IS8

Earth and Space Sciences Instructional Segment 8: Motion in the Universe

According to the NGSS storyline:

> High school students can examine the processes governing the formation, evolution, and workings of the solar system and universe. Some concepts studied are fundamental to science, such as understanding how the matter of our world formed during the Big Bang and within the cores of stars. Others concepts are practical, such as understanding how short-term **changes [CCC-7]** in the behavior of our [S]un directly affect humans. Engineering and technology play a large role here in obtaining and analyzing the data that support the theories of the formation of the solar system and universe. (NGSS Lead States 2013c)

EARTH AND SPACE SCIENCES INSTRUCTIONAL SEGMENT 8: MOTION IN THE UNIVERSE

Guiding Questions

- What are the predictable patterns of movement in our solar system and beyond?
- What can those motions tell us about the origin of the universe and our planet?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe. [Clarification Statement: Emphasis is on the astronomical evidence of the red shift of light from galaxies as an indication that the universe is currently expanding, the cosmic microwave background as the remnant radiation from the Big Bang, and the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).]

HS-ESS1-4. Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. [Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.] [*Assessment Boundary: Mathematical representations for the gravitational attraction of bodies and Kepler's Laws of orbital motions should not deal with more than two bodies, nor involve calculus.*]

HS-ESS1-6. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. [Clarification Statement: Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, Moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.] (Revisited from IS 7)

EARTH AND SPACE SCIENCES INSTRUCTIONAL SEGMENT 8: MOTION IN THE UNIVERSE

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	ESS1.A: The Universe and Its Stars ESS1.B: Earth and the Solar System ESS1.C: The History of Planet Earth PS4.B: Electromagnetic Radiation	[CCC-3] Scale, Proportion, and Quantity [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-6] Structure and Function [CCC-7] Stability and Change Connections to Engineering, Technology, and Applications of Science Interdependence of Science, Engineering, and Technology Connections to Nature of Science Scientific Knowledge Assumes an Order and Consistency in Natural Systems

Highlighted California Environmental Principles and Concepts:

Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services.

Principle II The long-term functioning and health of terrestrial, freshwater, coastal and marine ecosystems are influenced by their relationships with human societies.

Principle III Natural systems proceed through cycles that humans depend upon, benefit from, and can alter.

Principle IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.

CA CCSS Math Connections: A-SSE.1a–b; A-CED.2, 4; F-IF.5; S-ID.6.a–c; N-Q.1–3; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: RST.11–12.1, 2, 7, 9; WHST.9–12.2a–e, 7

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

In earlier grades, students observed and described **patterns [CCC-1]** of motion in the sky (1-ESS1-1, 5-ESS1-2). In this instructional segment, students will explore motion at a range of **scales [CCC-3]** that help **explain [SEP-6]** where Earth's materials came from, how they came together, and how they have been modified since then.

Students **analyze [SEP-4]** spectra of stars beyond the Sun by comparing them to a set of known spectral lines of different elements determined in a laboratory. To match the laboratory lines, they find that they need to shift the star spectra. Understanding the significance of this observation requires understanding of the Doppler effect, a process that builds on students' existing models of waves but is not required to meet other CA NGSS performance expectations. When stars move toward or away from a viewer, the wavelength of their light shifts. We can therefore use the Doppler shifts to map out the movements of stars toward or away from us. For example, we find that galaxies rotate, so even if overall the galaxy is moving away from us, stars on one side of it may have a smaller Doppler shift than stars on the other side. When students examine different stars in different parts of the sky, they will make the discovery that almost all galaxies are shifted toward longer wavelengths, revealing that the stars are all moving away from us. This effect is referred to as a *redshift* because all the other colors of visible light are shifted towards red, the longest wavelength of visible light, when their wavelength is lengthened.

Students are now ready to **obtain information [SEP-8]** from media about Edwin Hubble's surprising discovery that the universe is expanding (Sloan Digital Sky Survey/Sky Server n.d.b.; Kirshner 2004). At the time, scientists wondered if our universe has always looked the way it does today. Einstein assumed a **static [CCC-7]**, "ungrowing" universe in his equations of relativity, but others like Willem de Sitter showed that an expanding universe was also theoretically possible. Meanwhile, observational astronomers like Henrietta Leavitt developed techniques that allowed accurate distance measurements of objects in the universe, and Vesto Slipher cataloged the redshifts of entire galaxies. Hubble entered the debate by combining these techniques and noticing a **pattern [CCC-1]** in the redshifts: the farther away a galaxy is from Earth, the faster it moves away from us. Some of the most distant galaxies have such an extreme redshift that they appear to be receding from us at a speed faster than the speed of light when we calculate their velocity using Doppler shift alone. If they were moving that fast, their light would never reach us and we wouldn't be able to see them. Hubble proposed a bold **model [SEP-2]** that could **explain [SEP-6]** this pattern in which galaxies are not really moving in space, but rather the space between the galaxies is getting bigger (much like a lump of dough expanding and moving mixed-in raisins farther apart from one another). The redshifts must be the combined effect of Doppler shift and the wavelengths getting stretched by the stretching of space itself.

