INSTRUCT

INSTRUCTOR'S MANUAL CONTENTS

CHAPTER 1

Cosmology and the Birth of Earth

Learning Objectives

1. Students should be aware of the Big Bang theory and the major evidence supporting it. Distant galaxies are uniformly red-shifted rather than blue-shifted; this implies that they are all moving away from us. The farthest galaxies are those that are most strongly red-shifted, meaning that they are receding the fastest. Extrapolation of velocities and trajectories into the past suggests that all matter in the Universe was contained in a single point, approximately 13.7 billion years ago. At that time, the Universe explosively came into existence.
2. Stars, including our Sun, are nuclear fusion reactors. For most of their life histories (on the order of billions of years), hydrogen atoms are fused together to form helium. Later stages in stellar evolution include fusion of helium atoms and other, heavier elements; ultimately, iron is the heaviest element that can be produced through fusion reactions within stars.
3. After their cycles of fusion are complete, large stars violently explode (forming supernovae), producing elements heavier than iron and leaving behind a residue of diffuse nebulae, which may be recycled to form a new star at some point in the future.
4. Our Solar System is approximately 4.57 Ga (billion years old). All eight planets revolve around the Sun in coplanar, elliptical orbits. All planets orbit in the same direction (counterclockwise as viewed from above Earth's North Pole). These facts imply simultaneous planetary formation from a swirling nebula surrounding the Sun (the similarities in orbits would then be a natural result of conservation of angular momentum). The planets accreted from this

nebula through gravitational attraction and haphazard collisions. Pluto, long considered the "ninth planet," has seen its status demoted; astronomers now recognize eight major planets.

5. The terrestrial planets (Mercury, Venus, Earth, and Mars) are relatively small, dense, and rocky worlds. The giant planets are predominantly composed of the light gases hydrogen and helium (Jupiter and Saturn) or ices (Uranus and Neptune); they are much larger and much less dense than the terrestrial planets.
6. Our Moon is chemically similar to the Earth's mantle. The Moon is thought to have originated from debris accumulated when a protoplanet collided with Earth approximately 4.3 Ga.

Summary from the Text

The geocentric model placed Earth at the center of the Universe, with the planets and Sun orbiting around the Earth within a celestial sphere speckled with stars. The heliocentric model, which gained acceptance during the Renaissance, placed the Sun at the center.

Eratosthenes was able to measure the size of Earth in ancient times, but it was not until fairly recently that astronomers accurately determined the distances to the Sun, planets, and stars. Distances in the Universe are so large that they must be measured in light-years.

The Earth is one of eight planets orbiting the Sun, and this Solar System lies on the outer edge of a slowly revolving galaxy, the Milky Way, which is composed of about 300 billion stars. The Universe contains at least hundreds of billions of galaxies.

The red shift of light from distant galaxies, a manifestation of the Doppler effect, indicates that all distant galaxies are moving away from Earth. This observation leads to the expanding Universe theory. Most astronomers agree that this expansion began after the Big Bang, a cataclysmic explosion about 13.7 billion years ago.

The first atoms (hydrogen and helium) of the Universe developed within minutes of the Big Bang. These atoms formed vast gas clouds, called nebulae.

Gravity caused clumps of gas in the nebulae to coalesce into revolving balls. As these balls of gas collapsed inward, they evolved into flattened disks with bulbous centers. The protostars at the center of these disks eventually became dense and sufficiently hot that fusion reactions began within them. When this happened, they became true stars, emitting heat and light.

Heavier elements form during fusion reactions in stars; the heaviest are mostly made during supernova explosions. Earth and the life forms on it contain elements that could have only been produced during the life cycle of stars. Thus, we are all made of stardust.

According to the nebular theory of planet formation, planets developed from the rings of gas and dust surrounding protostars. The gas and dust condensed into planetesimals, which then clumped together to form protoplanets and finally true planets. Inner rings became the terrestrial planets; outer rings grew into giant planets.

The Moon formed from debris ejected when a protoplanet collided with Earth in the young Solar System.

