23.4 Pulsars and the Discovery of Neutron Stars

At least some supernovae leave behind a highly magnetic, rapidly rotating neutron star, which can be observed as a pulsar if its beam of escaping particles and focused radiation is pointing toward us. Pulsars emit rapid pulses of radiation at regular intervals; their periods are in the range of 0.001 to 10 seconds. The rotating neutron star acts like a lighthouse, sweeping its beam in a circle and giving us a pulse of radiation when the beam sweeps over Earth. As pulsars age, they lose energy, their rotations slow, and their periods increase.

23.5 The Evolution of Binary Star Systems

When a white dwarf or neutron star is a member of a close binary star system, its companion star can transfer mass to it. Material falling *gradually* onto a white dwarf can explode in a sudden burst of fusion and make a nova. If material falls *rapidly* onto a white dwarf, it can push it over the Chandrasekhar limit and cause it to explode completely as a type Ia supernova. Another possible mechanism for a type Ia supernova is the merger of two white dwarfs. Material falling onto a neutron star can cause powerful bursts of X-ray radiation. Transfer of material and angular momentum can speed up the rotation of pulsars until their periods are just a few thousandths of a second.

23.6 The Mystery of the Gamma-Ray Bursts

Gamma-ray bursts last from a fraction of a second to a few minutes. They come from all directions and are now known to be associated with very distant objects. The energy is most likely beamed, and, for the ones we can detect, Earth lies in the direction of the beam. Long-duration bursts (lasting more than a few seconds) come from massive stars with their outer hydrogen layers missing that explode as supernovae. Short-duration bursts are believed to be mergers of stellar corpses (neutron stars or black holes).

CHAPTER 24 — BLACK HOLES AND CURVED SPACETIME

24.1 Introducing General Relativity

Einstein proposed the equivalence principle as the foundation of the theory of general relativity. According to this principle, there is no way that anyone or any experiment in a sealed environment can distinguish between free fall and the absence of gravity.

24.2 Spacetime and Gravity

By considering the consequences of the equivalence principle, Einstein concluded that we live in a curved spacetime. The distribution of matter determines the curvature of spacetime; other objects (and even light) entering a region of spacetime must follow its curvature. Light must change its path near a massive object not because light is bent by gravity, but because spacetime is.

24.3 Tests of General Relativity

In weak gravitational fields, the predictions of general relativity agree with the predictions of Newton's law of gravity. However, in the stronger gravity of the Sun, general relativity makes predictions that differ from Newtonian physics and can be tested. For example, general relativity predicts that light or

radio waves will be deflected when they pass near the Sun, and that the position where Mercury is at perihelion would change by 43 arcsec per century even if there were no other planets in the solar system to perturb its orbit. These predictions have been verified by observation.

24.4 Time in General Relativity

General relativity predicts that the stronger the gravity, the more slowly time must run. Experiments on Earth and with spacecraft have confirmed this prediction with remarkable accuracy. When light or other radiation emerges from a compact smaller remnant, such as a white dwarf or neutron star, it shows a gravitational redshift due to the slowing of time.

24.5 Black Holes

Theory suggests that stars with stellar cores more massive than three times the mass of the Sun at the time they exhaust their nuclear fuel will collapse to become black holes. The surface surrounding a black hole, where the escape velocity equals the speed of light, is called the event horizon, and the radius of the surface is called the Schwarzschild radius. Nothing, not even light, can escape through the event horizon from the black hole. At its center, each black hole is thought to have a singularity, a point of infinite density and zero volume. Matter falling into a black hole appears, as viewed by an outside observer, to freeze in position at the event horizon. However, if we were riding on the infalling matter, we would pass through the event horizon. As we approach the singularity, the tidal forces would tear our bodies apart even before we reach the singularity.