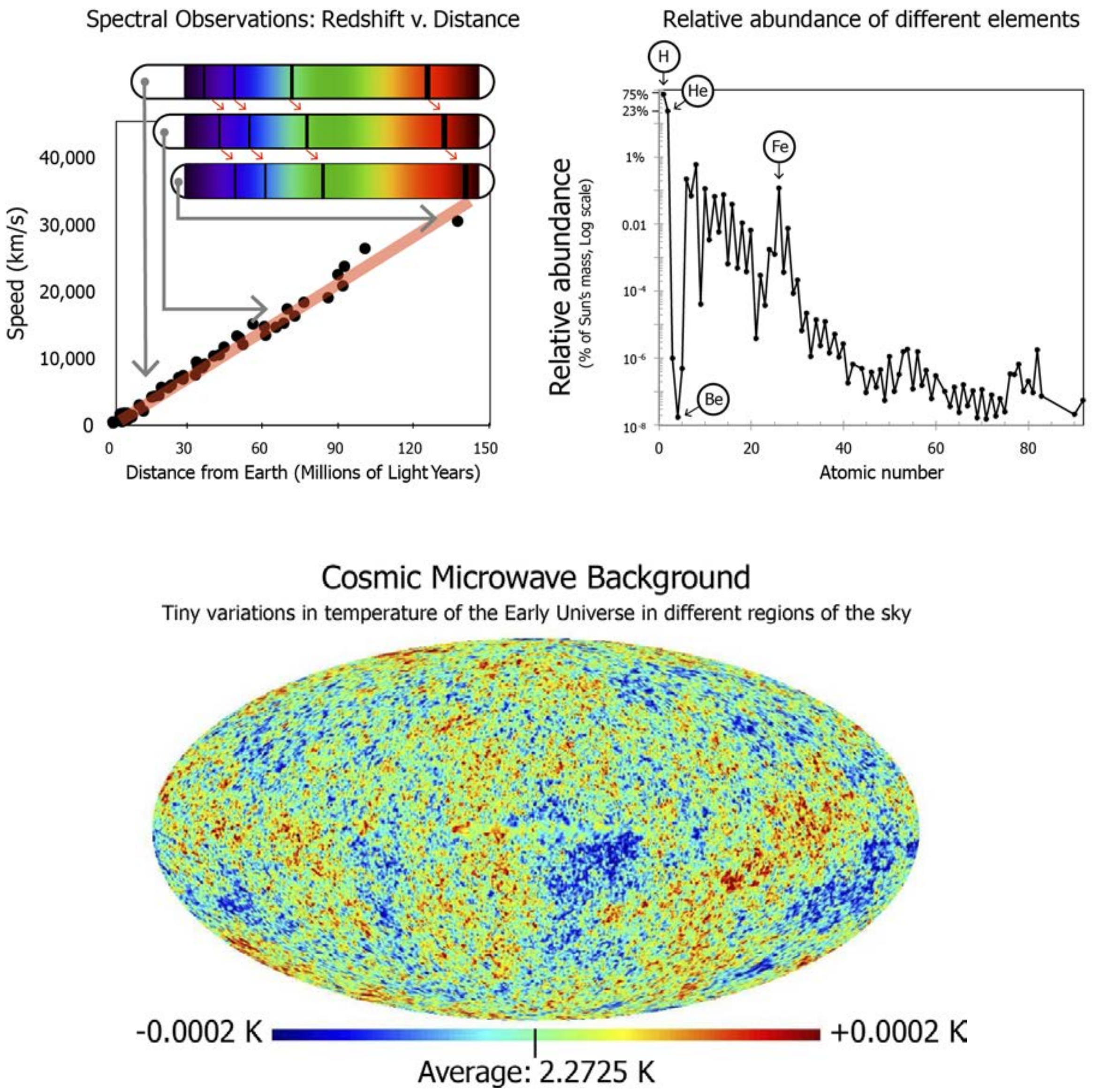
Students can perform their own **investigation [SEP-3]** of redshifts using simulated telescope data from online laboratory exercises. Two older examples include Project CLEA at https://www.cde.ca.gov/ci/sc/cf/ch8.asp#link88 or University of Washington Astronomy Department at https://www.cde.ca.gov/ci/sc/cf/ch8.asp#link89. This investigation requires an understanding of how distances are measured in the universe, which builds on the **argument [SEP-7]** students constructed in fifth grade that the apparent brightness of stars in the sky depends on their distance from Earth (5-ESS1-1). Students can work independently or in small groups to **obtain information [SEP-8]** about one of the methods for determining distance in the universe and then combine their findings with other students' findings to develop a report, a poster, or a presentation that describes the **scale [CCC-3]** of the universe and how it is measured.