A planet assumes a near-spherical shape when it becomes so soft that gravity can smooth out irregularities.

Answers to Review Questions

1. Why do the planets appear to move with respect to the stars?

ANS: Stars are so relatively distant that they appear fixed with respect to one another as viewed from Earth. As Earth and the other planets traverse through their orbits around the Sun, the positions of the planets vary with respect to the “fixed” celestial sphere.

2. Contrast the geocentric and heliocentric Universe concepts.

ANS: The geocentric concept placed Earth at the center of the Universe, with the Sun and the other planets revolving around it. The heliocentric concept placed the Sun at the center, with Earth and the other planets revolving around it.

3. Describe how Foucault’s Pendulum demonstrates that Earth is rotating on its axis.

ANS: Foucault set forth a heavy pendulum and observed its long-term behavior. Slowly but surely the swing path of the pendulum appeared to rotate about a vertical axis. According to the property of inertia, unless a new force is added, the pendulum will maintain its swinging plane. Foucault concluded correctly that Earth must have rotated in order for the plane to appear to have changed in this manner.

4. How did Eratosthenes calculate Earth's circumference?

   ANS: He knew that when the Sun's rays were directly overhead at the town of Syene, they were 7 degrees from vertical in Alexandria, a city due north of Syene. He measured the distance between the two cities, assumed Earth to be a sphere, and calculated a circumference of about 40,000 km (the calculation is given in the text). He was extremely close to the correct answer.

5. Imagine you hear the main character in a low-budget, science-fiction movie say he will "return 10 light-years from now." What is wrong with his use of the term *light-years*?

   ANS: Light-years are a measure of distance (not time), specifically the distance light travels through a vacuum in one year. There are approximately 3.26 light-years in a parsec.

6. Describe how the Doppler effect works.

   ANS: Sound waves (and light waves) emanating from an approaching source arrive at a higher frequency than they would if the object were stationary. This frequency shift arises because each successive sound wave is emanated from a closer distance than was the previous wave (see Fig. 1.7c of the text). Our brains interpret these high frequencies (after transmission through our ears) as a higher pitch. Once a wave source passes an observer, its sound waves have a reduced frequency, as each wave is emitted from a slightly more distant point.

7. What does the red shift of the galaxies tell us about their motion with respect to Earth?

   ANS: All distant galaxies are moving away from our own, with the farthest galaxies moving the fastest.

8. What is the Big Bang, and when did it occur?

   ANS: The Big Bang is an explosive phase of expansion of matter and space that occurred at the beginning of our Universe, 13.7 billion years ago.

9. When did hydrogen and helium atoms form?

ANS: Hydrogen and helium atoms formed during the cooling that occurred in the first few minutes after the Big Bang.

10. Where did heavier elements form?

ANS: Elements heavier than hydrogen and helium are the result of both nuclear fusion during the lives of stars and explosive supernovae at the ends of stellar lifetimes.

11. Describe the steps in the formation of our Solar System according to the nebular theory.

ANS: The mass in our Sun and the surrounding Solar System condensed from a swirling nebula (cloud of gas and dust). At the center of the nebula, most of the mass condensed to form the Sun, which graduated from protostar status when it became sufficiently massive—and thus hot enough—to fuse hydrogen. Within a flat protoplanetary disk surrounding the Sun, planets arose from gravity-driven accretion and the collisions of smaller bodies termed *planetesimals* and *protoplanets*. Light gases and other volatiles were ejected from the inner portion of the disk as the Sun's heat intensified, so the terrestrial planets ended up as smaller spheres of relatively high-density refractory substances (rock and metal). Farther out, the gas-giant planets incorporated abundant volatiles such as hydrogen and helium to become much more massive but less dense.

12. Describe how the Moon was formed.

ANS: The Moon formed when a planetesimal or small protoplanet collided with Earth early in the history of the Solar System. The force of the impact ejected material similar in composition to Earth's mantle. This mantle-like mass cooled and solidified, resulting in our Moon.

