Physics in the Universe: Unit 6

Stars and the Origins of the Universe

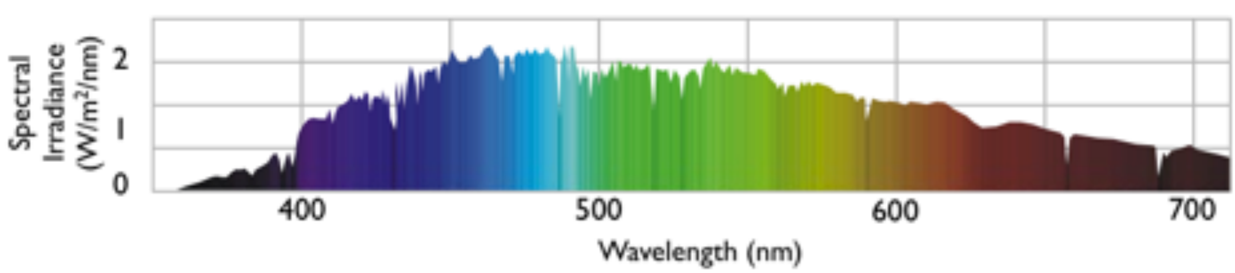
From the NGSS storyline:

> 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 in the behavior of our sun 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 2013)

Background for Teachers and Instructional Suggestions

The Colors of Stars

Students now apply their understanding of the electromagnetic spectrum to studying the light from stars. Teachers can start this instructional segment the same way humans have for millennia – looking up in the sky and wondering what is in the heavens. In a classroom, students can zoom in and out to explore the "maps" of the stars and galaxies in space (such as the Sloan Digital Sky Survey[1]) to engender interest in what is out there, and to get a basic sense that the Universe is a varied place, with dense and less dense regions of stars and gas distributed throughout it. Students discuss and share their favorite astronomical pictures and communicate to others about what they see.



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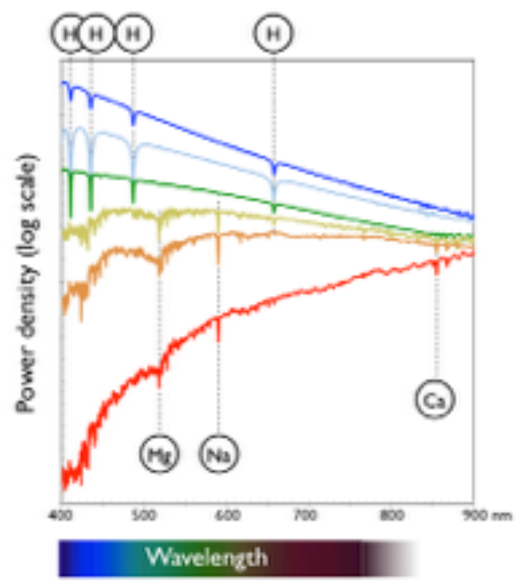
[1] Sloan Digital Sky Survey, SDSS DR12 Navigate Tool: http://skyserver.sdss.org/dr12/en/tools/chart/navi.aspx

Figure 11. 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. Image credit: (CC-BY-NC-SA) by M. d'Alessio.

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 11). 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*** such as the intensity of light at each wavelength. Students can collect color spectra from many different stars using an online tool[2] and compare them, noticing several important ***patterns***. These patterns give clues about the *cause* of different phenomena.



[2] Sloan Digital Sky Survey, What is Color: http://skyserver.sdss.org/dr1/en/proj/basic/color/whatiscolor.asp

Figure 12. Comparison between the color spectra of six different. Image credit: (CC-BY-NC-SA) by M. d'Alessio with data from Sloan Digital Sky Survey 2015b

Students notice that many stars have bands of low intensity at the exact same wavelength (Figure 12). 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*** and objects within it, can be deciphered using observations of their present condition together with knowledge of physics and chemistry. (NRC Framework, p. 173) 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 that is too small to see (*5-PS1-1*) by looking at the specific make-up of atoms (*HS-PS1-8*). They must understand that atoms are made of nuclei of protons and neutrons that the number of protons helps determine the physical properties of the diverse materials that make up the Universe, and that atoms have electrons that can move closer or further away from the nucleus. Understanding the evidence about light spectra requires building on the idea that light is part of the broader electromagnetic spectrum (PS4.B: *HS-PS4-1*). The dark bands common in star spectra occur because atoms of different elements absorb specific colors of light (Figure 13). Students have studied energy conversion as early as grade four 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 that hits them (or other energy from the electromagnetic spectrum), which pushes electrons to higher energy levels than their normal "ground state," temporarily storing the energy as a potential energy (Figure 13). 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 unique 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 12 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.

