How did the first stars form in space?

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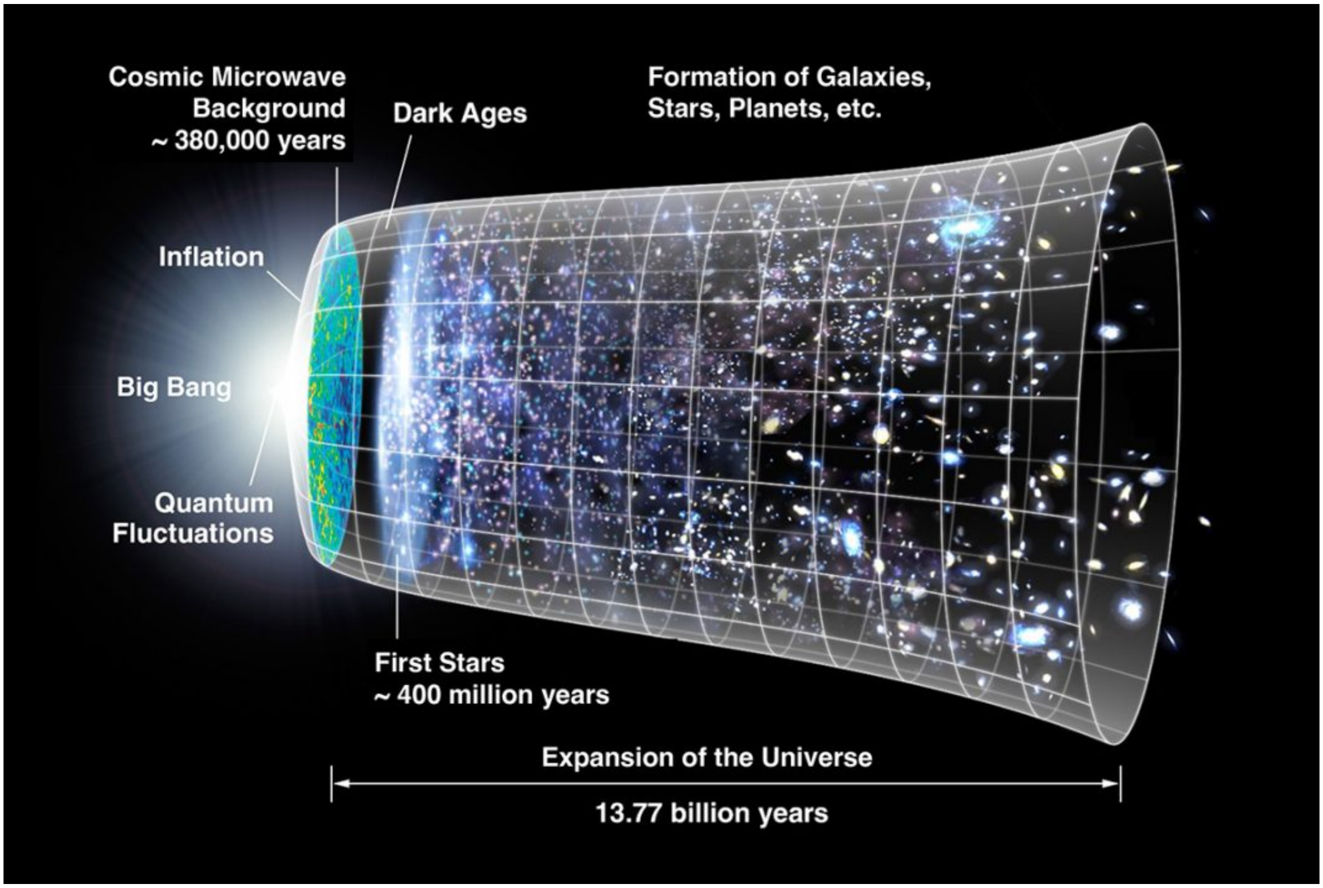

Figure 1: Sketch of the evolution of the Universe over the last 13.77 billion years. It started with the Big Bang, followed by an extremely short period of rapid exponential expansion. The furthest we can see is the cosmic microwave background, when radiation decoupled from matter, approximately 380,000 years after the Big Bang. This is followed by the 'dark ages,' during which this radiation redshifted from the visible regime into infrared and sub-mm wavelengths. The occurrence of the first stars, about 400 million years after the Big Bang, ended this phase, spearheading the formation of galaxies as we see them today. [Credit: NASA/WMAP Science Team, public domain]

Ralf Klessen, professor of theoretical astrophysics at Heidelberg University, investigates the physical processes that governed the formation of the first generation of stars in the early Universe

Understanding the physical processes that govern high-redshift star formation was the central research theme of the ERC Advanced Grant STARLIGHT, funded in the 7th Framework Program and led by Professor Ralf Klessen at the Center for Astronomy at Heidelberg University, with key results being summarized in a recent article in Annual

[Reviews of Astronomy and Astrophysics.] It also relates to the research activities in the ERC Synergy Grant ECOGAL, funded by Horizon 2020, and jointly led by Patrick Hennebelle, Ralf Klessen, Sergio Molinari, and Leonardo Testi.

Cosmic evolution

Through studying the cosmic microwave background, we know that the start of the Universe was pretty simple. It was, by and large, homogeneous and isotropic, with small fluctuations that can be described by linear perturbation analysis. This contrasts greatly with the highly structured and complex Universe we know today. Cosmic evolution is thus a progression from simplicity to ever-increasing complexity. A few hundred million years after the Big Bang, the appearance of the first stars marked a primary milestone in this transition, as sketched in Figure 1. Their light ended the so-called 'dark ages,' during which no visible light existed in the cosmos. They played a key role in the metal enrichment and reionization of the Universe, thereby shaping the galaxies we see today.

