IS7

Earth and Space Sciences Instructional Segment 7: Star Stuff

Once students have a firm grasp of what goes on here on Earth, the CA NGSS asks them to ponder how Earth fits into the broader universe. The previous instructional segments were ultimately focused on the practical ways in which Earth's **systems [CCC-4]** affect humanity today (always building towards ESS3.A, B, C, and D). However, science does not always need to be practical. The very first page of chapter 1 of the *NRC Framework* states, "Understanding science and the extraordinary insights it has produced can be meaningful and relevant on a personal level, opening new worlds to explore and offering lifelong opportunities for enriching people's lives" (National Research Council 2012, 7). This human dimension of science is codified in the science and engineering practices of the CA NGSS, which identify **asking questions [SEP-1]** and curiosity as a fundamental part of doing science. For this reason, IS7 and IS8 focus in on big picture questions about our origins and place in the universe (ESS1.A). To transition into these instructional segments, teachers might want to emphasize the different purpose of the science in the previous instructional segments from these final instructional segments.

EARTH AND SPACE SCIENCES INSTRUCTIONAL SEGMENT 7: STAR STUFF

Guiding Questions

- How do we know what are stars made out of?
- What fuels our Sun? Will it ever run out of that fuel?
- Do other stars work the same way as our Sun?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy in the form of radiation. [Clarification Statement: Emphasis is on the energy transfer mechanisms that allow energy from nuclear fusion in the sun's core to reach Earth. Examples of evidence for the model include observations of the masses and lifetimes of other stars, as well as the ways that the sun's radiation varies due to sudden solar flares ("space weather"), the 11-year sunspot cycle, and non-cyclic variations over centuries.] [*Assessment Boundary: Assessment does not include details of the atomic and sub-atomic processes involved with the sun's nuclear fusion.*]

HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. [Clarification Statement: Emphasis is on the way nucleosynthesis, and therefore the different elements created, varies as a function of the mass of a star and the stage of its lifetime.] [*Assessment Boundary: Details of the many different nucleosynthesis pathways for stars of differing masses are not assessed.*]

EARTH AND SPACE SCIENCES INSTRUCTIONAL SEGMENT 7: STAR STUFF

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.] (Repeated in IS8)

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-2] Developing and Using Models [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-8] Obtaining, Evaluating, and Communicating Information	ESS1.A: The Universe and Its Stars ESS1.C: The History of Planet Earth PS1.C: Nuclear Processes PS3.D: Energy in Chemical Processes and Everyday Life	[CCC-1] Patterns [CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, Proportion, and Quantity [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

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

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.11–12.1, 2, 7, 8, 9; WHST.9–12.1a–e, 2a–e, 7

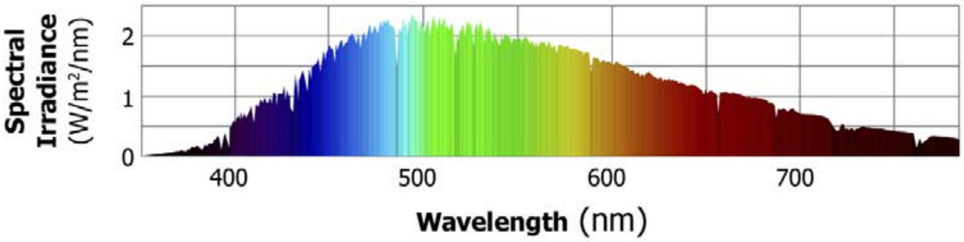
CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

The title of IS7 derives from a quote by Carl Sagan: “Some part of our being knows this is where we came from. We long to return. And we can. Because the cosmos is also within us. We're made of star-stuff.” This rather philosophical statement may resonate well with students, as distant objects in the universe are made familiar to them and they become able to understand that the universe can indeed be explored and studied.

The Colors of Stars

Looking carefully, students notice different stars have slightly different colors—those differences reveal a huge amount about what stars are and the way they work. When viewing the rainbow of light from our Sun through a prism, some colors appear brighter than others (figure 8.67). What causes these variations? Are they the result of errors in the equipment, something peculiar about our Sun, or a common feature of stars? Like all good science, this general observation with the naked eye can be refined with detailed measurement of specific **quantities [CCC-3]** such as the intensity of light at each wavelength (a color spectrum). Students can **obtain [SEP-8]** color spectra from many different stars using an online tool (such as the Sloan Digital Sky Survey/Sky Server, *What is Color* at https://www.cde.ca.gov/ci/sc/cf/ch8.asp#link87) and **compare them [SEP-4]**, noting several important **patterns [CCC-1]**. These patterns give clues about the **cause [CCC-2]** of different phenomena.