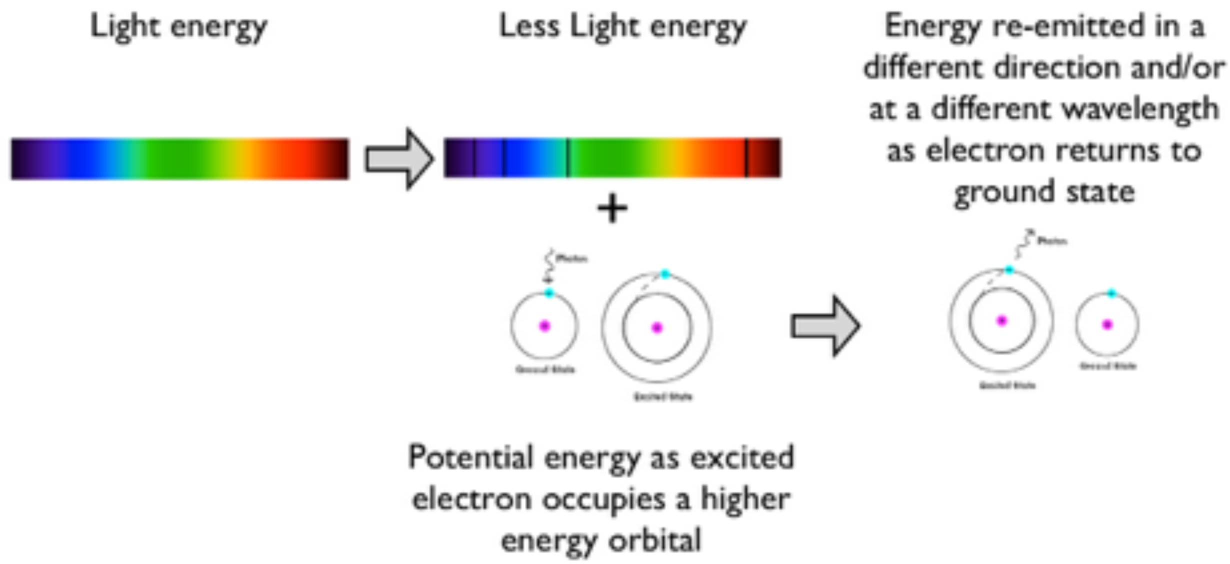


Figure 13. Absorption spectra work because individual atoms can temporarily convert light energy into potential energy. Image credit: (CC-BY-NC-SA) by M. d'Alessio with public domain images from Wikipedia and NASA.

The absorption of specific wavelengths of electromagnetic waves occurs in stars, but also all around on Earth, including greenhouse gases in Earth's atmosphere. Elements like CO_2 and water vapor absorb infrared energy heading away from the planet and re-emit it back towards Earth so that energy that would have otherwise have left the system is retained. This process is fundamental to Earth's energy balance as discussed in instructional segment 2 (*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 (the most energy-dense self-contained fuel he could think of at the time) (Kelvin 1854). Even at the time, geologists had evidence that the Earth needed to be 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 fuel that could release previously inconceivable amounts of energy, nuclear fusion (instructional segment 4). 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, collisions can bring their nuclei enough together that 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 about how long the Sun can last if it continues to emit energy at its current rate, but this time using information he didn't have about the composition of the Sun from spectral lines (not gunpowder, but 75% hydrogen) and the energy release of hydrogen fusion (instead of chemical reactions). This approximate calculation of the ***scale*** of energy release shows that the Sun's lifetime will be on the order of several billion years, which is consistent with what we know from radiometric dating about the age of our Solar System.

A Model of Fusion in Stars Over Their Lifecycle

The key to fusion is getting atoms up to a high enough temperature that they move fast 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*** 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*** of the ***system***. 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 up 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*** 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 balancing feedback between the explosive force of fusion and the attraction due to gravity keeps stars stable 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.

