CHAPTER 10

CORE IDEA ESS1

EARTH'S PLACE IN THE UNIVERSE

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What Is This Disciplinary Core Idea, and Why Is It Important?

The first disciplinary core idea (DCI) in the Earth and space sciences section of *A Framework for K–12 Science Education* (*Framework*; NRC 2012), ESS1: Earth's Place in the Universe, "describes the universe as a whole and addresses its grand scale in both space and time. This idea includes the overall structure, composition, and history of the universe, the forces and processes by which the solar system operates, and Earth's planetary history" (NRC 2012, p. 170). Studying this topic allows students to understand how our planet is part of the largest system imaginable: the universe. This DCI begins to answer some of the important questions that have long intrigued human kind: "What is out there, beyond our world?" "What is our relationship to the universe as a whole?" and "Where did our world come from, and what is its history?" This DCI helps students learn how to make sense of the changing skies above them and to interpret astronomical phenomena they read about in the news, because new discoveries in astronomy are part of the everyday world they live in. It also supports the kind of knowledge students need to have to interpret evidence that tells us about the history of our planet, from the formation of familiar landscapes to long-term changes in climate.

ESS1 is organized around three major components. The first addresses the nature, structure, history, and composition of the universe, including how it was formed according to the big bang theory, our use of light to understand this and other processes in the universe, and the life cycle of stars. The second component examines the Earth's place in the solar system, concentrating on how motions of objects in the solar system explain our observations from the Earth's surface, the nature of those objects, and the use of physics to explain the patterns of motion of the objects. The third component focuses on the history of the planet Earth, with particular attention to our evidence for the sequences of events that occurred to create the Earth as we know it and the formation of the solar system itself. The ideas that make up Earth's Place in the Universe are not easy to define in a single underlying model, as is often the case for other DCIs. Instead, these ideas hold together as multiple ways of understanding and explaining phenomena that exist at the largest scales and across the longest time spans. For example, students may initially learn explanations for how the Earth's rotation causes the Sun's daily apparent motion in the sky separately from explanations for how the relative movement of the Sun, Earth, and Moon cause the changing lunar phases, but as they develop more sophisticated understandings of these individual explanations, students also learn that the two are related and recognize how they are part of a larger explanatory system for the way the universe behaves.

The understandings included in the ESS1 portion of the *Framework* differ in notable ways from previous standards for astronomy and Earth history. Rather than focusing on a collection of facts and concepts, the DCI is organized to help students grasp the major explanatory models that govern our understanding of the world around us. This puts further emphasis on helping students understand not just the *what* of Earth and space sciences but also the *how do we know* of these big ideas, via the integration of science practices. The *Framework* also emphasizes the importance of crosscutting concepts that span all the DCIs, such as the role of patterns and energy in the ideas included in ESS1. For example, observing patterns in celestial phenomena such as the lunar phases or the change in seasons leads to questions about how these patterns arise and in turn to the development of explanations that use the patterns of motion of the Earth and Moon in the solar system. Similarly, global patterns of rock strata led scientists to develop explanations that account for the history of events that shaped the Earth.

In the following sections, I will discuss how the ESS1 DCI is organized around increasingly sophisticated explanations for the Earth's place in the universe, first by discussing progress toward the explanatory models of astronomy in the DCI and then showing how this connects to understanding elements of Earth and space sciences included in this DCI.

Overview of Component Ideas

The *Framework* looks at the Earth's Place in the Universe concept from three perspectives: (1) how the Earth fits into the structure of the universe and the processes that formed the universe (ESS1.A), (2) developing explanations for our observations of the solar system using the Earth's motion (ESS1.B), and (3) understanding the evidence we have for how the planet was shaped and evolved over the course of its history (ESS1.C). These strands are woven together, with concepts developed at lower grades supporting increasingly sophisticated explanations across different spatial and temporal scales as students move through school.

ESS1.A: THE UNIVERSE AND ITS STARS

The *Framework* begins by posing a guiding question to organize how students should come to understand the universe: "What is the universe, and what is the Earth's place in it?" The first component idea of this DCI, ESS1.A: The Universe and Its Stars, begins the task of answering that question. The universe is everything … everything we can observe and beyond, including our planet, the stars, other planets, our galaxy, and other galaxies. The universe began in an event known as the big bang about 13.8 billion years ago, when the universe was extremely hot and dense. Immediately, the space between matter began to expand rapidly. During the early moments of the big bang, nearly all of the hydrogen and helium in the universe was formed, followed by the formation of the first stars and galaxies. The *Framework* has placed these elements of the DCI primarily at the middle and high school level because delving into these explanations requires an understanding of other fundamental aspects of chemistry and physics. For example, the evidence for the big bang and the history of the early universe relies on an interpretation of the cosmic microwave background radiation (CMBR); thus, knowledge of light and spectra (discussed in PS4.B: Electromagnetic (EM) Radiation; see Chapter 5, p. 75) is important to understanding how the CMBR was released in the early moments of the universe and how this evidence fits predictions that the universe began in a period of extreme temperature and density.