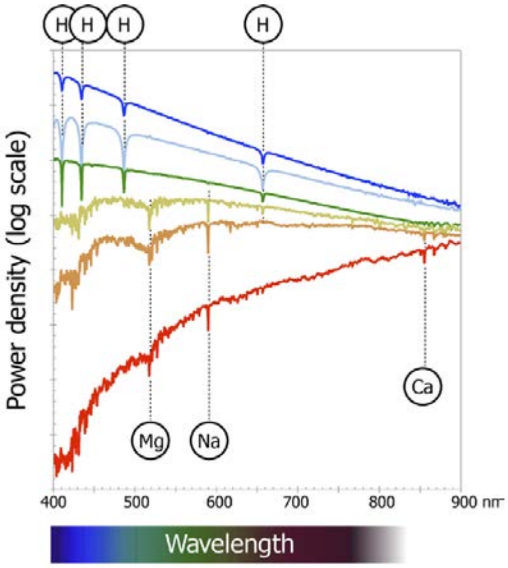
Figure 8.67. Color Spectrum of Our Sun



Color spectrum of our Sun. The rainbow image and the height of the graph depict the same information. The rainbow image is created by splitting the light from a telescope with a prism. The values of the graph are measurements of the relative intensity of each color. The graph dips lower where the rainbow image is dimmer. Graph by M. d’Alessio
Long description of Figure 8.67.

Students notice that many stars have bands of low intensity at exactly the same wavelength (fig. 8.68). Understanding this observation requires additional background in physical science. The *NRC Framework* lays out strong connections between the DCIs in this instructional segment and physical science: “The history of the universe, and of the **structures [CCC-6]** and objects within it, can be deciphered using observations of their present condition together with knowledge of physics and chemistry” (National Research Council 2012, 173).

Figure 8.68. Spectra of Six Different Stars

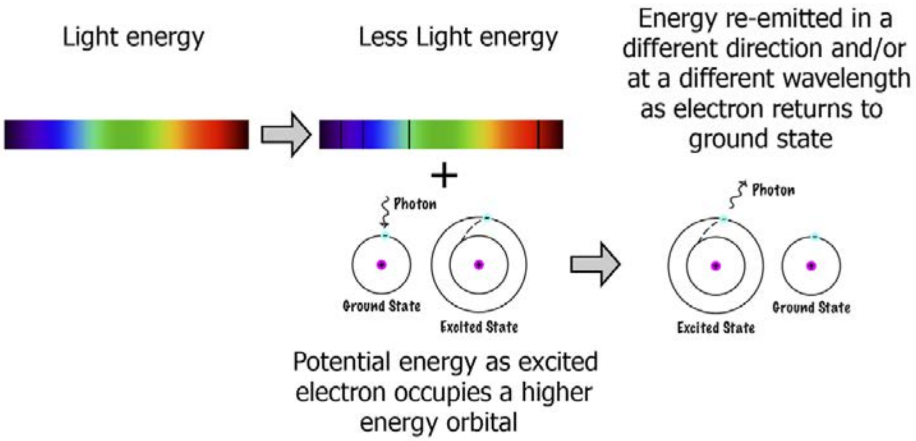


Circles indicate spectral lines from different elements on the periodic table. Graph by M. d’Alessio with data from Sloan Digital Sky Survey/SkyServer n.d.a
Long description of Figure 8.68.