13. Why is Earth round?

ANS: Gravity forces objects the size of Earth to be nearly spherical (the most compact shape, minimizing the distance of points from the center).

On Further Thought

14. Look again at Figure Bx1.2a. The North Star, a particularly bright star, lies just about at the center of the circles of light tracked out by the other stars. (a) What does this mean about the position of the North Star relative to Earth's spin axis? Why is it called the North Star? (b) Consider the wobble of Earth's axis. Will the North Star be in the same position in a photograph taken from the same location as Figure Bx1.2a in the future? Why ?

ANS:

(a) The North Star is approximately collinear with the axis of Earth's rotation. The North Star (more formally named Polaris) appears on the northern horizon to all those who can observe it. (It is visible only from the northern hemisphere; to an observer at the North Pole, the star is directly overhead.)

(b) Earth's wobble will cause the current North Star to appear to wander away from its current location of celestial North Pole in the next 10,000 years, and it will appear to be just another star circling the new celestial pole.

15. The horizon is the line separating the sky from Earth's surface. Consider the shape of Earth. How does the distance from your eyes to the horizon change as your elevation above the ground increases? To answer this question, draw a semicircle to represent part of Earth's surface and draw a vertical tower up from the surface. With your ruler, draw a line from various elevations on the tower to where the line will be tangent to the surface of Earth. (A *tangent* is a line that touches a circle at one point and is perpendicular to a radius.)

ANS: As elevation increases, distance to the horizon increases.

16. Astronomers discovered that more-distant galaxies move away from Earth more rapidly than do nearer ones. Why? To answer this question, make a model of the problem by drawing three equally spaced dots along a line; the dot at one end represents Earth, and the other two represent galaxies. "Stretch" the line by drawing the line and dots again, but this time make the line twice as long. This stretching represents Universe expansion. Notice that the dots are now farther apart. Using the following equation for velocity—Velocity = Distance / Time—if you pretend that it took 1 second to stretch the line (so Time = 1 second), measurement of the distance that each galaxy moved relative to Earth allows you to calculate velocity.

ANS: The galaxies that are farthest from Earth will necessarily be those that have been traveling away from us most rapidly ever since the Big Bang.

17. Consider that the deaths of stars eject quantities of heavier elements into space, and that these elements then become incorporated in nebulae from which the next generation of stars forms. Do you think that the ratio of heavier to lighter elements in, say, a sixth-generation star is larger or smaller than the ratio in a second-generation star? Why?

ANS: The sixth-generation star will have a greater ratio of heavy to light elemental abundance. Second-generation stars are made from remnants of first-generation stars, which themselves formed from the primordial matter of the Universe (essentially all hydrogen and helium from the Big Bang). First-generation stars produced heavier elements during their lives (stellar fusion) and deaths (as supernovae). Second-generation stars began with the remnants of the first generation and added heavier elements during their lives and deaths. Each successive generation of stars will have increasingly heavier elements to start with thanks to the efforts of previous generations.

CHAPTER 2

Journey to the Center of the Earth

Learning Objectives

1. Earth is chemically divided into a thin, rocky crust dominated by silicate minerals; a thick mantle composed mostly of iron- and magnesium-rich silicates (subject locally to partial melting); and a thick, metallic core made primarily of iron (the outer portion of which is liquid). Students should know how seismic waves tell us that the outer core must be liquid.
2. Physically, the uppermost layers of Earth are the rigid lithosphere (crust and uppermost mantle) and the asthenosphere, which is weaker and flows plasticly. The "plates" of plate tectonics theory are discrete slabs of lithosphere, which move with respect to one another atop the asthenosphere.
3. Earth is composed of a variety of materials with disparate physical properties (minerals, organics, gases, and melts). This has led to a complex physical chemistry and biochemistry, allowing both Earth's surface and its constituent life to evolve dramatically over time.
4. Students should be aware of the presence of Earth's magnetic dipole field, how the magnetic field arises, and its important consequences for life on Earth.