Across grade levels, students build toward understanding how our observations from the Earth only tell part of the story. Central to this is the awareness of how the *relative* size and distances of stars compares with the Earth and nearby celestial objects and the ways that this understanding allows students to develop more sophisticated explanations for phenomena they observe from the Earth. For example, in elementary school, children can begin this process by learning how stars only appear to be small points of light when they are actually large like our Sun and at great distances from us compared with the distance to the Sun and Moon. This understanding of size and distances takes a dramatic leap in middle school as students learn about our place in comparison to our own galaxy and other galaxies and as they begin to explore the history of the solar system and the universe through a study of the formation process of the solar system as well as how the big bang led to the formation of the universe. Finally, in high school, students develop even more sophisticated explanations for the nature of the universe as they learn to use light spectra as evidence for the big bang theory and the nature of stars. Their understanding of stars and our own solar system is further extended through explanations of how stars form and their life cycles.

ESS1.B: THE EARTH AND THE SOLAR SYSTEM

While ESS1.A establishes the Earth's place with respect to the stars and galaxies, as well as the history of the formation of our solar system and universe, the second component idea, ESS1.B: The Earth and the Solar System, concentrates on supporting student understanding of observable patterns of motion in the solar system and explanations for those motions. The *Framework* poses a question to guide how students learn across grades: "What are the predictable patterns caused by Earth's movement in the solar system?" This question hints at the progress of science, as it is scientists' observations, predictions, and identifications of patterns that lead to the development of models that help scientists explain the universe. This progression of understanding begins with students learning the patterns of motion and change in celestial objects as observed from the Earth's surface. Such phenomena may include daily patterns in the Sun, Moon, and stars' apparent motion, seasonal patterns in the Sun's motion, seasonal changes in constellations, phases of the Moon, and the wandering pattern of the planets against the background of stars. It continues as students learn to explain these phenomena with the motion of the Earth, Moon, and planets in the solar system, and to recognize how these objects' relative positions, as well as our own position on the spherical Earth, can be used to explain those patterns of motion and change. These ideas are explored further in ESS2.D: Weather and Climate when students build on their understanding of the causes of seasonal patterns in temperature change to begin to reason about long-term patterns in climate data. Eventually, students also develop explanations that include more sophisticated concepts of physics, such as gravity to explain orbital motion and energy to explain the seasons.

ESS1.C: THE HISTORY OF THE PLANET EARTH

In addition to considering explanations for phenomena by looking out beyond the Earth, the third component of this DCI, ESS1.C: The History of Planet Earth, delves into the evidence for how the Earth was shaped and has evolved. The *Framework* poses the question, "How do people reconstruct and date events in Earth's planetary history?" Because children's everyday experiences with the world around them may suggest that the Earth's surface is relatively static, studying the history of the Earth helps put current Earth surface phenomena in the context of how the planet changes over time. Developing this understanding allows children to see how seemingly divergent Earth phenomena, such as earthquakes and mountain chains, are part of a bigger system that is constantly changing. This idea is developed further in ESS2: Earth's Systems; students cannot understand our dynamic Earth without also understanding its history.

Students begin by examining evidence from observations of "the structure, sequence, and properties of rocks, sediments, and fossils, as well as the locations of current and past ocean basins, lakes, and rivers, to reconstruct events in Earth's planetary history" (NRC 2012, p. 177). In doing so, they begin to learn how the relative ages of events in Earth's history are revealed by studying the layering of rocks and fossils; further complexity is introduced as students make sense of rock layers that have been rearranged as the result of plate tectonics (see ESS2.B: Plate Tectonics and Large-Scale System Interactions [pp. 207–210]). To fully explain this planetary history requires connecting to their understanding of the Earth's place in the solar system, because studying the Earth's formation process yields additional information about its history. For example, though dynamic processes have destroyed much of the evidence for events that occurred on the Earth's surface during its early formation, the density of craters on other objects in the solar system, such as the Moon and other rocky worlds, provides evidence for the age of the Earth and its early history of bombardment from asteroids.

How Does Student Understanding of This Disciplinary Core Idea Develop Over Time?

The answers to the three guiding questions for the component ideas of ESS1 develop together toward a coherent understanding of the Earth's place in the universe as students' understanding of astronomy improves across grades.

Lower Elementary

In grades K–2, the *Framework* recommends students learn that we can begin to understand celestial objects, such as stars, planets, and the Moon, by observing their light and that telescopes can help us see more stars than we can see with the naked eye and show additional details of the Moon and planets. In this manner, students should begin to understand the discipline of astronomy from their own Earth-based perspective. Children's early experiences using tools such as binoculars to distinguish new details will help them begin to understand how astronomers built our complex understanding of space using more sophisticated tools of astronomy, including telescopes.

Understanding celestial objects from their own perspective continues through the elementary grades as children learn to describe patterns observable from the Earth's surface, such as the daily pattern of the motions of the Sun, Moon, and stars and seasonal changes in the Sun's path. Children may already know that the Sun and Moon appear to move, but they may not understand that this pattern of motion is a regular, smooth path across the sky; further, they are unlikely to recognize that the stars also appear to move (Plummer 2009a). This is because children's everyday experiences are unlikely to lead to an understanding of these patterns of motion, including the change in the Sun's path over the seasons, given the complexity of making the observations needed to reveal the patterns across position and time. Though these patterns of rising and setting of celestial objects are the result of the Earth's rotation, that is not the way that students on the Earth's surface experience them. Thus, in early elementary grades it is important for students to begin building an understanding of these patterns from their own perspective, such as tracing the Sun's apparent motion relative to their home or their school, rather than starting by learning about the Earth's rotation. Beginning with children's own Earth-based observations of celestial phenomena is an important foundation for their understanding of astronomy; they must first develop an understanding of astronomical phenomena before later learning how to explain those observations. This process mirrors the way scientists work by first recognizing and studying a phenomena and later trying to explain it using scientific principles and theories.