24.6 Evidence for Black Holes

The best evidence of stellar-mass black holes comes from binary star systems in which (1) one star of the pair is not visible, (2) the flickering X-ray emission is characteristic of an accretion disk around a compact object, and (3) the orbit and characteristics of the visible star indicate that the mass of its invisible companion is greater than $3 M_{\text{Sun}}$. A number of systems with these characteristics have been found. Black holes with masses of millions to billions of solar masses are found in the centers of large galaxies.

24.7 Gravitational Wave Astronomy

General relativity predicts that the rearrangement of matter in space should produce gravitational waves. The existence of such waves was first confirmed in observations of a pulsar in orbit around another neutron star whose orbits were spiraling closer and losing energy in the form of gravitational waves. In 2015, LIGO found gravitational waves directly by detecting the signal produced by the merger of two stellar-mass black holes, opening a new window on the universe.

CHAPTER 25 — THE MILKY WAY GALAXY

25.1 The Architecture of the Galaxy

The Milky Way Galaxy consists of a thin disk containing dust, gas, and young and old stars; a spherical halo containing populations of very old stars, including RR Lyrae variable stars and globular star clusters; a thick, more diffuse disk with stars that have properties intermediate between those in the thin disk and the halo; a peanut-shaped nuclear bulge of mostly old stars around the center; and a

supermassive black hole at the very center. The Sun is located roughly halfway out of the Milky Way, about 26,000 light-years from the center.

25.2 Spiral Structure

The gaseous distribution in the Galaxy's disk has two main spiral arms that emerge from the ends of the central bar, along with several fainter arms and short spurs; the Sun is located in one of those spurs. Measurements show that the Galaxy does not rotate as a solid body, but instead its stars and gas follow differential rotation, such that the material closer to the galactic center completes its orbit more quickly. Observations show that galaxies like the Milky Way take several billion years after they began to form to develop spiral structure.

25.3 The Mass of the Galaxy

The Sun revolves completely around the galactic center in about 225 million years (a galactic year). The mass of the Galaxy can be determined by measuring the orbital velocities of stars and interstellar matter. The total mass of the Galaxy is about $2 \times 10^{12} M_{\text{Sun}}$. As much as 95% of this mass consists of dark matter that emits no electromagnetic radiation and can be detected only because of the gravitational force it exerts on visible stars and interstellar matter. This dark matter is located mostly in the Galaxy's halo; its nature is not well understood at present.

25.4 The Center of the Galaxy

A supermassive black hole is located at the center of the Galaxy. Measurements of the velocities of stars located within a few light-days of the center show that the mass inside their orbits around the center is about 4.6 million M_{Sun} . Radio observations show that this mass is concentrated in a volume with a diameter similar to that of Mercury's orbit. The density of this matter concentration exceeds that of the densest known star clusters by a factor of nearly a million. The only known object with such a high density and total mass is a black hole.

25.5 Stellar Populations in the Galaxy

We can roughly divide the stars in the Galaxy into two categories. Old stars with few heavy elements are referred to as population II stars and are found in the halo and in globular clusters. Population I stars contain more heavy elements than globular cluster and halo stars, are typically younger and found in the disk, and are especially concentrated in the spiral arms. The Sun is a member of population I. Population I stars formed after previous generations of stars had produced heavy elements and ejected them into the interstellar medium. The bulge stars, most of which are more than 10 billion years old, have unusually high amounts of heavy elements, presumably because there were many massive first-generation stars in this dense region, and these quickly seeded the next generations of stars with heavier elements.

25.6 The Formation of the Galaxy

The Galaxy began forming a little more than 13 billion years ago. Models suggest that the stars in the halo and globular clusters formed first, while the Galaxy was spherical. The gas, somewhat enriched in heavy elements by the first generation of stars, then collapsed from a spherical distribution to a rotating disk-shaped distribution. Stars are still forming today from the gas and dust that remain in the disk. Star formation occurs most rapidly in the spiral arms, where the density of interstellar matter is highest. The Galaxy captured (and still is capturing) additional stars and globular clusters from small galaxies that

ventured too close to the Milky Way. In 3 to 4 billion years, the Galaxy will begin to collide with the Andromeda galaxy, and after about 7 billion years, the two galaxies will merge to form a giant elliptical galaxy.