Summary from the Text

A traverse through the Solar System crosses many features. The Solar System is surrounded by the Oort Cloud of icy particles, attracted by the Sun's gravitational field. The edge of the Solar System itself, a bubble-like surface called the heliosphere, marks the limit at which the pressure of solar wind is countered by that of cosmic rays. The Kuiper

Belt of icy objects, the outer planets, the asteroid belt of rocky and metallic material, and the inner planets are all inboard.

A magnetic field surrounds the Earth. The field shields the planet from solar wind. Closer to Earth, the field creates the Van Allen belts, which also traps cosmic rays.

A layer of gas, the atmosphere, surrounds the Earth. Air in the atmosphere consists of 78% nitrogen, 21% oxygen, and 1% other gases. Air pressure decreases with elevation, so 99% of the gas in the atmosphere resides below 50 km.

The surface of Earth can be divided into land (30%) and ocean (70%). Most of the land surface lies within 1 km of sea level. Earth's land surface has a great variety of landscapes due to variations in elevation and climate.

Earth materials include organic chemicals, minerals, glasses, rocks (igneous, metamorphic, and sedimentary), grains, sediment, metals, melts, and volatiles. Most rocks on Earth contain silica (SiO_2) and are thus called silicate rocks. We distinguish between felsic, intermediate, mafic, and ultramafic rocks based on the proportion of silica.

The Earth's interior can be divided into three compositionally distinct layers, named in sequence from surface to center: the crust, the mantle, and the core. The first recognition of this division came from studying the density and shape of Earth. The image has been refined by studying how the speed of earthquake waves changes with depth.

Pressure and temperature both increase with depth in the Earth. At the center, pressure is 3.6 million times greater than at the surface, and the temperature reaches over 4,700°C. The rate at which temperature increases as depth increases is the geothermal gradient.

Studies of seismic waves have revealed the existence of sublayers in the core (liquid outer core and solid inner core) and mantle (upper mantle and lower mantle). The lower part of the upper mantle is the transition zone.

The crust is a thin skin that varies in thickness from 7 to 10 km (beneath oceans) to 25 to 70 km (beneath continents). Oceanic crust is mafic in composition, whereas average upper continental crust is felsic to intermediate. The mantle is composed of ultramafic rock. The core is made of iron alloy and consists of two parts—the outer core is liquid, and the inner core is solid. Flow in the outer core generates the magnetic field.

The crust plus the upper part of the mantle constitute the lithosphere, a relatively rigid shell up to 150 km thick. The lithosphere lies over the asthenosphere, mantle that is capable of flowing, and therefore, convecting.

Answers to Review Questions

1. Why do astronomers consider the space between planets to be a vacuum, in comparison with the atmosphere near sea level?

   ANS: Because of the very low density of matter in the space between planets.

2. Name the features that a spacecraft traversing the Solar System and its surroundings would encounter.

   ANS: From outside in: interstellar space, the Oort Cloud, the edge of the heliosphere, the Kuiper Belt, the giant planets (Neptune, Uranus, Saturn , Jupiter), the asteroid belt, the terrestrial planets (Mars, Earth, Venus, Mercury), and finally the Sun.

3. What is Earth's magnetic field? Draw a representation of the field on a piece of paper; your sketch should show the direction in which charged particles would flow if placed in the field.

   ANS: The magnetic field of Earth is a region of space affected by the magnetic force of Earth (see Fig. 2.3c for a sketch).

4. How does the magnetic field interact with solar wind? Be sure to consider the magnetosphere, the Van Allen radiation belts, and the aurorae.

   ANS: The dipole field of Earth is deformed by solar wind into a teardrop shape, which points away from the Sun. Charged particles from solar wind are deflected by Earth's magnetic field and travel along field lines, accumulating in relatively great density at two levels of elevation to form the Van Allen belts. Some of these particles are channeled toward the North or South Pole by the field lines and interact with gases in the upper atmosphere to produce the aurorae.