Also at this time, children should begin to learn about geologic events, including those that occur relatively quickly, such as earthquakes, and those that take much longer, such as the formation of the Grand Canyon. Developing an understanding of the relative temporal scales of Earth phenomena will help students begin to categorize these events and will provide a foundation as they work toward a deeper understanding of time in later grades. Phenomena can also be categorized in terms of whether they occur in cycles, such as day and night, or as distinct events with a beginning and end, such as volcanic eruptions (NRC 2012). Children are likely to have some ideas about these events prior to instruction; Ross and Shuell (1993) found that early elementary students are already aware of the earthquake phenomena before instruction but are likely to conflate it with other types of natural hazards, such as volcanoes and inclement weather. Children may be drawing on what they hear from the media to develop their understanding of these events (Ross and Shuell 1993).

Upper Elementary

In grades 3–5, students should build on their understanding of how tools help us understand celestial objects as they learn that the Sun is merely a very nearby star and that stars come in a wide variety of sizes and are different distances from the Earth and Sun. While children may be able to parrot the idea that "the Sun is a star," this is not sufficient for them to understand what it means that the Sun and other bright objects in the nighttime sky are the same type of object (e.g., Agan 2004). Children often believe that the stars are smaller than the Moon and located in the solar system or around the Moon (Agan 2004; Plummer, Kocareli, and Slagle 2014). Even with instruction addressing the actual size of the stars with respect to the Sun and planets, children continue to believe that, in addition to very large stars located at great distances, there are also very small stars located in our solar system (Plummer et al. 2014). Thus, even by upper elementary, the *Framework* is asking students to engage in sophisticated reasoning about sizes and scales to progress in their understanding of astronomy.

Comprehending the relative sizes and distances between objects may also support their developing explanations for the observed patterns of motion. In upper elementary grades, children begin to use the Earth's own motion to explain observable patterns developed in early elementary, such as the day–night cycle, the changes in length and direction of shadows, and the daily, monthly, and yearly change of position of the Sun, Moon, and stars. They also learn about the change in the planets' positions in the sky as they orbit the Sun. These explanations use students' developing spatial reasoning abilities to visualize how movement observed from their own Earth-based observations can be explained by the Earth and other celestial objects' motions and relative positions (Plummer et al. 2014). For example, the Sun's apparent rising and setting across the sky can be visualized from an Earth-based perspective, but its explanation requires visualizing how the Earth's rotation would cause us to see the Sun appear to move when it is actually we who are moving. Beginning this process of visualizing the connections between their own observations and how objects actually move in space will help them as they move toward more sophisticated explanations that rely on this same shifting of perspectives in middle and high school when they learn to explain lunar phases and the seasons (Plummer 2014).

Similarly, the temporal focus of early elementary continues in grades 3–5 as children develop increasingly complex notions of how the surface of the Earth changes over time. This can include understanding processes of weathering and erosion as well as how earthquakes change rock formations over time (see also Chapter 11, "Core Idea ESS2: Earth's Systems," p. 205). Children should also begin to understand the evidence available to interpret the history of rock layers, such as identifying the relative location of different fossils to determine the order in which layers of rock have been formed. Learning to use static records of rock layers to understand notions of time may be challenging for children because it relies on them grasping the principle involved in interpreting layers of sediment being laid down sequentially over time and relating this to notions of "deep time"—timescales that extend far beyond the child's own experiences (Dodick and Orion 2003).

Middle School

In grades 6–8, students should develop increasingly sophisticated explanations for celestial phenomena that explain patterns of Earth-based observations, with elements of the how objects move in space relative to our position on Earth along with an understanding of relative size and scale. For example, the *Framework* includes explanations for the lunar phases and seasonal changes in temperature across the globe at the middle grades. These require more complex reasoning than explanations for phenomena developed in elementary school, as children are asked to apply knowledge of light and energy to make sense of these phenomena. For example, explaining the seasons requires understanding the ways in which our observations of the Sun change due to our location on the spherical Earth and our position in its yearly orbit. But it also requires understanding how the changing position of the Sun in the sky changes the amount of energy our location receives, thus affecting the local temperature patterns. A significant body of literature points to the challenges students face in constructing these explanations due to the nature of the spatial reasoning involved (Kavanagh, Agan, and Sneider 2005). Students will need support during instruction on how to imagine the Moon as a sphere, illuminated by the Sun as it orbits the Earth (Plummer 2014) or how the Sun's altitude and path length changes seasonally as a result of the changing orientation of one's position on the Earth during its orbital cycle (Plummer and Maynard 2014). Supporting students over time in visualizing and using these changing perspectives is important for them to successfully engage with this DCI.