CHAPTER 26 — GALAXIES

26.1 The Discovery of Galaxies

Faint star clusters, clouds of glowing gas, and galaxies all appeared as faint patches of light (or nebulae) in the telescopes available at the beginning of the twentieth century. It was only when Hubble measured the distance to the Andromeda galaxy using cepheid variables with the giant 2.5-meter reflector on Mount Wilson in 1924 that the existence of other galaxies similar to the Milky Way in size and content was established.

26.2 Types of Galaxies

The majority of bright galaxies are either spirals or ellipticals. Spiral galaxies contain both old and young stars, as well as interstellar matter, and have typical masses in the range of 10^9 to 10^{12} M_{Sun} . Our own Galaxy is a large spiral. Ellipticals are spheroidal or slightly elongated systems that consist almost entirely of old stars, with very little interstellar matter. Elliptical galaxies range in size from giants, more massive than any spiral, down to dwarfs, with masses of only about 10^6 M_{Sun} . Dwarf ellipticals are probably the most common type of galaxy in the nearby universe. A small percentage of galaxies with more disorganized shapes are classified as irregulars. Galaxies may change their appearance over time due to collisions with other galaxies or by a change in the rate of star formation.

26.3 Properties of Galaxies

The masses of spiral galaxies are determined from measurements of their rates of rotation. The masses of elliptical galaxies are estimated from analyses of the motions of the stars within them. Galaxies can be characterized by their mass-to-light ratios. The luminous parts of galaxies with active star formation typically have mass-to-light ratios in the range of 1 to 10; the luminous parts of elliptical galaxies, which contain only old stars, typically have mass-to-light ratios of 10 to 20. The mass-to-light ratios of whole galaxies, including their outer regions, are as high as 100, indicating the presence of a great deal of dark matter.

26.4 The Extragalactic Distance Scale

Astronomers determine the distances to galaxies using a variety of methods, including the period-luminosity relationship for cepheid variables; objects such as type Ia supernovae, which appear to be standard bulbs; and the Tully-Fisher relation, which connects the line broadening of 21-cm radiation to the luminosity of spiral galaxies. Each method has limitations in terms of its precision, the kinds of galaxies with which it can be used, and the range of distances over which it can be applied.

26.5 The Expanding Universe

The universe is expanding. Observations show that the spectral lines of distant galaxies are redshifted, and that their recession velocities are proportional to their distances from us, a relationship known as Hubble's law. The rate of recession, called the Hubble constant, is approximately 22 kilometers per

second per million light-years. We are not at the center of this expansion: an observer in any other galaxy would see the same pattern of expansion that we do. The expansion described by Hubble's law is best understood as a stretching of space.

CHAPTER 27 — ACTIVE GALAXIES, QUASARS AND SUPERMASSIVE BLACK HOLES

27.1 Quasars

The first quasars discovered looked like stars but had strong radio emission. Their visible-light spectra at first seemed confusing, but then astronomers realized that they had much larger redshifts than stars. The quasar spectra obtained so far show redshifts ranging from 15% to more than 96% the speed of light. Observations with the Hubble Space Telescope show that quasars lie at the centers of galaxies and that both spirals and ellipticals can harbor quasars. The redshifts of the underlying galaxies match the redshifts of the quasars embedded in their centers, thereby proving that quasars obey the Hubble law and are at the great distances implied by their redshifts. To be noticeable at such great distances, quasars must have 10 to 100 times the luminosity of the brighter normal galaxies. Their variations show that this tremendous energy output is generated in a small volume—in some cases, in a region not much larger than our own solar system. A number of galaxies closer to us also show strong activity at their centers—activity now known to be caused by the same mechanism as the quasars.