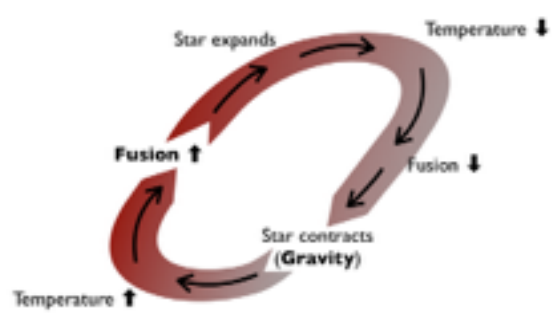


Figure 14. Negative ("Balancing") feedbacks in stars. The explosive force of fusion balances the attractive force of gravity keeping stars stable during most of their lives. Image credit: (CC-BY-NC-SA) by M. d'Alessio

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 a higher temperature, and all stars eventually fuse all the hydrogen in their core into helium, so fusion stops (marking the end of the period called the main sequence). Without fusion pushing the star outward, the balancing feedback shown in Figure 14 becomes unbalanced, and then gravity acts alone to contract 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 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 been 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

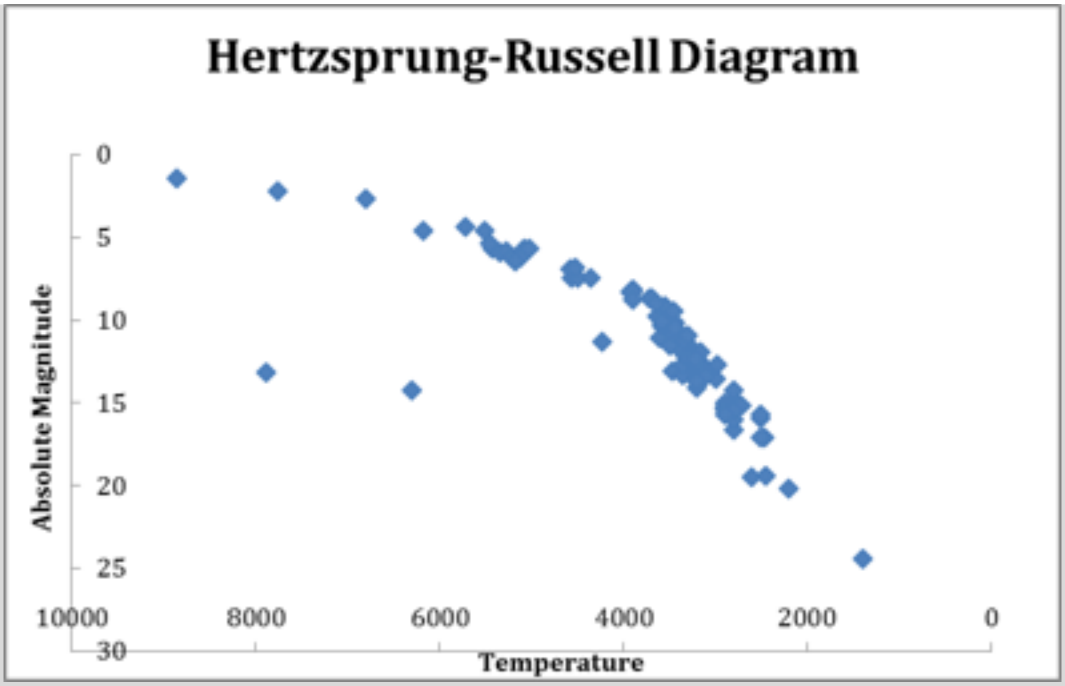
Once hydrogen fusion stops in the Sun's core, hydrogen fusion in its envelope will cause it to grow to be a giant star. Eventually its envelope will expand away and leave behind a core made primarily of carbon and oxygen. That core will still be incredibly hot and it will continue to glow for a long 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 entirely with 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*** to fuse elements larger than iron. Practically all of the atoms in the Universe larger 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 has said, “We are made of star stuff.”

Students combine their model of fusion (*HS-PS1-8*) with the balancing feedbacks in Figure 14 to construct a **model** 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?”