Students should also begin to develop a systematic understanding of the properties and motions of objects in the solar system. This builds on some of their initial understanding of the nature of celestial objects, such as the Sun, Earth, and Moon, as well as the motion of those objects (rotation and revolution), which they gained as they explained observable phenomena throughout elementary school. Rather than understanding that planets orbit the Sun in the same direction and roughly on a plane, students often enter middle school believing that the organization of the planets in the solar system is random, with some objects holding stationary or moving erratically (Sharp and Keurbis 2005). While gravity as a force that pulls objects down is introduced to explain everyday observations in elementary school (see Chapter 3, "Core Idea PS2: Motion and Stability: Forces and Interactions," p. 33), this is extended to explaining how objects move in the solar system in middle grades. In particular, students should learn that planets and other solar system objects, such as comets and asteroids, maintain their orbits about the Sun, rather than flying off into space, due to the gravitational force of attraction between the object and the Sun. On the Earth, we observe the attractive force between objects and the Earth when objects fall as they are dropped or thrown. However, planets and other objects in stable orbits are traveling forward in their orbital trajectory at a velocity great enough to maintain a constant, roughly circular "fall" about the Sun. Many students are likely to have alternative ideas about the nature of gravity, such as the belief that there is no gravity in space or that gravity only extends as far as the Earth's atmosphere (Williamson and Willoughby 2012). Students also often believe that only certain objects exert a gravitational force rather than all objects with mass (Plummer et al. 2015). And even when students have learned that planets are held in orbit around the Sun due to the Sun's gravitational pull on them, students are often unsure why planets do not crash into the Sun because they are unable to articulate the role of the planets' tangential velocity in maintaining the orbital motion (Plummer et al. 2015). Exploring the explanation for planetary orbits at a conceptual level (considering both the role of gravity and the planet's tangential velocity) will provide a stronger foundation for more sophisticated quantitative reasoning about orbital phenomena in high school.

Students' systematic exploration of solar system phenomena should also include organizing and classifying objects in the solar system toward a better understanding of the common properties and patterns of the solar system's constituents (Rubin et al. 2014). While instruction often focuses on the individual properties of the different planets in the solar system, a constructive approach is to focus on grouping objects according to their properties. This allows students to see how planets and other solar system objects with similar compositions and sizes (such as asteroids, comets, or Kuiper belt objects) are found at similar distances from the Sun. The focus shifts from superficial details and facts to systematic properties that organize the solar system. This way, students can begin to engage with important questions, such as, "Why do objects in the solar system orbit the Sun in the same direction and on the same plane?" and "Why are objects with similar physical properties found at similar distances from the Sun?" These and other observable patterns can be explained by the solar system's formation process.

The solar system formed from a cloud of dust and gas, drawn together by gravity. By shifting the focus from learning about the solar system as a collection of disconnected facts toward a coherent system with important patterns, students have further opportunity to learn how science is a process of developing models that explain our observations of interesting phenomena. To learn how the formation model explains our current observations of the solar system, students will need to continue to develop an understanding of how gravitational forces and momentum can shape how the solar system came to be and how it continues in its present form. Explaining how the planets formed involves learning how microscopic materials (gas, dust, and ices) can build up by "sticking together" (through electrostatic forces) until sufficient mass has accumulated such that gravitational forces can take over the building process at a macroscopic scale. Different types of planets and other objects formed initially because of the decrease in temperature with distance from the Sun; rocky and metallic objects, such as asteroids and the rock planets, formed closer to the Sun, whereas gas giant planets, comets, and Kuiper belt objects formed farther out where gases could condense into ice particles. One challenge that students have when first learning about this model is that they confuse the solar system's formation process with the big bang theory, an event that occurred billions of years before our solar system formed (Prather, Slater, and Offerdahl 2002).

In middle school, students should also have the opportunity to extend their understanding of sizes and scales of phenomena in the universe by learning how the Earth and the solar system are part of our Milky Way galaxy, one of billions of galaxies in the observable universe. Research suggests that students are likely to overestimate the distance to the Moon while underestimating, often by several orders of magnitude, the distances to the Sun, nearest stars, and other galaxies (Miller and Brewer 2010). Rather than just teaching children about the relative size and scale of objects in the universe, scales can be contextualized while teaching them to explain how the solar system formed from a large cloud of gas and dust that was itself part of a larger nebula in our Milky Way galaxy. This may help students place these objects on a scale and connect objects and relative size to important events and explanations in astronomy. Appreciation of the relative size of the cloud that formed the solar system may help students understand that the Sun and planets formed from an large cloud of gas that contracted due to gravity rather than from an explosion of material, a common idea held among students (Plummer et al. 2015). Student can build on this perspective of the relative size of the initial gas cloud and our own solar system to help appreciate how we fit into a larger collection of star systems, which formed from similar gas clouds, which make up the Milky Way galaxy.

With respect to Earth's own history, middle school students deepen their understanding of how we use evidence from rock layers and fossil records to understand the history of major events that have shaped the Earth and consider ways to organize our understanding of the long time periods of the Earth's history. Analysis of rock strata and the fossil record provide evidence for events such as volcanic eruptions, the formation of mountain chains, large-scale extinction events, and periods of mass glaciation. However, at this level, students' understanding of the evidence only leads to relative ordering of events and not an absolute timescale. Research on middle school students suggests that they may be aware of major geologic events, such as the movement of continents or ice ages, but their sense of the chronology is limited. Instead, they tend to focus on grouping events as "extremely ancient" and "less ancient" (Trend 1998). Several other studies with students from middle school to college also suggest that students do not have a grasp of deep time (e.g., Dodick and Orion 2003; Kortz and Murray 2009).