5. What is Earth's atmosphere composed of? Why would you die of suffocation if you were to eject from a fighter plane at an elevation of 12 km without taking an oxygen tank with you?

ANS: Earth's atmosphere is mostly nitrogen and oxygen, with minor amounts of argon, carbon dioxide, and other gases. The atmosphere becomes less and less dense with altitude; at 12 km, oxygen molecules are too sparse to support human life.

6. What is the proportion of land area to sea area on Earth? From studies of the hypsometric curve, approximately what proportion of Earth's surface lies at elevations above 2 km?

ANS: Earth consists of 30% land area as opposed to 70% sea area. About 4% lies above 2 km (Fig. 2.7).

7. What are the two most abundant chemical elements within the Earth? Describe the major categories of materials constituting Earth. Does the crust have the same composition as the whole Earth?

ANS: Iron and oxygen are the two most abundant chemical elements within the Earth. Categories of materials include **organic chemicals**, which make up the majority of living matter. These carbon- and hydrogen-based compounds (including oil and natural gas) can be quite complex, sometimes incorporating oxygen (as in sugars, starches, and fats), sometimes nitrogen (as in proteins), and occasionally some phosphorus and sulfur. **Minerals** are solid, inorganic materials in which there is a fixed arrangement of atoms (often termed a *crystalline lattice*). Quartz and calcite are important, familiar examples. Mineral crystals are commonly weathered to produce fragments with rough or rounded surfaces, which are termed *grains*. **Glasses** are physically solid structures in which the atoms are internally disordered (as in liquids, but without the tendency to rapidly flow). Commercial glass is produced when quartz is melted and then cooled rapidly (quenched in cool water), so that atoms cannot align themselves into the quartz crystalline arrangement before the rigidity of cooling sets in. **Rocks** are cohesive aggregates of crystals or grains. Igneous rocks crystallize from molten (liquid) rock. Sedimentary rocks arise from the cementation of loose grains (sand, mud, pebbles, etc.) and through chemical precipitation (from the ocean or continental bodies of water). Metamorphic rocks arise from heat- and pressure-induced alteration of preexistent rock (without melting). Grains are crystals within rock or loose fragments of crystals. **Sediments** are loose accumulations of mineral grains. **Metals** are solids made up of metallic elements only (to a strong approximation), such as gold, iron, and copper. (Naturally occurring metals are a subset of minerals.) **Melts** are hot liquids that crystallize at surface temperatures to form igneous rocks. Melts within Earth are termed *magma*; melts extruded on the surface are termed *lava*. **Volatiles** are substances that are stable in a gaseous state at the relatively low temperatures of Earth's surface.

The crust of the Earth is greatly enriched in silicon and impoverished with respect to iron in comparison to the whole Earth.

8. What are silicate rocks? Give four examples of such rocks, and explain how they differ from one another in terms of their chemical composition.

ANS: Granite is a felsic rock (made of silicate minerals rich in silica, aluminum, and potassium). Gabbro and basalt are both mafic (mostly iron- and magnesium-rich silicate minerals). Peridotite is ultramafic (richer in iron and magnesium than the mafic rocks, and mostly consisting of olivine and pyroxene).

9. How did researchers first obtain a realistic estimate of Earth's average density? What observations led to the realization that Earth is largely solid and that a particularly dense core lies at the center?

ANS: The first realistic estimate of density came from measuring the deflection of a plumb bob caused by a nearby mountain; as a result, it was learned that Earth's interior must be denser than that of surface rocks. That Earth does not exhibit tidal variation in surface elevation is evidence of a largely solid interior. If the concentration of mass were not greatest at the center, Earth's rotation would flatten it into a more disk-like form.

10. What are seismic waves? Does the velocity at which an earthquake wave travels change or stay constant as the wave passes through Earth?

ANS: Seismic waves are vibrational waves that pass through Earth and are caused by the release of stress during an earthquake along a fault in Earth. The velocities of these waves change with depth (generally gradually increasing with depth).