The concept of absorption lines in spectra from stars unites the study of matter and the study of waves. Students must build upon their understanding of matter too small to see (5-PS1-1) by developing a model of the internal structure of atoms (HS-PS1-8). They must understand that atoms are made of nuclei of protons and neutrons and that the number of protons and neutrons helps determine the physical properties of the diverse materials that make up the universe, and that atoms have electrons that can move closer or farther away from the nucleus. If students take this ESS course before the physics or chemistry course, teachers must develop that model here since it is not included in the performance expectations for the middle grades. Understanding the **evidence [SEP-7]** about light spectra requires building on the idea that light is part of the broader electromagnetic spectrum (PS4.B: HS-PS4-1 in the high school physics course). The dark bands common in star spectra occur because atoms of different elements absorb specific colors of light. Students have studied **energy [CCC-5]** conversion as early as fourth grade and throughout the grade spans (PS3.B: 4-PS3-4, MS-PS3-3, 4, 5, HS-PS3-3), and now they must consider a very sophisticated example of individual atoms working as tiny energy conversion devices.

Atoms absorb some of the light energy (or other energy from the electromagnetic spectrum) that hits them, which pushes electrons to higher energy levels than their normal “ground state” and temporarily stores the energy as a potential energy. The atom quickly converts the energy back to light energy to return to its ground state, but that energy may be emitted in a completely different direction than the original energy or may be at a different wavelength. Each element on the periodic table has a unique configuration of electron orbitals, so different elements absorb light energy at very specific colors (wavelengths). Students can therefore use the absorption bands as fingerprints to identify the types and relative quantity of elements in a given star. Figure 8.68 shows that common star spectra include fingerprints of a number of elements, and more detailed analysis allows scientists to determine the full range of elements and even their relative abundance to construct the complete chemical composition of a star’s atmosphere. For students to be able to **explain [SEP-6]** this multi-step process, the class could act out the process using their bodies to represent different components of the **system [CCC-4]** in a physical **model [SEP-2**. Using the language of **systems [CCC-4]** helps focus student attention on the energy inputs (light), the internal workings of the system (electrons in different energy-level orbitals), and the energy outputs (light emitted in a different direction or at a different frequency than the energy input) (figure 8.69).

Figure 8.69. A Model of Absorption Lines



Absorption spectra occur because individual atoms can temporarily convert light energy into potential energy. Diagram by M. d’Alessio with images from Wereon 2006 and NASA 2010
Long description of Figure 8.69.

The absorption of specific wavelengths of electromagnetic waves occurs in stars, but also all around on Earth, including in greenhouse gases in Earth’s atmosphere. Materials like CO_2 and water vapor absorb infrared energy leaving the planet and re-emit it back toward

Earth so that energy that would otherwise have left the system is retained. This process is fundamental to Earth's **energy [CCC-5]** balance as discussed in the high school Chemistry in the Earth System course (HS-ESS2-4).

Evidence for Fusion

For ages, scientists have pondered what has caused the Sun to shine. In 1854 William Thomson (who later became so well known as a scientist that he was knighted and now is known as Lord Kelvin) published a paper calculating that the Sun would run out of fuel completely in just 8,000 years if it were made entirely of gunpowder, which was the most energy-dense self-contained fuel he could think of at the time (Kelvin 1854). Even in the 1850s, geologists had evidence that the Earth is considerably older than that, so controversy ensued over what causes the Sun to shine.

Lord Kelvin correctly determined that no chemical reaction would yield enough energy to power the Sun, but he incorrectly concluded that the Sun must be getting a constant replenishment of energy from meteors that collide with it. He died in 1907, more than a decade before scientists discovered a process that could release previously inconceivable amounts of energy, nuclear fusion (IS4). Under most conditions, when two atoms collide they bounce off one another because of the repulsive forces between their nuclei. If the atoms are moving fast enough, their nuclei may get close enough together so that when they collide, they fuse, releasing more than a million times more energy per unit of mass than any chemical reaction.

Students can repeat Lord Kelvin's **calculation [SEP-5]** about how long the Sun can last if it continues to emit energy at its current rate, but this time using information he did not have about the composition of the Sun from spectral lines (not gunpowder, but 75 percent hydrogen) and the energy release of hydrogen fusion (instead of chemical reactions). This approximate calculation of the **scale [CCC-3]** of energy release shows that the Sun's lifetime will be on the order of several billion years. Students can **support or refute the claim [SEP-7]** that this result is reasonable using evidence of the age of the Earth from IS4.

A Model of Fusion in Stars Over Their Lifecycle

For fusion to occur, atoms must reach a high enough temperature that they move quickly enough to fuse together, typically millions of degrees. Such temperatures do not occur naturally anywhere on Earth—they only happen in the interiors of stars where temperatures and pressures are so high due to gravity and the kinetic energy of in-falling matter. But even at the center of a star, conditions can **change [CCC-7]** that cause fusion to start and stop. As a result, we say that stars are born and die.