As with the study of astronomy, students' study of the Earth's history also engages them in particular elements of spatial reasoning that draw on the ability to understand geologic structures. Students will need support in this area as research has found that some have difficulty with the type of visualization needed to interpret these problems (Kali and Orion 1996). The challenge in understanding the three-dimensional nature of rock strata may also make interpreting the temporal scales challenging, since students are using these structures to interpret timelines of events (Dodick and Orion 2003). Student understanding of how rock strata and the fossil record could provide evidence of the Earth's history may also be limited because many believe sedimentary rock is formed just beneath the Earth's surface or that these layers are the same as the larger-scale layers of the crust and mantle (Kortz and Murray 2009). These alternative ideas suggest different ways that students misunderstand the spatial scales involved, and perhaps the temporal scales of the formation process as well. While sedimentary rocks are initially formed from the deposition of materials at the Earth's surface or within water, to form this material into rock requires a long-term process of sediment deposition that compresses lower layers sufficiently to compact the material into rock. Thus, rather than sedimentary rocks being a shallow feature of the Earth's surface, they are actually formed at great depths in order for enough pressure to be exerted from the weight of the surface layers. Further, the deposition of those layers requires immense amounts of time. Students often confuse sedimentary layers with crust and mantle layers, indicating they do not appreciate the spatial scale of these different types of "layers"; sedimentary rock is only a thin overlay on the Earth's crust.

High School

In high school, students build on concepts learned in middle school by developing more quantitative explanations for phenomena in the solar system while also expanding the range of phenomena they can explain to include those that occur on longer timescales than just days, months, and years. Students extend their understanding of orbital motion, developed at a descriptive level in elementary and middle school, to more quantitative explanations of these patterns using the mathematics of Kepler's laws and exploring how gravitational interactions can influence orbital motions. Students should also build from their explanations for seasonal temperature changes in middle school to learn about cycles of climate change on the Earth's surface that happen on much longer timescales (e.g., tens to hundreds of thousands of years). These changes occur due to long-term shifts in the shape of the Earth's orbit and the tilt in the Earth's rotational axis with respect to its orbital plane. Over time, these two factors alter the distance between the Earth and Sun at different times of the year and affect the intensity of sunlight, thus changing the patterns of energy absorption across the Earth's surface (see also ESS2.D: Weather and Climate [pp. 211–214]). Developing a sophisticated explanation for natural climate change provides a background for students to engage in understand human-induced climate change (Lombardi, Sinatra, and Nussbaum 2013), discussed in more detail in Chapter 12, "Core Idea ESS3: Earth and Human Activity" (p. 225).

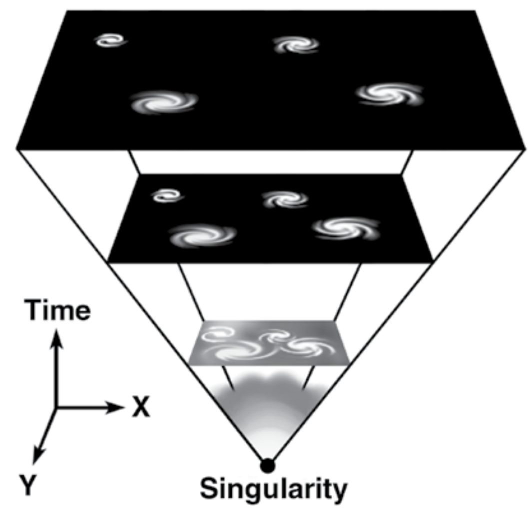
Students deepen their understanding of our Sun and the billions of stars in the universe, as well as how the big bang began the processes that led to the formation of the universe, by further developing their explanations for astronomical phenomena in ways that extend their notions of both spatial and temporal scales. For example, students' observations of the Sun and stars from an Earth-based perspective and across their own life span may suggest that these objects are constant. However, stars, though long-lived, have life cycles that culminate in millions to billions of years. The Sun can be studied as an exemplar case of how stars form from clouds of gas and dust (first discussed in middle school), exist stably for most of their lives, and then die dramatically as their fuel source (hydrogen, initially) runs out. Our own Sun will end as an expanding red giant star after exhausting its source of hydrogen for nuclear fusion (see PS1.C: Nuclear Processes [p. 27], which discusses the process of nuclear fusion in middle and high school) and then become a planetary nebula, leaving behind its core as a white dwarf star. Understanding the stellar evolution of more massive stars will help students understand where many of the building blocks of life and all that we know on Earth originated. A sufficiently massive star will eventually go supernova, spewing out a multitude of elements heavier than those formed during the big bang (hydrogen and helium). These elements are then seeded into new clouds forming new stars and planets, continuing the cycle of star birth, life, and death.

While in middle school, students learned about how the solar system formed only 4.6 billion years ago, in high school students more deeply explore how the universe itself began around 13.8 billion years ago with the rapid expansion of space between matter, as described by the big bang theory. The development of our model of how the universe began is an elegant story that can engage students with a series of phenomena that are consistent with the predictions of the big bang theory. The first phenomenon that led astronomers to the development of the big bang theory was the apparent motion of distant galaxies away from our own position in space. Just as the Sun *appears* to move across the sky during the day due to the Earth's own rotation, the galaxies are not actually moving away from us; it only *appears* this way from our Earth-based perspective. Instead, the apparent motion is due to the expansion of the space between clusters of galaxies. If one imagines this process running in reverse, the conclusion drawn is that the universe began with everything packed together in a hot, dense state (see Figure 10.1). This concept of the early universe leads to the next piece of observable evidence for the big bang: the ratio of low-mass elements in the universe. Astronomers predicted that during those first moments, when the universe was extremely hot and dense, it behaved similarly to the core of a star. Particles collided to fuse, forming the first atoms: hydrogen, helium, and a small amount of lithium. Current observations of the ratios of these elements match what was predicted by the big bang theory. The final strong piece of observational evidence for the big bang is the CMBR. An object that is extremely hot and dense will emit a characteristic spectrum of light that corresponds to its temperature; the very early universe itself was hot and dense, which produced this characteristic spectrum of light based on its temperature. A few minutes after the universe began to expand, that light became free to stream through space. We are still able to observe this leftover light from the early moments of the universe. Its spectrum matches what astronomers predicted we would observe if the universe began in that hot, dense state.

