14.4: The First Stars

Learning Objectives

- You will know the evidence that the first stars and galaxies formed when the Universe was ~400 Myr old.
- You will know the evidence that the first stars contained no heavy elements, making them different from later generations of stars
- You will understand the physical conditions under which the first stars formed

What Do You Think: When Did the First Objects Form?

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Thus far we have discussed the formation of the largest-scale structures, clusters, and galaxies, but what do we know about the first stars? What were they like? What was their relationship to the larger structures, and what were conditions like in the Universe at that time?

14.4.1: Evidence for When the First Stars Formed

Stellar evolution is the processes involved with the formation, the lifetimes, and the deaths of stars. From the study of stellar evolution we know that stars form from clouds of gas that contract due to gravity and then heat up until nuclear fusion begins. During their lifetimes, stars fuse heavier and heavier atomic nuclei. These nuclei are then dispersed into the surrounding interstellar medium when a tar either explodes as a supernova or sheds its outer layers as a planetary nebula or red giant star. Through these processes, successive generations of stars are made with an increasingly higher abundance of heavy nuclei. Because none of this had happened until stars formed, we expect the first generation of stars to contain only hydrogen, helium, and trace amounts of lithium. These elements were produced in the first minutes after Big Bang itself. All heavier nuclei were fused in the cores of stars and were thus not available to form any part of the first generation of stars.

No direct detection of stars free of heavy elements has been made. Not yet. Astronomers hope to detect them with the upcoming James Webb Space Telescope. Though we have not been able to detect the first stars directly, there is much indirect evidence that tells us about their properties and how they formed. We can see the effects they must have had, much like the fabled three bears discovering that the child Goldilocks had visited their home.

Because the first stars were made entirely of light elements and devoid of heavy elements, they were distinct in their properties compared with later generations of stars. Though they fused hydrogen into helium like massive stars today, the first stars could not use heavy elements as catalysts in the process, so they had to be hotter. As a result, they emitted higher energy radiation (for a given stellar mass) than stars do today. This radiation from the first stars influenced the surrounding inter-galactic medium, causing the Universe to become ionized (separating electrons from the nuclei of their atoms). Finding this ionization signature will tell us when the first stars must have formed.

Constraints on when the first stars formed come from different lines of evidence. Observations from the WMAP satellite, which are sensitive to a small percentage of the Universe being ionized, have shown that the first stars must have turned on around a redshift of $z \sim 10$. This corresponds to a time when the Universe was about 400 million years old. Observations of systems of hydrogen gas clouds in the SDSS are a sensitive probe of the time when there was only a small percentage of neutral hydrogen remaining, after most of the gas had been ionized. This occurs around a redshift of $z \sim 6$, when the Universe was about 1 billion years old.

The first stars, then, were major players on the cosmological scene between 400 million and 1 billion years into the history of the Universe—such small objects influenced conditions in the Universe from the smallest to the largest scales! The ionization at this time was called reionization because this was the second time the Universe was ionized; the first was from its birth through the first 380,000 years (when the cosmic microwave background formed). Though the first stars may not resemble today's stars exactly, the data show that reionization was indeed caused by stars or star-like objects and could not have been caused by other energy sources such as quasars.

14.4.2: Models of Formation of the First Stars

What does it take to form a star from a cloud of gas? It may not seem obvious, but gas will not condense into a star unless it starts out cold, on the order of 200–300 K (about 0 °F). To understand why that is, we will examine the competing forces involved.

Primordial clouds of hydrogen sit embedded in large, roughly spherical halos of dark matter. Due to gravitational interactions alone, the gas particles must collapse toward the center of the halo. Just as your hands heat up when you rub them together, a gas will heat up as atoms get closer together and start interacting and colliding more frequently. This heat leads to an outward thermal pressure, which competes directly with the inward gravitational force (Figure 14.24). When the effect of pressure gets high enough, collapse halts. To learn more about the mass required to form a star, see **Going Further 14.2: Jeans Mass**.

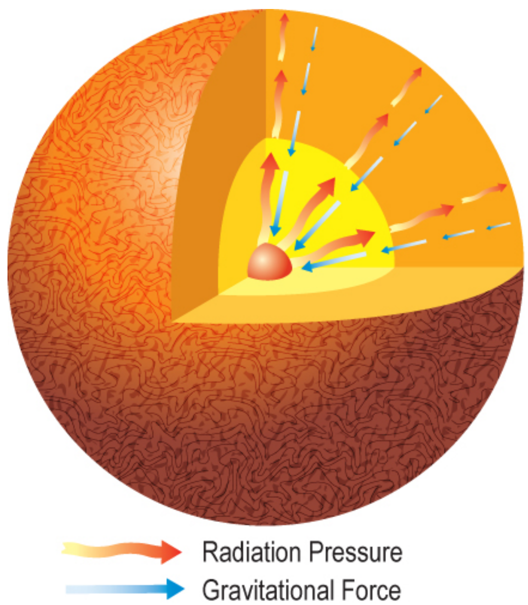

Figure 14.24: As a cloud of gas condenses it gradually heats up. When matter becomes warm, it radiates energy. This outward radiation force opposes the collapse of gravity if it is too strong. Credit: NASA/SSU/Aurore Simonnet

The only way to get rid of excess pressure is for the gas to cool. A single atom of hydrogen is limited in the amount of energy it can shed—the maximum is 13.6 eV (which will ionize the atom, completely removing the electron from the nucleus). Heavier elements can emit energy through many different electron ionizations and state changes, and molecules can also lose energy through vibrations and rotations. Since the first stars were composed of only hydrogen and helium and no heavy elements, the avenues for cooling were limited. The Sun formed from gas composed of much heavier elements, so it cooled more efficiently than the first generation of stars did. To learn more about cooling, see **Going Further 14.3: Cooling Gas**.