27.2 Supermassive Black Holes: What Quasars Really Are

Both active galactic nuclei and quasars derive their energy from material falling toward, and forming a hot accretion disk around, a massive black hole. This model can account for the large amount of energy emitted and for the fact that the energy is produced in a relatively small volume of space. It can also explain why jets coming from these objects are seen in two directions: those directions are perpendicular to the accretion disk.

27.3 Quasars as Probes of Evolution in the Universe

Quasars and galaxies affect each other: the galaxy supplies fuel to the black hole, and the quasar heats and disrupts the gas clouds in the galaxy. The balance between these two processes probably helps explain why the black hole seems always to be about 1/200 the mass of the spherical bulge of stars that surrounds the black hole. Quasars were much more common billions of years ago than they are now, and astronomers speculate that they mark an early stage in the formation of galaxies. Quasars were more likely to be active when the universe was young and fuel for their accretion disk was more available. Quasar activity can be re-triggered by a collision between two galaxies, which provides a new source of fuel to feed the black hole.

CHAPTER 28 — THE EVOLUTION AND DISTRIBUTION OF GALAXIES

28.1 Observations of Distant Galaxies

When we look at distant galaxies, we are looking back in time. We have now seen galaxies as they were when the universe was about 500 million years old—only about five percent as old as it is now. The universe now is 13.8 billion years old. The color of a galaxy is an indicator of the age of the stars that populate it. Blue galaxies must contain a lot of hot, massive, young stars. Galaxies that contain only old

stars tend to be yellowish red. The first generation of stars formed when the universe was only a few hundred million years old. Galaxies observed when the universe was only a few billion years old tend to be smaller than today's galaxies, to have more irregular shapes, and to have more rapid star formation than the galaxies we see nearby in today's universe. This shows that the smaller galaxy fragments assembled themselves into the larger galaxies we see today.

28.2 Galaxy Mergers and Active Galactic Nuclei

When galaxies of comparable size collide and coalesce we call it a merger, but when a small galaxy is swallowed by a much larger one, we use the term galactic cannibalism. Collisions play an important role in the evolution of galaxies. If the collision involves at least one galaxy rich in interstellar matter, the resulting compression of the gas will result in a burst of star formation, leading to a starburst galaxy. Mergers were much more common when the universe was young, and many of the most distant galaxies that we see are starburst galaxies that are involved in collisions. Active galactic nuclei powered by supermassive black holes in the centers of most galaxies can have major effects on the host galaxy, including shutting off star formation.

28.3 The Distribution of Galaxies in Space

Counts of galaxies in various directions establish that the universe on the large scale is homogeneous and isotropic (the same everywhere and the same in all directions, apart from evolutionary changes with time). The sameness of the universe everywhere is referred to as the cosmological principle. Galaxies are grouped together in clusters. The Milky Way Galaxy is a member of the Local Group, which contains at least 54 member galaxies. Rich clusters (such as Virgo and Coma) contain thousands or tens of thousands of galaxies. Galaxy clusters often group together with other clusters to form large-scale structures called superclusters, which can extend over distances of several hundred million light-years. Clusters and superclusters are found in filamentary structures that are huge but fill only a small fraction of space. Most of space consists of large voids between superclusters, with nearly all galaxies confined to less than 10% of the total volume.

28.4 The Challenge of Dark Matter

Stars move much faster in their orbits around the centers of galaxies, and galaxies around centers of galaxy clusters, than they should according to the gravity of all the luminous matter (stars, gas, and dust) astronomers can detect. This discrepancy implies that galaxies and galaxy clusters are dominated by dark matter rather than normal luminous matter. Gravitational lensing and X-ray radiation from massive galaxy clusters confirm the presence of dark matter. Galaxies and clusters of galaxies contain about 10 times more dark matter than luminous matter. While some of the dark matter may be made up of ordinary matter (protons, neutrons, and electrons), perhaps in the form of very faint stars or black holes, most of it probably consists of some totally new type of particle not yet detected on Earth. Observations of gravitational lensing effects on distant objects have been used to look in the outer region of our Galaxy for any dark matter in the form of compact, dim stars or star remnants, but not enough such objects have been found to account for all the dark matter.