For students to understand how astronomers develop complex explanations for stellar, galactic, and extragalactic phenomena, they will need to develop increasingly sophisticated understandings of how astronomers interpret the light received from these objects. For example, as mentioned above, one piece of evidence for how the universe began is drawn from our observations of the motion of galaxies. When we view the spectrum of light emitted by the stars that make up a galaxy, we observe a pattern of bright bands and dark lines. The dark lines are where light emitted by stars has been absorbed by elements in the stars' atmospheres. Each element has a characteristic pattern of these dark absorption lines that can be used like a fingerprint to identify that element, because they always appear in the same pattern and at the same wavelengths of light. However, if the objects that contain the atoms that are absorbing the light are in motion—in this case, the stars in a distant galaxy—those lines will be shifted proportionally to the speed of

FIGURE 10.1

The Expanding Universe



Time moves forward from the bottom to the top of the figure. While the size of the galaxies (shown as spirals) stays the same, the space between them expands. At the time of the big bang, the universe was an infinitely dense singularity.

the object's motion. Therefore, when we observe that a galaxy's spectrum with its characteristic pattern of absorption lines appears to be shifted toward the red end of the spectra, we interpret this as the galaxy itself moving away from us (relatively speaking) due to the expansion of the universe. This aspect of the DCI connects to the understanding of light that students are developing in PS4.B: Electromagnetic Radiation, which examines the nature of light across the electromagnetic spectrum, how it travels, and how it interacts with matter.

Similarly, across elementary and middle school grades, students develop increasingly sophisticated notions of how we establish evidence for long-scale change over time on the Earth. This serves as the foundation for developing more sophisticated explanations in high school. Students should begin using knowledge of radioactive decay lifetimes and isotopic content as the method to date rock layers and develop an absolute scale for the history of events on Earth. In doing so, students will need an initial understanding of nuclear physics (See PS1.C: Nuclear Processes [p. 27]). Students may have alternative ideas about radioactive decay that will make using this concept to explain our understanding of Earth's history challenging. For example, students may have more colloquial ideas about the word *decay*, such as suggesting that the atoms are losing pieces or disintegrating, that electrons are simply change states, or that radioactive decay involves an interaction between the nucleus and valence electrons (Prather 2005). Their understanding of half-life may be similarly problematic; students often believe that half of the radioactive material will be gone after a half-life rather than having become a different element (Prather 2005). Addressing the full history of the Earth and its formation may need to include a focus on the relationship between when life arose on the planet Earth; many college students believe life already existed on Earth when it formed (Libarkin et al. 2005).

Radiodating only provides an age for the oldest rock on Earth; however, given the Earth's state of constant change due to plate tectonics and erosion (see Chapter 11, "Core Idea ESS2: Earth's Systems," p. 205), students should learn how looking out into the solar system can provide evidence for the age of the Earth and its early history. Rocky objects in the solar system, such as the Moon and asteroids, have gone through much less change during the course of the solar system's history compared to the Earth. Planetary scientists use radiodating on meteorites to determine the age of the Earth and solar system. As they connect the age of the Earth's formation in the solar system to other events in the universe's history, students will need support in understanding that the big bang occurred well before the Sun formed (13.8 billion vs. 4.6 billion years ago) as students often conflate these two events (e.g., Trend 2000). The earliest epoch of the Earth's existence was a time of heavy bombardment of asteroids and comets throughout the solar system. Though little evidence of this past bombardment is evident on the Earth itself, the record of this period in the Earth's history can be inferred from observations of the Moon, Mercury, and other rocky objects in the solar system. We can still observe evidence of their past bombardment through the numerous craters on their surfaces. Thus, students will need to understand that the solar system's formation process must have produced far more asteroids and comets than we currently observe to account for the impacts seen on the rocky planets and moons.

What Approaches Can We Use to Teach About This Disciplinary Core Idea?

Progress in the Earth's Place in the Universe requires integrating key science practices with instruction that moves students toward more sophisticated explanations for the nature and origins of the solar system, the stars, and the universe. In elementary school, instruction should support students in developing representations for the observable patterns of change and motion. This is a good opportunity to begin engaging students in making claims based on patterns they uncover in observations of celestial objects. Data could include their own observations of the Sun's location throughout the day or the visibility of stars at night but not during the day. And while it is important for students to have the opportunity to make their own firsthand observations in astronomy, time and weather can limit the extent to which this can happen in the classroom. Students can also make and record observations using computer simulations of the day and night sky, such as *Stellarium* (*www.stellarium.org*) or *Starry Night* (*astronomy.starrynight.com*) which show realistic views of the sky as seen from the Earth's surface (e.g., Hobson, Trundle, and Saçkes 2010; Plummer, Wasko, and Slagle 2011). Looking for patterns in their observations, such as the apparent path of the Sun and Moon or the changing appearance of the Moon's phases, engages students in the science practice of analyzing and interpreting data.