Snapshot: Asking Questions About Patterns in Stars

Students review a table of a number of properties of the 100 nearest stars and the 100 brightest stars using a spreadsheet. They construct graphs of different properties looking for ***patterns*** in this data. They find that many of the factors, are uncorrelated (“It looks like bright stars can be located both near and far from us.”), but they should see a definite pattern between brightness and temperature—hotter stars are brighter and colder stars are dimmer. They may begin with a linear ***scale***, but with such a large range in the brightness of stars (less than 1% as bright up to 100 times brighter than the Sun), they discover will need to adjust to a logarithmic ***scale***.



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 **ask questions** that lead 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 for CA NGSS Teaching and Learning in the 21st Century chapter)).

This ***pattern*** 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 or "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*** emissions (*HS-ESS1-1*) because it helps explain the overall broad range of colors emitted by the Sun in Figure 11. It relates to the star's lifecycle because most of the stars fall along the central diagonal line in the H-R diagram, which is referred to as the main sequence. As they move through their life cycle and stop fusing elements in their core, stars plot in different sections of the H-R diagram than they did during their main sequence.

Getting Energy to Earth

As early as grade five in the *CA NGSS*, students generate a **model** showing that most of the ***energy*** that we see on Earth originated in the Sun (*5-PS3-1*). In instructional segment 2, students expand that model to a complete energy balance within the Earth ***system***. Now students will expand their system model to trace the flow of energy back to fusion in the Sun's hot core (*HS-ESS1-1*). Students will draw on their understanding of physical science where they conduct experiments to observe a number of processes that transfer thermal energy from hot components to cold components of a system (*HS-PS3-4*) such as radiation and convection. They developed a model of convection at Earth's surface at the middle grade level (*MS-ESS2-6*) and in Earth's interior in instructional segment 3, now they can apply it to the interior of the Sun. Convection occurs in a large section of the outer envelope, moving heat from the interior out to the visible surface (Figure 15). Evidence for this convection can be seen in high resolution optical images of the sun's surface that look like 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 2003). Some of these variations are periodic (the Sun's magnetic field flips about every 11 years, ***causing changes*** in the amount of radiation of about 0.1%) while slightly larger variations are less well understand but can make a big difference in Earth's climate over much longer ***timescales*** (from decades to millions of years). The existence of these variations is evidence for convection, which constantly bubbles up new high temperature material that emits more ***energy*** than the material 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 13.

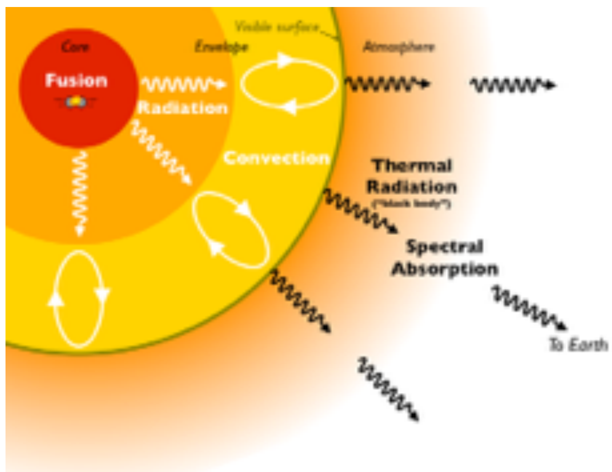


Figure 15. Energy transfer by radiation and convection moves energy from the Sun's core to Earth. There are a number of steps along the way. Image credit: (CC-BY-NC-SA) by M. d’Alessio

Origins of the Universe

Students will apply their skill at **analyzing** spectra to stars beyond the Sun. They are given examples of stellar spectra and asked to match the multiple absorption lines to a set of correctly spaced and identified lines determined in a laboratory. They find that they must shift the star spectrum as a whole to higher or lower frequency in order to match the lines from the laboratory. Understanding the significance of this observation requires understanding of the Doppler Effect, a topic that builds on physical science DCIs related to waves but is not required to meet other *CA NGSS* PEs. When stars move towards 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 towards 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 be less Doppler shifted 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 shifted towards longer wavelengths, revealing that they are all moving away from us. Since longer wavelengths are closer to the red end of the visible spectrum, this effect is referred to as a 'redshift.'