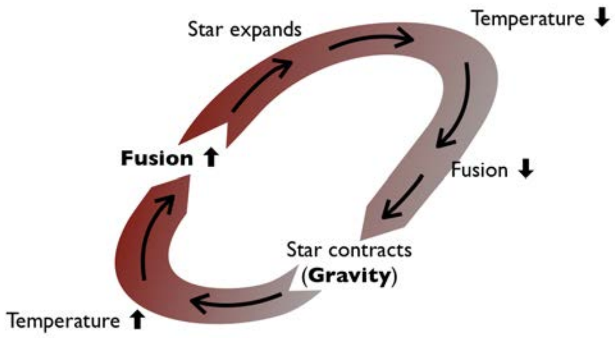
Stellar Birth and Activating Fusion

A star begins its life as a cold cloud of dust and gas. Gravity attracts the individual dust and gas particles and they fall towards one another, decreasing the gravitational potential **energy [CCC-5]** of the **system [CCC-4]**. Since energy must be conserved in the system, the particles gain kinetic energy (much like a ball falling downward speeds up as it gets lower). The temperature of an object is a measure of the average kinetic energy of its molecules, so we say that the star warms as it contracts. At some point, the particles may be moving fast enough that they undergo nuclear fusion when they collide. Within the same cloud of dust and gas, many objects can form simultaneously. Objects that accumulate enough mass to start fusion are called stars. Planets are made of the exact same material as stars and accumulate by the exact same gravitational processes, but their mass is not sufficient to begin fusion.

Mid-life as a Star: A Balance

Once fusion begins, the **energy [CCC-5]** it releases causes particles to push one another apart and the star begins to expand again. This is the opposite situation as the original star formation and involves an increase in gravitational potential energy that must be balanced by the particles slowing down (much like a ball thrown upward slows down as it gets higher). At slower speeds, fusion is less likely to occur and the star stops expanding. This counterbalancing feedback between the explosive force of fusion and the attraction due to gravity keeps stars **stable [CCC-7]** during most of their lifespan. This stable period of a star's life is referred to as the main sequence and it means that hydrogen is fusing in the star's core (figure 8.70). This stable period of a star's life is referred to as the main sequence and it means that hydrogen is fusing in the star's core.

Figure 8.70. Counterbalancing Feedback in Stars



The explosive force of fusion balances the attractive force of gravity keeping stars **stable [CCC-7]** during most of their lives. Diagram by M. d'Alessio

Long description of Figure 8.70.

Growing Older

Even the core of a young star is not typically hot enough to fuse anything except hydrogen. Larger stars burn it more quickly because they are hotter, and all stars eventually fuse all the hydrogen in their core to form helium. At that time, fusion stops, marking the end of the period called the main sequence. Without fusion pushing the star outward, the counterbalancing feedback shown in figure 8.70 becomes unbalanced, and then gravity acts alone to contract the star.

Contraction causes temperature increases in both the core and the surrounding envelope. If the star has enough mass, it may heat enough for helium atoms to begin fusing together. If that helium gets used up, the same processes will create, in sequence, large elements up to the size of iron. Only stars that start off their lives with a large enough mass are able to generate elements larger than helium during their lifetimes. Contraction of the star's envelope triggers hydrogen to begin fusing there. The outer envelope (surrounding gaseous material) is less dense, so gravity does not act as effectively to hold the star together and fusion in the envelope causes the star to expand to a massive size, which is why some stars are called *giants* and *supergiants*.

Our Sun is currently in its main sequence, so it has not yet become a giant and still only fuses hydrogen in its core. So how does it get all the more massive elements than helium that show up in its spectra? Where did they come from?

The End of Stars

Once hydrogen fusion stops in the Sun's core, hydrogen fusion in its envelope will cause it to grow to be a giant star. Eventually its envelope will expand, leaving behind a core made primarily of carbon and oxygen. That core will still be incredibly hot and it will continue to glow for a long time even without fusion. Some of the stars we see in the night sky are actually the hot, dying cores of stars that have finished fusion.

