First Stars and First Light: The Epoch of Reionization

<u>Overview</u>: The “Epoch of Reionization” is a period in the history of the universe that likely arose as a result of the arrival of the first stars and galaxies. Prior to this, the universe was dark, suffused with a dense, obscuring fog of primordial gas. As the first stars switched on, their ultraviolet energy began to reionize the cosmos, punching ever-larger holes in their murky surroundings. Eventually, the effect of these young, massive stars and their infant galaxies enabled light to shine freely through space.

<u>Background</u>: For its first 370,000 years, the universe was filled with a hot, dense fog of ionized gas. As the universe cooled and expanded, electrons and protons were able to combine to form the first neutral atoms.

When this happened, thermal energy from the Big Bang was able to travel freely throughout the universe. This high-energy radiation has, over cosmic time, cooled and been red-shifted by a factor of more than 1,000 due to the expansion of the universe. We see the remnants of this today as the cosmic microwave background (CMB).

Studies of the CMB, beginning in the early 1990s, revealed that the very early universe, though generally smooth, contained tiny density fluctuations (on the order of one part in 100,000) that rippled through space. More fine-grained studies by instruments, such as WMAP, helped better-establish the composition of the universe and fixed its age at 13.7 billion years.

After the CMB became imprinted on the universe, the cosmos became opaque at shorter wavelengths due to the absorbing effects of atomic hydrogen. This began a long period known as the Dark Ages, so-called because of the absence of stars and the extremely dense intervening neutral hydrogen gas.

Over time, areas of higher-gas density began to collapse under gravity, and the neutral matter in the universe began to clump together. Eventually, these regions cooled and collapsed, igniting nuclear fusion in their cores and leading to the first stars and galaxies.

As the first stars emerged, their energy heated the surrounding medium, once again ionizing the hydrogen in the universe. At first, these areas were like small bubbles of ionized gas surrounding bright energy sources. As these bubbles grew and punched ever-larger holes into the neutral universe, they eventually began to overlap, enabling ionizing radiation to travel farther and farther through space.

The first stars also significantly altered the chemical makeup of the cosmos. Through nucleosynthesis in the cores of these short-lived stars—which may have been as much as 1,000 times more massive than the sun—and as a result of powerful supernovae, a fraction of the universe’s initial constituents of hydrogen and helium were converted into carbon, oxygen, iron and other heavier elements.

Once the majority of the universe was reionized, approximately one billion years after the Big Bang, light across much of the electromagnetic spectrum could travel unimpeded through the cosmos, eventually revealing the universe as we see it today.

Peering into the Reionization era has been both a challenge and a quest for astronomers, with today’s best telescopes giving tantalizing clues as to the nature of these early stars and the assembly of the very first galaxies.

Studies of the distant and ancient universe with the next-generation of ground-based observatories will be able to probe further into the epoch of reionization. Leading questions for these future optical, infrared and radio observatories include:

<u>What is the role of galaxies in reionizing the universe?</u> To understand the role of early galaxies in reionization, astronomers first need a more accurate census of these galaxies as far back in time as possible. This will require exquisitely sensitive and fine-grained, near-infrared studies, which will be possible with future large, ground-based observatories equipped with adaptive optics.

What is the processes that drove galaxy formation? The majority of galaxies in the early universe are expected to be relatively small, making studying their shape and movement extremely difficult. With higher-resolution images and Doppler studies of their internal velocities, astronomers will be able to better understand how these galaxies emerged from the primordial gas, and how they evolved into the large galaxies we see in the universe today.

What is the process of early star formation? The process of star formation is difficult to unravel, even in nearby star-forming regions today. Current conditions that effect star formation include the cooling of superheated gas, feedback from supernovae, and even the effects of supermassive black holes that are believed to reside at the center of most galaxies today. In the very early universe, these complex conditions become even more muddled. These early galaxies would have contained massive stars formed from primordial gas (referred to as Population III stars). They would be unlike any stars in the universe today and would likely have formed and evolved under radically different conditions.