Students now have **evidence [SEP-7]** that the universe is expanding, so teachers can invite them to **ask questions [SEP-1]** such as "What is causing this expansion?" and "What would the universe look like if we could 'rewind' this expansion to look back in time?" The inevitable answer is that everything that we can see as far as we can look out into the universe was at one time all contained in a tiny region smaller than the size of an atomic nucleus. This region was extremely hot and dense at this time until everything started rapidly to spread apart in what we call the Big Bang. We can see evidence of this expansion in the **matter and energy [CCC-5]** that exists in the universe today. As the material spread apart, it started to cool enough for atomic nuclei to form, but calculations by scientists show that only specific elements would form and in specific proportions. We can look for that "fingerprint" by using spectral lines and other techniques to determine the relative abundance of different elements in stars like our Sun (graph in the top right in figure 8.73). While the Sun's relatively small proportion of heavier elements was formed in distant supernovas, its overall composition is similar to most other stars and matches the fingerprint predicted by the Big Bang with roughly three-quarters hydrogen and one-quarter helium.

In 1963, a group of scientists detected another piece of evidence of the Big Bang when they observed a constant stream of microwave radiation coming toward Earth in every direction. They were worried something was wrong with their equipment, but it became apparent that the signal they were detecting was also consistent with **models [SEP-2]** of a hot early universe that emitted radiation, which should still be traveling toward Earth today. We now call that **energy [CCC-5]** the Cosmic Microwave Background Radiation and can use it to describe what the universe looked like shortly after the initial Big Bang (image on the bottom in figure 8.73). Like so many scientific discoveries, engineering and technology have had a profound impact on scientists' ability to make measurements. Cosmic Microwave

Background Radiation was not measurable in the days of Hubble because the technology did not exist to observe it. Students should be able to **explain [SEP-6]** each of these pieces of evidence.

Figure 8.73. Evidence for the Big Bang



Evidence of the Big Bang comes from the redshift versus distance of stellar spectra (top left), the relative abundance of elements in the Sun determined from absorption spectra (top right), and the Cosmic Microwave Background Radiation that reveals minute differences in temperature in the early universe (bottom). *Sources*: M. d'Alessio with data from Jha, Riess, and Kirshner 2007; M. d'Alessio with data from Lodders 2003; NASA 2008

Long description of Figure 8.73.

Predicting Motions

In IS7, students develop a model for the birth of the Sun from a cloud of dust and gas. That model also predicts that planets and other bodies in the solar system all formed the same way from the same initial materials. The force of gravity causing particles to coalesce into larger and larger objects is at the heart of this model. This nebular theory provides a framework used to explain many major features in the solar system, such as the compositional difference between the rocky inner planets, the gaseous outer planets, and the asteroid belt where planetesimals and smaller bodies continue to circulate today. A consequence of the gravity-driven motion in the early solar system is that random variations **cause [CCC-2]** all of the bodies in a region to start rotating the same direction as they accumulate more mass. Motion in our solar system shows **evidence [SEP-7]** for this effect, as most objects rotate and revolve in a common direction, rather than randomly. Observations of those consistent motions, including the period of each planet's orbit, can be the driving observation behind the discussion of the use of Kepler's laws to predict those motions (HS-ESS1-4).