28.5 The Formation and Evolution of Galaxies and Structure in the Universe

Initially, luminous and dark matter in the universe was distributed almost—but not quite—uniformly. The challenge for galaxy formation theories is to show how this “not quite” smooth distribution of matter developed the structures—galaxies and galaxy clusters—that we see today. It is likely that the

filamentary distribution of galaxies and voids was built in near the beginning, before stars and galaxies began to form. The first condensations of matter were about the mass of a large star cluster or a small galaxy. These smaller structures then merged over cosmic time to form large galaxies, clusters of galaxies, and superclusters of galaxies. Superclusters today are still gathering up more galaxies, gas, and dark matter. And spiral galaxies like the Milky Way are still acquiring material by capturing small galaxies near them.

CHAPTER 29 — THE BIG BANG

29.1 The Age of the Universe

Cosmology is the study of the organization and evolution of the universe. The universe is expanding, and this is one of the key observational starting points for modern cosmological theories. Modern observations show that the rate of expansion has not been constant throughout the life of the universe. Initially, when galaxies were close together, the effects of gravity were stronger than the effects of dark energy, and the expansion rate gradually slowed. As galaxies moved farther apart, the influence of gravity on the expansion rate weakened. Measurements of distant supernovae show that when the universe was about half its current age, dark energy began to dominate the rate of expansion and caused it to speed up. In order to estimate the age of the universe, we must allow for changes in the rate of expansion. After allowing for these effects, astronomers estimate that all of the matter within the observable universe was concentrated in an extremely small volume 13.8 billion years ago, a time we call the Big Bang.

29.2 A Model of the Universe

For describing the large-scale properties of the universe, a model that is isotropic and homogeneous (same everywhere) is a pretty good approximation of reality. The universe is expanding, which means that the universe undergoes a change in scale with time; space stretches and distances grow larger by the same factor everywhere at a given time. Observations show that the mass density of the universe is less than the critical density. In other words, there is not enough matter in the universe to stop the expansion. With the discovery of dark energy, which is accelerating the rate of expansion, the observational evidence is strong that the universe will expand forever. Observations tell us that the expansion started about 13.8 billion years ago.

29.3 The Beginning of the Universe

Lemaître, Alpher, and Gamow first worked out the ideas that are today called the Big Bang theory. The universe cools as it expands. The energy of photons is determined by their temperature, and calculations show that in the hot, early universe, photons had so much energy that when they collided with one another, they could produce material particles. As the universe expanded and cooled, protons and neutrons formed first, then came electrons and positrons. Next, fusion reactions produced deuterium, helium, and lithium nuclei. Measurements of the deuterium abundance in today's universe show that the total amount of ordinary matter in the universe is only about 5% of the critical density.

29.4 The Cosmic Microwave Background

When the universe became cool enough to form neutral hydrogen atoms, the universe became transparent to radiation. Scientists have detected the cosmic microwave background (CMB) radiation

from this time during the hot, early universe. Measurements with the COBE satellite show that the CMB acts like a blackbody with a temperature of 2.73 K. Tiny fluctuations in the CMB show us the seeds of large-scale structures in the universe. Detailed measurements of these fluctuations show that we live in a critical-density universe and that the critical density is composed of 31% matter, including dark matter, and 69% dark energy. Ordinary matter—the kinds of elementary particles we find on Earth—make up only about 5% of the critical density. CMB measurements also indicate that the universe is 13.8 billion years old.

29.5 What Is the Universe Really Made Of?

Twenty-seven percent of the critical density of the universe is composed of dark matter. To explain so much dark matter, some physics theories predict that additional types of particles should exist. One type has been given the name of WIMPs (weakly interacting massive particles), and scientists are now conducting experiments to try to detect them in the laboratory. Dark matter plays an essential role in forming galaxies. Since, by definition, these particles interact only very weakly (if at all) with radiation, they could have congregated while the universe was still very hot and filled with radiation. They would thus have formed gravitational traps that quickly attracted and concentrated ordinary matter after the universe became transparent, and matter and radiation decoupled. This rapid concentration of matter enabled galaxies to form by the time the universe was only 400–500 million years old.