In upper elementary and middle school, these initial evidence-based claims about the patterns in celestial motion become the impetus to construct more complex model-based explanations that lead to an understanding of the relative motions of objects in the solar system. Students can engage in scientific argumentation as they collaborate with peers and are guided by their teacher to construct models of the Sun, Earth, and Moon to explain the observed patterns. Though the phenomena differ, this trend of developing evidence-based claims about the patterns of celestial events and then engaging in argumentation with models to make sense of the patterns continues from the simplest phenomena, such as the daily apparent motion of the Sun, through the most complex, such as the seasonal change in temperatures (Plummer, Kocareli, and Slagle 2014; Plummer and Maynard 2014; Plummer 2014). The use of models in the classroom should do more than simply show students motions and relationships; students need to engage in using models to explain their observations. For example, after developing a representation of the Sun's apparent path across the sky (from observations of changes in their shadows over the course of the day or by recording the Sun's position while watching a computer simulation, like *Stellarium*), students can use models to explain their observations. Using a ball or lamp to represent the Sun and a globe to represent the Earth, small groups of students can then work together to determine which direction the globe should rotate for the Sun to appear to move from east to west as they observed in their data.

Engaging students with physical models offers several advantages in supporting student learning. Physical models may be key to improving students' spatial thinking in astronomy (Parker and Heywood 1998; Plummer 2014). Engagement with physical models may help reduce the amount of information students need to keep in mind at one time, because elements are kept in the models and available for use when needed (Wilson 2002). Engagement with physical models may also provide teachers with access to their students thinking during instruction, because teachers can observe the ways in which students manipulate those models to solve problems. For example, if students are trying to make their Earth globe orbit the Sun when modeling the reason the Sun appears to rise and set, the teacher can visually assess that the students have an alternative idea about the reason for the day/night cycle. Finally, these types of experiences will allow students to learn how models and modeling is central to the authentic practices of scientists (Rivet and Kastens 2012).

Students' own kinesthetic and embodied experiences (physical movements), as they attempt to construct explanations in astronomy, can also support the complex spatial reasoning in this domain (Plummer 2014). Gesture use may help facilitate problem solving (e.g., Liben, Christensen, and Kastens 2010; Parnafes 2012) and has been found to help students solve tasks that require visualization and mental transformations, such as those required to explain how our Earth-based observations are explained by relative motions in space (Chu and Kita 2011). Gestures and whole-body interaction can be designed to be a purposeful part of instruction and to support student learning (e.g., Padalkar and Ramadas 2011; Plummer 2009b; Plummer et al. 2014). For example, students can physically trace out the apparent path of the Sun as it appears to move across the sky and then model the explanation by pretending to be the Earth as they rotate and observe a model Sun appearing to move from their location (Plummer, Wasco, and Slagle 2011; Plummer, Kocareli, and Slagle 2014). These experiences offer both visual and kinesthetic support for students learning to explain astronomical phenomena.

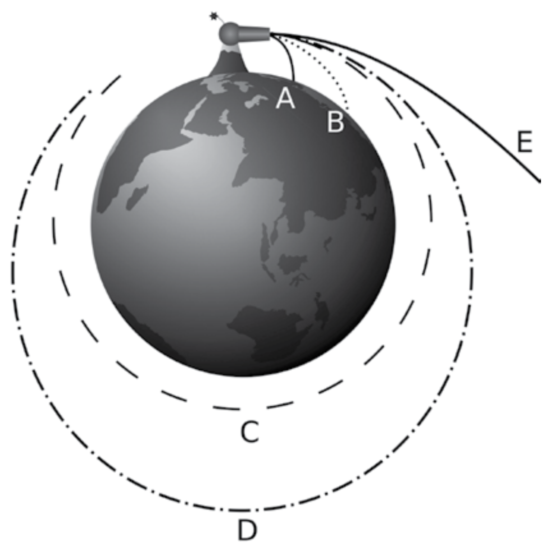
Students' investigations of the solar system in middle school can also be an opportunity to engage in scientific argumentation to promote a systems-based understanding of our place in the solar system. Students can learn to organize the objects in the solar system according to their properties, such as composition, distance from the Sun, and size (Rubin et al. 2014). Students should be encouraged to gather and record data about multiple properties (e.g., mass, size, distance from the Sun, density) for solar system objects from reliable websites (such as those created by NASA). They should then use these data to make claims about how to group objects and back up their claims with evidence from the data they collected from websites. Though students may want to use existing classification schemes, they should be encouraged to focus on using the evidence they have gathered to develop groups for themselves. In doing so, they move toward an understanding of the solar system that focuses on the underlying features needed to be explained by its formation process (Rubin et al. 2014), in particular patterns in objects' composition, distance, and size.

Once students appreciate the different properties of objects in the solar system and how they are distributed, they can learn to explain solar system formation by participating in a whole-class modeling activity called *Active Accretion* (Ristvey, Bogner, and Cobb, n.d.). During this model, each student represents a particle from the initial cloud of gas and dust that collapsed to form the Sun, planets, and other objects. During the course of simulating collisions between particles, students "stick" to the same particle type (such as metals or ices) through electrostatic forces until a particle of sufficient mass has built up (enough students) so that gravity can take over the process of pulling in more material to build up a planet. This simulation helps middle school students understand the microscopic process of small particles sticking together to begin building up to form planets; but students may still need more support in understanding gravity's role in how planets build from small planetesimals to full-sized planets (based on research by Julia Plummer, Christopher Palma, KeriAnn Rubin, Alice Flarend, and Yann Shiou Ong).