Science and Engineering Practices and the History of Gravity

Although scientists have studied gravity and electromagnetism intensely for centuries, many mysteries remain concerning the nature of these forces. The CA NGSS learning progression mirrors the historical development of our understanding of gravity and orbital motion. In 1576 Danish scientist Tycho Brahe set up the world's most sophisticated astronomical observatory of its time. He methodically **investigated [SEP-3]** and recorded the motion of celestial objects across the sky. Just before he died, Brahe took on Johannes Kepler as a student who **analyzed the data [SEP-4]** to develop a simple descriptive **model [SEP-2]**. Even though his model did a superb job of predicting the motion of objects in the sky, it was incomplete because it could not explain the fundamental forces driving the motions. In late 1600s Isaac Newton extended Kepler's model by describing the nature of gravitational forces. From his fundamental equations of gravity, Newton was able to derive Kepler's geometric laws and match the observations of Brahe. Newton is known not only for his innovative thinking, but for his ability to **communicate [SEP-8]** clearly; many twenty-first century physics classes still read his book *Principia Mathematica* to learn about his ideas. In the CA NGSS, elementary students mirror the work of Brahe, recognizing **patterns [CCC-1]** in the sky (1-ESS1-1, 5-ESS1-2). At the middle grades level, students mirror the work of Kepler by making simple **models [SEP-2]** that describe how galaxies and the solar system are shaped (MS-ESS1-2). In high school, students add **mathematical thinking [SEP-5]** to their descriptive model (using Kepler's laws, HS-ESS1-4) and then finally extend their model to a full explanation with the equations of the force of gravity from Newton's model (HS-PS2-4).

Even though students quantitatively describe the force of gravity in physical science

(HS-PS2-4), deriving Kepler's Laws for elliptical orbits directly from the gravitational force is beyond the mathematical scope of many students. Instead, focus should be on interpreting the **evidence [SEP-7]** of the orbital period of different bodies in our solar system, including planets and comets. These laws form an excellent illustration of the crosscutting concept of **scale, proportion, and quantity [CCC-3]**. By comparing the distance of objects away from the Sun and the time it takes them to complete one orbit, students recognize a **pattern [CCC-1]**. Table 8.10 shows that the ratio determined by Kepler (orbital period squared divided by orbital distance cubed) is nearly constant for objects in our solar system. Students can calculate this ratio for Earth and other planets and then make measurements of the orbital path of comets to try to estimate how often they will return. The ratio is only true for objects orbiting the same body (illustrated by the dramatically different ratio for the Moon in table 8.10). But students can use measurements of the Moon to predict the height of satellites in geosynchronous orbit, which have an orbital period of exactly one day, allowing them to always be in the same position in the sky. Satellite television receives signals from these satellites. Alternately, students can use the orbital period of the International Space Station from its height above Earth. Students can also use the more complete form of Kepler's laws to calculate the mass of distant stars using only the orbital period of newly discovered planets that orbit them.

Table 8.10. Orbital Period and Distance from the Sun of Objects in our Solar System

PLANET	PERIOD (yr)	AVERAGE DISTANCE (AU)	KEPLER'S RATIO: T^2/R^3 (yr^2/AU^3)
Mercury	0.241	0.39	0.98
Venus	0.615	0.72	1.01
Earth	1	1	1.00
Mars	1.88	1.52	1.01
Jupiter	11.8	5.2	0.99
Saturn	29.5	9.54	1.00
Uranus	84	19.18	1.00
Neptune	165	30.06	1.00
Pluto (dwarf planet)	248	39.44	1.00
Halley's Comet	75.3	17.8	1.00
Comet Hale-Bopp	2,521	186	0.99
Moon (relative to Earth)*	0.0766	0.00257	345667*

*Kepler's ratio only works for objects orbiting around the same body. Since the Moon orbits Earth, its ratio should be much different.

Engineering Connection: Computational Models of Orbit

When a company spends millions of dollars to launch a communications satellite or the government launches a new weather satellite, they employ computer models of orbital motion to make sure these satellites will stay in orbit and the investment is not lost. These **models [SEP-2]** are based on the exact equations introduced in the CA NGSS high school courses. In fact, students can gain a deeper understanding of the orbital relationships and develop **computational thinking [SEP-5]** skills by interacting directly with computer models of simple two-body **systems [CCC-4]**. Even with minimal computer programming background, students could learn to interpret an existing computer program of a two-body gravitational system. They could start by being challenged to identify an error in the implementation of the gravity equations in sample code given to them. Next, students modify the code to correctly reflect the mass of the Earth and a small artificial communications satellite orbiting around it. They can vary different parameters in the code such as the distance from Earth or initial speed and see how those parameters affect the path of the satellite (HS-ESS1-4). At what initial launch speeds will the satellite stay in orbit? What is the tradeoff between the cost of fuel and the payload mass?

(Note: Appendix 3 in this framework provides guidance about teaching computer coding aligned with the CA NGSS.)