Larger stars continue fusing atoms until they end up with only iron in their cores and spontaneous fusion stops. The core is already very dense and gravity can cause the entire core to collapse within a few seconds. This rapid core collapse leads to such high temperatures and pressures that there is finally enough extra **energy [CCC-5]** to fuse elements larger than iron. Practically all of the atoms in the universe heavier than iron formed during the cataclysmic collapse of these large stars. The collapsing core rebounds in a dramatic explosion called a supernova, ejecting all of its material out into space where it can eventually coalesce into new stars. The carbon in our bodies came from carbon made in a star that exploded and was ejected into a region of space where our solar system was born. As Carl Sagan once said, "We are made of star stuff."

Students combine their model of fusion (HS-PS1-8) with the counterbalancing feedback in figure 8.70 to construct a **model [SEP-2]** of how fusion relates to a star's lifecycle (HS-ESS1-1). They apply this model to a product that communicates how material got from the random hydrogen atoms inside a young star to the complex range of elements inside their own bodies (HS-ESS1-3). They create a diagram, storyboard, movie, or other product that illustrates this step-by-step sequence. At each stage of their diagram, they should be able to answer the question, "What is the evidence that this particular stage happens?"

Earth and Space Science Snapshot 8.10: Asking Questions About Patterns in Stars

Investigative phenomenon: Bright stars can be located near or far from Earth, but they are typically hotter.

Students reviewed a table of a number of properties of the 100 nearest stars and the 100 brightest stars using a spreadsheet (figure 8.71). They constructed graphs of different properties looking for **patterns [CCC-1]** in the data. They found that many of the factors were uncorrelated. For example, they probably noticed that bright stars are located both near and far from Earth, but they should have seen a definite pattern between brightness and temperature—hotter stars are brighter and colder stars are dimmer. They may have begun with a linear **scale [CCC-3]**, but with such a large range in the brightness of stars (less than 1 percent as bright up to 100 times brighter than the Sun), they discovered the need to adjust to a logarithmic **scale [CCC-3]**.

Figure 8.71: How Does Star Brightness Depend on Temperature?

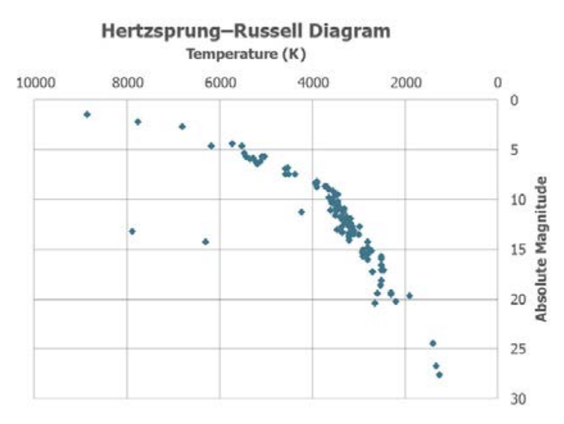


Diagram by M. d'Alessio

Long description of Figure 8.71.

Earth and Space Science Snapshot 8.10: Asking Questions About Patterns in Stars

Anaya: Not all the bright stars are hot, though. Are those outliers?
Cole: And not all the dim stars are cold.
Ms. M: Why do you think that is? Should we graph more data?
Jordan: Maybe those dim ones are farther away.
Diego: I don't think so. We graphed distance versus brightness and there wasn't any trend. But I'll look specifically at the data for those stars to make sure.
Jordan: Well maybe they're smaller then. If they're small, maybe they wouldn't be very bright even if they were hot.
Anaya: And maybe those cold ones would be bright if they were really big.