Computer simulations can also support students as they learn to explain how and why objects orbit in the solar system. For example, students can engage with a computer simulation (such as those from PhET at *http://phet.colorado.edu*) that models the solar system to test how varying mass, distance, and initial velocity influence the nature of planetary orbits. Student groups can share data they have collected from such a computer simulation to look for trends across data sets (Flarend and Palma 2013). This allows them to begin developing claims that relate the balance of velocity to the magnitude of the gravitational pull in maintaining a stable orbit. Another useful simulation is *Newton's Cannon* (*http://waowen.screaming.net/revision/force&motion/ncananim.htm*), which can also be used as a thought experiment in class. Imagine a large cannon is placed on top of the tallest mountain on Earth. Cannonballs are then shot out horizontally with different amounts of force and therefore different initial velocities. Those with small initial velocities will fly small distances and eventually crash to the surface of the Earth because of the pull of gravity. Those with very high velocities will move fast enough to escape. But a cannonball fired with just the right initial velocity will be pulled down by gravity in a path that matches the curvature of the Earth's surface, forming an orbit around the Earth (see path C in the Figure 10.2).

FIGURE 10.2

Cannonball Trajectories for the Newton's Cannon Thought Experiment



Newton's Cannon is a thought experiment describing a large cannon placed on top of a tall mountain on Earth. The cannonballs fired for trajectories A and B were fired with small initial velocities, and therefore gravity pulled them down to the Earth's surface. The cannonball fired for trajectory E was fired at the highest initial velocity and escaped Earth's gravity. Cannonballs fired for trajectories C and D were fired with velocities that sufficiently balanced the gravitational pull on the cannonballs as they fell toward the Earth, producing an orbital path.

In high school, students can continue to develop model-based explanations for observed phenomena as they study the relative size and distances of stars, the evolution of stars, and the formation of the universe. Instruction should engage students in constructing explanations that support the big bang theory using available evidence. This will require students to apply knowledge of light spectra to interpret evidence from the apparent recession of distant galaxies and the nature of the CMBR, and to use atomic physics to understand how the proportions of light elements found in the current universe can be explained by the process in which they were formed 13.8 billion years ago. Thus, instruction should shift toward helping students construct their own explanations for how all the disparate pieces of evidence support an explanation for the formation of the universe.

Instruction that supports students in developing a deep and rich understanding of Earth's history integrates experiences with science practices as the students work toward explanations for the history of events on the Earth. This can begin with early elementary students' investigations of the timescales of natural events on Earth. Such investigations could engage students in obtaining and evaluating information about the length of events such as volcanic eruptions, earthquakes, and erosion to determine that some happen quickly and others very slowly. This can lead to more sophisticated opportunities to construct explanations based on evidence from rock formations and fossils in rock layers observed during classroom investigations. As students engage with gathering data by making observations of rock strata to learn how geologists sequence events in geologic history, it will be important for them to make contextualized observations. Specifically, the science practice of observing is discipline specific, relying on the students developing understanding of the theoretical constructs of geology (Ford 2005).

Students should continue to learn about the history of the Earth by constructing explanations based on evidence from rock strata in middle school. However, the level of sophistication increases as they work toward understanding the geologic timescale of the Earth's history, rather than a more localized approach to understanding changes in landscape over time in elementary school. In middle school, teachers should support students in using their developing understanding of scientific principles in geology to support their process of explaining evidence of the geologic timescale. This may build on their understanding of how fossils can be used to establish relative ages of major events, the processes that led to the formation of mountain chains and ocean basins, and the theory of evolution (NGSS Lead States 2013). Constructing explanations will also require students to interpret spatially complex geologic structures. Instruction should be designed with this in mind so teachers can help students envision cross sections of structures and improve their perception of spatial configuration of layers in complex structures (Kali and Orion 1996). Students may be more likely to use gesture as they are learning new concepts (Liben, Kastens, and Christensen 2010) and should be encouraged to do so; teachers can promote gesture use by engaging students with 2-D representations, physical models, or other artifacts (Kastens, Agrawal, and Liben 2008). For example, when interpreting events in Earth's history from maps or representations showing different layers of rock strata, students should be encouraged to gesture both to each other and to their teacher in ways that help them identify key elements and relationships, such as how one layer relates to another layer, and to manipulate these representations in ways that help them make sense of how to interpret change over time. Research has found a link between children's knowledge of geology and their spontaneous gesture use (Matlen et al.

2012). Teachers can also use gestures to help convey spatially complex issues (Kastens et al. 2008).

Conclusion

The Earth's Place in the Universe DCI engages students in increasingly large spatial and temporal scales as they move from elementary to middle to high school. Supporting student learning across the grades begins with supporting their connections to what they can observe and experience but then quickly moves out to scales that require models, simulations, and representations within which to interact and make sense of the phenomena. Students will need support in engaging in the types of spatial reasoning required to construct scientific explanations in this DCI. They will also need to begin integrating other DCIs as they move up the grades, including those about gravitational forces, nuclear processes, and energy.

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