Once the gas is dense enough to ignite hydrogen fusion, a star is born. Computer simulations have shown that the first stars could form only from very large gas clouds. If a gas cloud is large enough, the gravitational attraction will win out over the pressure, even with inefficient cooling, and the star will collapse. Because the Sun was able to cool more efficiently, it was able to form from a much smaller cloud. In trying to determine the masses of these early stars, some researchers have hypothesized that these stars formed exclusively in the range of 100 solar masses or greater. Their argument is based upon the previously discussed cooling problem.

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An important property of stars with no heavy elements is that they have higher surface temperatures than stars with compositions like that of the Sun. The production of nuclear energy at the center of a star is less efficient without heavy elements, and the star would have to be hotter and more compact to produce enough energy to counteract gravity. This would explain why we see no stars free of heavy elements today—because they would have died long ago (massive stars have short lifetimes). The problem with this theory of only massive first stars is that simulations show that these hypothesized stars and associated supernovae do not actually lead to the observational properties of the Universe that were used as evidence to support their existence in the first place. Determining the masses of the first stars is therefore a subject of ongoing study and great research interest.

▼ **GOING FURTHER 14.2:** JEANS' MASS

▼

GOING FURTHER 14.3: COOLING GAS

14.4.3: The Relationship Between the First Stars and the First Galaxies

At the time when the first stars formed, galaxies were also starting to form. From computer simulations we know that galaxies were much less massive in the past, probably only about a million solar masses at the time of the first stars (compare this to the Milky Way which is about a trillion solar masses today). One outstanding question is whether these early galaxies could have sustained the first stars. Galaxy formation and star formation are inter-related because stars are dependent on galaxies; the stars from from the gas collected in the galaxies. Furthermore, supernovae can trigger star formation by compressing gas, or halt it by blowing the gas away. Some calculations show that massive galaxies are necessary to sustain star formation. For example, galaxies should have a mass of at least 100 million solar masses to sustain star formation. But galaxies of such large mass would have formed only later. The relationship between the first stars and the first galaxies is therefore also a subject of ongoing study.

To further probe the growth of structure during the reionization era, a number of research groups have used radio arrays to investigate the ratio of neutral to ionized hydrogen present in the early Universe. Neutral hydrogen emits a faint glow at a wavelength of 21 cm, corresponding to a frequency of 1420 MHz, in the radio band. This radiation is used to map out hydrogen clouds in our Galaxy and other galaxies locally, but it can also be used to probe the general presence of neutral hydrogen in the Universe when it was only 400 million to 1 billion years old.

As the Universe becomes more and more ionized due to ultraviolet light from the first stars, the glow from the neutral hydrogen becomes fainter because there is less neutral hydrogen and more ionized hydrogen. By this technique, it is possible to determine the amount of neutral hydrogen at different eras; recall that the emission is redshifted to different frequencies due to the expansion of the Universe. So, for example, emission coming from neutral hydrogen when the Universe is 400 million years old will have a longer wavelength and lower frequency, compared to emission coming from a time of 1 billion years. Each frequency "channel," then, gives a snapshot of how ionized the Universe was at each era.

These radio measurements have a problem equivalent to that of needing a dark sky in optical light. Because of the redshift of the radio waves, the radio arrays actually observe at lower frequencies than the rest frequency of 1420 MHz; they must observe at frequencies between 50 and 200 MHz. This band contains channels 2–13 on broadcast television! In order to escape interference from TV broadcasts, the measurements are being done from the most remote parts of the globe, including areas of China and Australia. They cannot be done from the United States at all.

The redshift range of $z \sim 6$–10, which corresponds to times when the Universe was between 400 million and 1 billion years old, is now the critical epoch for theorists and observers for the next decade. It represents a time in the history of the Universe that we are just on the verge of being able to directly observe. What we can say right now is that star-like objects were present and becoming important in the Universe at $z \sim 10$ or so, and that these first stars likely died by $z \sim 6$. There are plenty of exciting theories, computer simulations, and tantalizing data so far, but much more is unknown. However the arrival of much more relevant data is imminent, so stay tuned for the next 10–20 years!

Formation of Structure Timeline

In this activity you will use an interactive timeline to answer questions about when various structures formed. The timeline is divided into three time periods: the Early Universe, the Matter Dominated Universe, and the Modern Universe. The period when matter dominated the Universe is when much of the structure formation that we have discussed in this chapter occurred. To learn more about an event , first click the "Matter Dominated Universe" tab, then click the tab for the event.

Play Activity

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