While Kepler's laws present a simple view of orbital shapes and periods, the *NRC Framework* pushes teachers to emphasize the importance of **changes [CCC-7]** in orbits, as these **changes [CCC-7]** have large impacts on Earth's internal **systems [CCC-4]**:

> Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. Cyclical changes in the shape of Earth's orbit around the [S]un, together with changes in the orientation of the planet's axis of rotation, both occurring over tens to hundreds of thousands of years, have altered the intensity and distribution of sunlight falling on Earth. These phenomena cause cycles of ice ages and other gradual climate changes. (National Research Council 2012, 176)

Using realistic computer simulations of Earth's orbit (HS-ESS1-4), students can **investigate [SEP-3]** the **effects [CCC-2]** collisions (such as the impact that led to the creation of the Moon) or explore the variation in the Earth–Sun distance to look for **evidence [SEP-7]** of cyclic **patterns [CCC-1]**. They would discover some cyclic **patterns [CCC-1]** called Milankovitch cycles, which have a strong influence on Earth's ice age **cycles [CCC-5]**.

The CA NGSS pushes teachers to connect these ideas so that Earth's place in the universe is strongly integrated with our understanding of the complete Earth system.

Concept Map of Earth and Space Science Disciplinary Core Ideas

In meeting the performance expectations selected for this course, instructors must introduce some DCIs as well as build on the DCIs introduced in the middle grades. Figure 8.74 shows a concept map with the relationships between DCIs introduced during the middle grades and high school levels. This concept map is not a conceptual flow with a specific order or sequence, nor is it a comprehensive illustration of all ideas that should be taught in the courses. It may, however, be helpful in identifying how DCIs build from middle grades to high school and relate to one another. This map is explicitly placed at the end of the instructional segment so that readers view them with a full appreciation of how these DCIs must be explored using the other two dimensions of the CA NGSS as outlined in the course above. The concept map is limited only to DCIs, so even if students had a full appreciation of what is in these maps they also need practice in doing SEPs and identifying big picture relationships to other disciplines (CCCs).

Figure 8.74. Relationship of DCIs in Earth and Space Science, Including High School and Middle Grades Content

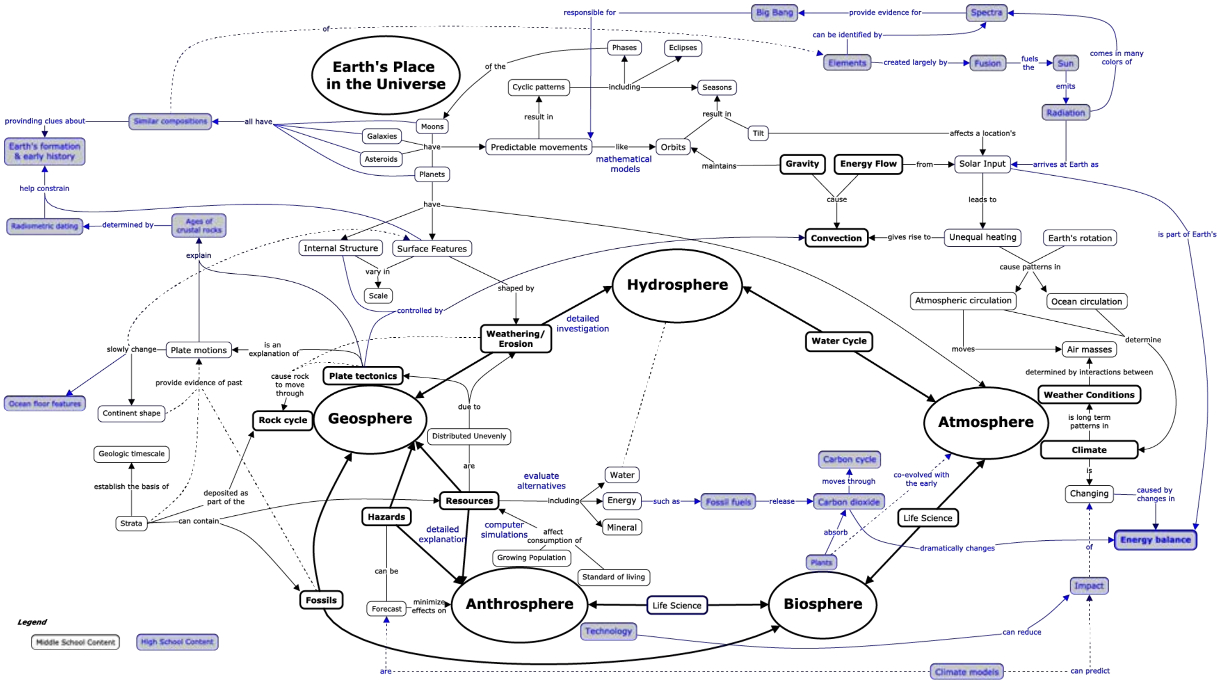


Diagram by M. d'Alessio

Long description of Figure 8.74.