29.6 The Inflationary Universe

The Big Bang model does not explain why the CMB has the same temperature in all directions. Neither does it explain why the density of the universe is so close to critical density. These observations can be explained if the universe experienced a period of rapid expansion, which scientists call inflation, about 10^{-35} second after the Big Bang. New grand unified theories (GUTs) are being developed to describe physical processes in the universe before and at the time that inflation occurred.

29.7 The Anthropic Principle

Recently, many cosmologists have noted that the existence of humans depends on the fact that many properties of the universe—the size of density fluctuations in the early universe, the strength of gravity, the structure of atoms—were just right. The idea that physical laws must be the way they are because otherwise we could not be here to measure them is called the anthropic principle. Some scientists speculate that there may be a multiverse of universes, in which ours is just one.

CHAPTER 30 — LIFE IN THE UNIVERSE

30.1 The Cosmic Context for Life

Life on Earth is based on the presence of a key unit known as an organic molecule, a molecule that contains carbon, especially complex hydrocarbons. Our solar system formed about 5 billion years ago from a cloud of gas and dust enriched by several generations of heavier element production in stars. Life is made up of chemical combinations of these elements made by stars. The Copernican principle, which suggests that there is nothing special about our place in the universe, implies that if life could develop on Earth, it should be able to develop in other places as well. The Fermi paradox asks why, if life is common, more advanced life-forms have not contacted us.

30.2 Astrobiology

The study of life in the universe, including its origin on Earth, is called astrobiology. Life as we know it requires water, certain elemental raw materials (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur), energy, and an environment in which the complex chemistry of life is stable. Carbon-based (or organic) molecules are abundant in space and may also have been produced by processes on Earth. Life appears to have spread around our planet within 400 million years after the end of heavy bombardment, if not sooner. The actual origin of life—the processes leading from chemistry to biology—is not completely understood. Once life took hold, it evolved to use many energy sources, including first a range of different chemistries and later light, and diversified across a range of environmental conditions that humans consider “extreme.” This proliferation of life into so many environmental niches, so relatively soon after our planet became habitable, has served to make many scientists optimistic about the chances that life could exist elsewhere.

30.3 Searching for Life beyond Earth

The search for life beyond Earth offers several intriguing targets. Mars appears to have been more similar to Earth during its early history than it is now, with evidence for liquid water on its ancient surface and perhaps even now below ground. The accessibility of the martian surface to our spacecraft offers the exciting potential to directly examine ancient and modern samples for evidence of life. In the outer solar system, the moons Europa and Enceladus likely host vast sub-ice oceans that may directly contact the underlying rocks—a good start in providing habitable conditions—while Titan offers a fascinating laboratory for understanding the sorts of organic chemistry that might ultimately provide materials for life. And the last decade of research on exoplanets leads us to believe that there may be billions of habitable planets in the Milky Way Galaxy. Study of these worlds offers the potential to find biomarkers indicating the presence of life.

30.4 The Search for Extraterrestrial Intelligence

Some astronomers are engaged in the search for extraterrestrial intelligent life (SETI). Because other planetary systems are so far away, traveling to the stars is either very slow or extremely expensive (in terms of energy required). Despite many UFO reports and tremendous media publicity, there is no evidence that any of these are related to extraterrestrial visits. Scientists have determined that the best way to communicate with any intelligent civilizations out there is by using electromagnetic waves, and radio waves seem best suited to the task. So far, they have only begun to comb the many different possible stars, frequencies, signal types, and other factors that make up what we call the cosmic haystack problem. Some astronomers are also undertaking searches for brief, bright pulses of visible light and infrared signatures of huge construction projects by advanced civilizations. If we do find a signal someday, deciding whether to answer and what to answer may be two of the greatest challenges humanity will face.

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