Students are now ready to read or watch a historical account of Edwin Hubble's surprising discovery that the Universe is expanding (Sloan Digital Sky Survey 2015a). Hubble noticed a ***pattern*** in the redshifts: the farther away a galaxy is from Earth, the faster it moves away from us. In fact, some very distant galaxies appear from their redshift to be receding from us at greater than the speed of light, which is impossible (if they were moving that fast, their light would never reach us and we would not be able to see them). He made a model that could explain this pattern in which stars are not really moving in space, but rather the space between the stars is getting bigger (much like raisins expanding in a lump of dough). This model replaces the Doppler shift with a different explanations where the wavelengths got stretched by the stretching of space itself! Students can perform their own **investigation** of redshifts using simulated telescope data from online laboratory exercises[3]. That investigation requires an understanding of how distances are measured in the Universe, which builds on the **argument** students constructed in 5th 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** about one of the methods for determining distance in the Universe and then combine their findings with other students to develop a report, a poster, or a presentation that describes the **scale** of the universe and how it is measured.

Students now have **evidence** that the Universe is expanding, which invites them to **ask questions** 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

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[3] Two older examples include Project CLEA: http://www3.gettysburg.edu/~marschal/clea/hublab.html or University of Washington Astronomy Department: http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/hubbletitle.html. More modern resources could be developed.

inevitable answer is that everything that we can see as far as we can look out into the Universe was all once contained in a tiny region smaller than the size of an atomic nucleus! This region was so hot and dense at this time that it effectively exploded in what we call the Big Bang. We can see evidence of this explosion in the ***matter and energy*** that exists in the Universe today. Calculations by scientists reveal that the massive explosion would produce elements in specific proportions, and we can look for that fingerprint by using spectral lines to determine the relative abundance of different elements in stars like our Sun (graph in the middle in Figure 16). While Sun's relatively small proportion of heavier elements were 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. A hot, dense early Universe would also have emitted radiation, which should still be traveling towards us. In 1963, a group of scientists detected a constant stream of microwave radiation coming in every direction. They were worried it was something wrong with their equipment, but it became apparent that the signal they were detecting was also consistent with **models** of emissions of the hot early Universe. We now call that ***energy*** the Cosmic Microwave Background Radiation and can use it to get a picture of what the Universe looked like shortly after the initial Big Bang (image on the right in Figure 16).

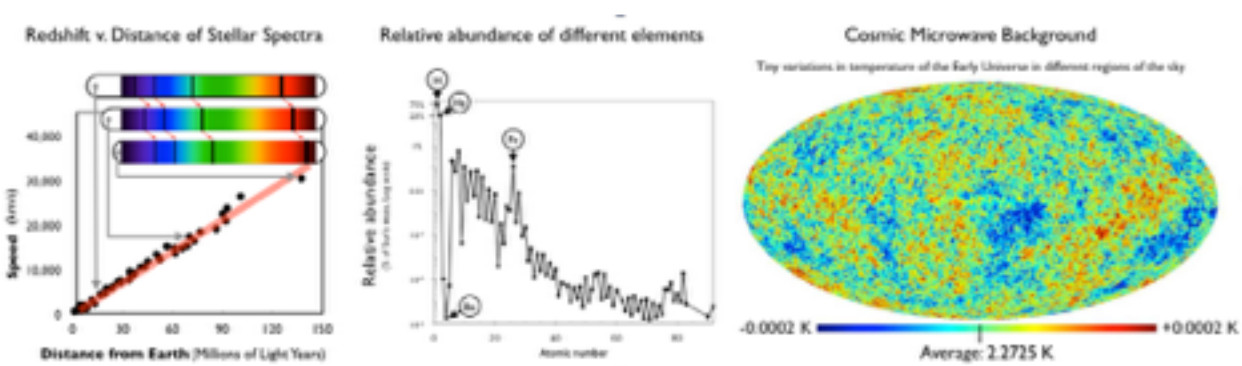

Figure 16. Evidence of the Big Bang comes from the redshift versus distance of stellar spectra (left), the relative abundance of elements in the Sun determined from absorption spectra (middle) and the Cosmic Microwave Background Radiation that reveals minute differences in temperature in the early Universe (right). Image credit: LEFT (CC-BY-NC-

SA by M. d'Alessio with data from Jha, Riess, and Kirshner 2007; MIDDLE (CC-BY-NC-SA) by M. d'Alessio with data from Lodders (2003); RIGHT NASA 2008