11. What are the principal layers of Earth? What happens to earthquake waves when they reach the boundary between layers?

ANS: Major layers of Earth are the crust, mantle, and core; seismic-wave velocities change abruptly at the boundaries between layers, speeding up as they travel from crust to mantle, but slowing abruptly as they pass from mantle to core.

12. How do temperature and pressure change with increasing depth in the Earth? Be sure to explain the geothermal gradient.

ANS: Both temperature and pressure increase with increasing depth. The rate of downward temperature increase, which varies somewhat, is termed the *geothermal gradient*. The geothermal gradient is greatest (20–30 degrees Celsius per kilometer) in the upper crust and declines farther in.

13. What is the Moho? How was it first recognized? Describe the difference between continental crust and oceanic crust.

ANS: The Moho is the crust-mantle boundary, first recognized by an abrupt change in seismic-wave velocities. Continental crust is thicker, less mafic, and more variable in chemistry than oceanic crust.

14. What is the mantle composed of? What are the three sublayers within the mantle? Is there any melt within the mantle?

ANS: The mantle is mostly made of an ultramafic silicate rock termed *peridotite*. Its layers are the upper mantle, the transition zone, and the lower mantle. There is a small amount of melt in the upper mantle.

15. What is the core composed of? How do the inner core and outer core differ from each other? We can't sample the core directly, but geologists have studied samples of materials that are probably very similar in composition to the core. Where do these samples come from?

ANS: The core is mostly iron; the inner part is solid, whereas the outer part is liquid. Samples of similar materials are found in some meteorites.

16. What is the difference between a meteor and a meteorite? Are all meteorites composed of the same material? Explain your answer.

ANS: A meteor is an object from space that enters Earth's atmosphere and starts to evaporate due to friction with the atmosphere to produce a glowing streak. Meteors that do not completely vaporize in the atmosphere impact Earth and are termed *meteorites*. Meteorites may be rocky or metallic or a combination of the two.

17. What is the difference between the lithosphere and the asthenosphere? Which layer is softer and flows more easily? At what depth does the lithosphere-asthenosphere boundary occur? Is this above or below the Moho?

ANS: The lithosphere is relatively cool and rigid compared to the hot, soft asthenosphere, which flows more readily. The lithosphere consists of the crust (oceanic basalt and gabbro, or continental granite) plus the uppermost mantle (peridotite) down to a depth of about 100 to 150 km. This boundary lies below the Moho.

On Further Thought

18. (a) Recent observations suggest that the Moon has a very small, solid core that is less than 3% of its mass. In comparison, Earth's core is about 33% of its mass. Explain why this difference might exist. Hint: Recall the model for Moon formation presented in Chapter 1. (b) The Moon has virtually no magnetosphere. Why? Hint: Remember what causes Earth's magnetic field.

ANS:

(a) The Moon is thought to have formed when a Mars-sized body collided with Earth early in its history. The impact hurled a portion of Earth, mostly mantle material with no contribution from the core, into orbit about our Earth, where it solidified to form our Moon. The moon differentiated (as the Earth had earlier) but with a minute amount of iron compared to the Earth (which had already seen most of its iron descend into its larger core).

(b) Convective circulation of liquid iron in the outer core of Earth generates our magnetic field; with only a modest amount of iron in the core, an extremely weak field is generated by the Moon.

19. Popular media sometimes imply that the crust floats on a "sea of magma." Is this a correct image of the mantle just below the Moho? Explain your answer.

ANS: No, the mantle just beneath the crust is not only solid but rigid, and along with the crust, it forms the lithosphere. Even the asthenosphere is mostly solid, though weak and ductile.

20. The measured temperature at the bottom of the deepest drill hole is about 180ºC (356ºF). What is the geothermal gradient at the location of this hole?

ANS: The deepest drill hole is 12.3 km beneath the surface, as given in the text. The surface temperature of the Earth is approximately 15ºC. Thus, the local geothermal gradient is (180 – 15)ºC / 12.3 km = 13.4ºC/km.