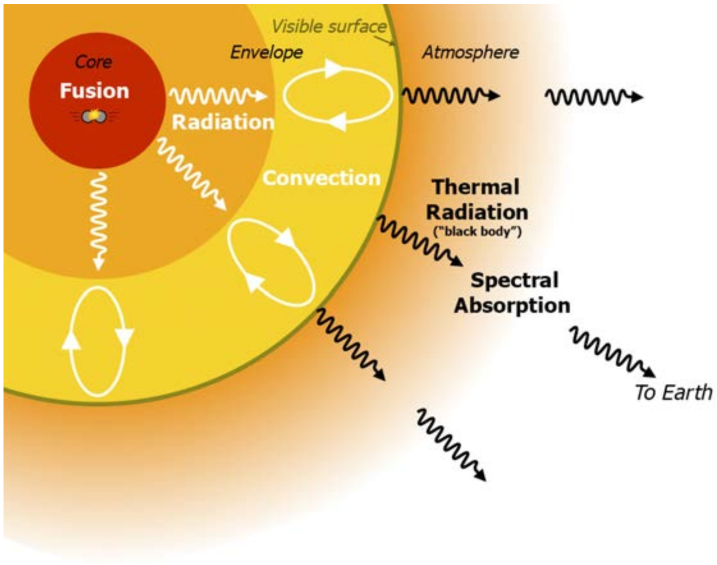
Students **asked questions [SEP-1]** that led them to further investigation. The example student dialog is idealized, but effective talk moves can help structure conversations so that students move towards this ideal (as outlined in the "Instructional Strategies" chapter of this framework).

This **pattern [CCC-1]** in the data was discovered by Ejnar Hertzsprung and Henry Russell around 1910 and is commonly referred to as a Hertzsprung-Russell (H-R) Diagram. It appears in several different forms including color (spectral type) instead of temperature. Like the coals in a fire, cooler stars are red and hotter stars are orange, yellow, or even blue. (Several online simulations are available to allow students to explore this relationship between temperature and color.) Students can add this relationship to their model of the Sun's **energy [CCC-5]** emissions (HS-ESS1-1) because it helps explain the overall broad range of colors emitted by the Sun in figure 7.62. It relates to the star's lifecycle because most of the stars plot along the central diagonal line in the H-R diagram, which is referred to as the *main sequence*. As each star moves through its life cycle and stops fusing elements in its core, it plots in a different section of the H-R diagram than it did during its main sequence.

Getting Energy to Earth

As early as grade five in the CA NGSS, students generated a model showing that most of the energy that we see on Earth originated in the Sun (5-PS3-1). Now students will expand their system **model [SEP-2]** to trace the **flow of energy [CCC-5]** back to fusion in the Sun's hot core (HS-ESS1-1). Students will need to use models of heat transfer within a system such as radiation and convection from physical science (HS-PS3-4). They develop a model of convection at Earth's surface in the middle grades (MS-ESS2-6) and in Earth's interior in the high school Chemistry in the Earth System course. Now they can apply that model to the interior of the Sun. Convection occurs in a large section of the Sun's outer envelope, moving heat from the interior out to the visible surface (figure 8.72). Students can directly observe evidence of this convection in high-resolution optical images of the Sun's surface that resemble a bubbling cauldron. This convection plays a role in the eruption of solar flares and other variations in solar intensity, which have been recorded for centuries (NASA 2003b). Some of these variations are periodic (the Sun's magnetic field flips about every 11 years, **causing changes [CCC-7]** in the amount of radiation of about 0.1 percent) while slightly larger variations are less well understood but can make a big difference in Earth's climate over much longer **timescales [CCC-3]** (from decades to millions of years). The existence of these variations is further evidence for convection, which constantly bubbles up new high-temperature material that emits more **energy [CCC-5]** than the cooler and denser material that sinks down. Even though no fusion occurs on the visible surface, it still shines via a process known as thermal radiation (or *black body* radiation). Most of this radiation travels directly towards earth, but a small fraction of it is absorbed, creating the absorption spectra of figure 8.69.

Figure 8.72. Energy Transfer from the Sun to Earth



Energy transfer by radiation and convection moves energy from the Sun's core to Earth. There are a number of steps along the way. Diagram by M. d'Alessio
Long description of Figure 8.72.

Opportunities for ELA/ELD Connections

Students select, read, and report out on biographies about or autobiographies/memoirs by famous or influential scientists known for their work about the stars, Sun, planets, or universe. (Note: The teacher may provide a list of names to select from to ensure certain concepts are highlighted.) The report should include the critical concept, knowledge, or discovery by the scientist; identify relevant or key symbols, key terms, or other words/phrases relevant to the topic; and incorporate a visual presentation. A checklist may help students keep track of all the features the teacher expects in the reports.

CA CCSS for ELA/Literacy Standards: RST.9–12.2, 4, 8; SL. 9–12.4, 5
CA ELD Standards: ELD.PI. 9–12.6, 10