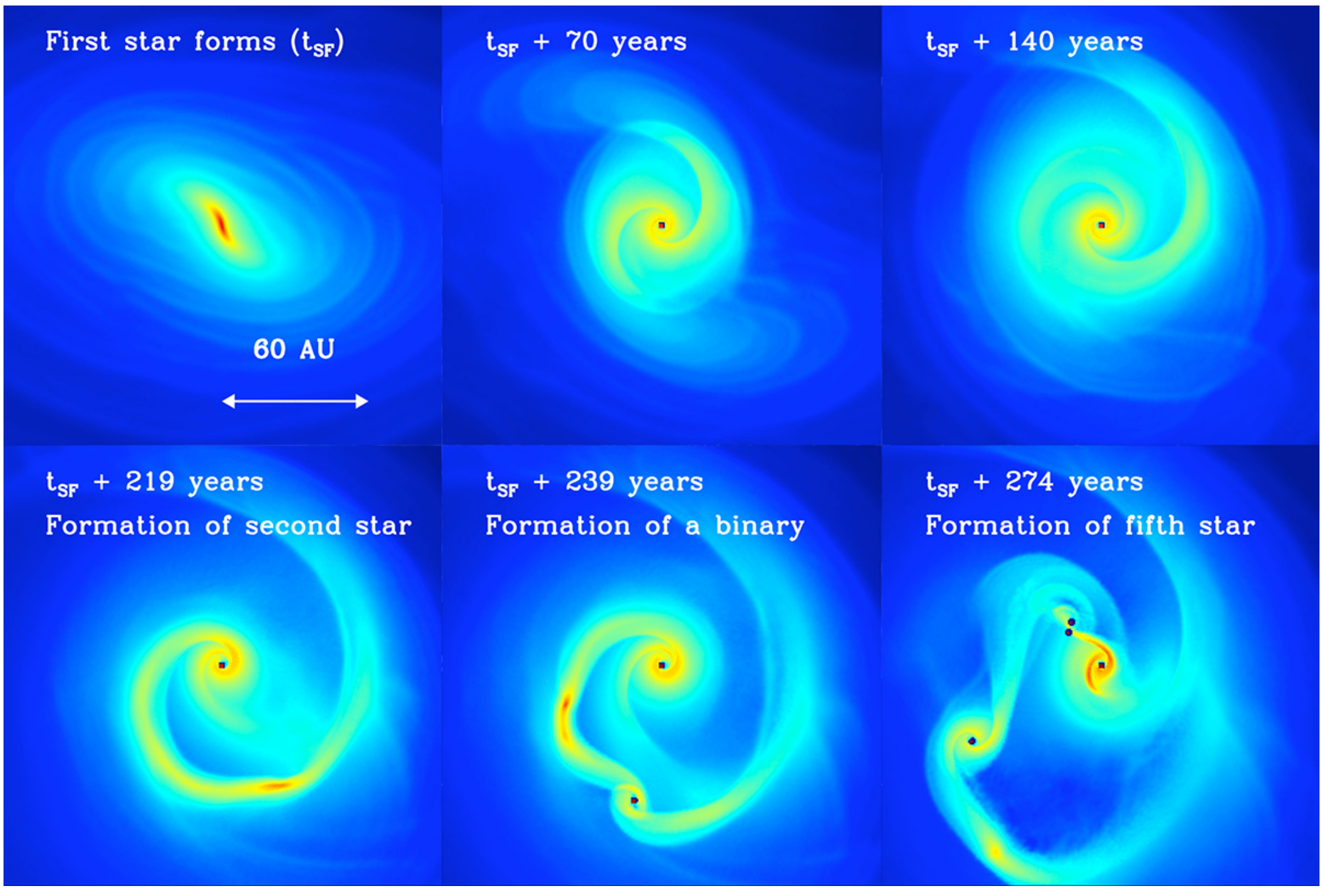

Figure 2: Fragmentation of the accretion disk surrounding a nascent Population III star. The disk becomes gravitationally unstable and develops spiral arms with increasing density. These arms interact non-linearly, leading to the formation of companion stars within a few hundred years, thus rapidly creating a small stellar cluster. [Adopted from Clark et al. (2011) with permission from the authors.]

Star formation in the early Universe

The first generation of stars, the so-called Population III stars, formed from truly primordial gas consisting predominantly of hydrogen and helium due to Big Bang nucleosynthesis. In contrast, second-generation stars, sometimes termed early Population II stars, formed from material enriched with heavy elements. These elements were produced by nuclear reactions in the interiors of the first stars and dispersed across large distances when they died in highly energetic supernova explosions. The field of stellar archaeology seeks to learn more about these processes by compiling observational databases of stars with extremely low metallicities, with the goal of characterizing the physical origins of the very first and second generations of stars.

Paradigm shift

Studying stellar birth in the primordial Universe is still a relatively nascent area of astrophysical science. Only with the advent of new numerical methods and powerful supercomputers did the numerical modeling of early star formation become feasible.

Consequently, there is still little consensus on the physical processes that govern the formation of the first stars in our Universe. Truly primordial Population III stars were originally thought to live short, solitary lives, with only one massive star – about one hundred solar masses or more – forming at each site. However, these early models were quite limited. It was the introduction of advanced computational approaches, drawn from the repertoire of present-day star formation studies, that led to a dramatic change in our understanding of stellar birth in the early Universe over the past decade or so.

Current models of primordial star formation

Today's understanding of the birth of Population III stars is based on our much improved knowledge of the intricate interplay between gravity and turbulent motions in star-forming gas, the presence of magnetic fields, and the impact of various forms of stellar feedback. This includes the intense radiation emitted by hot stars and the momentum and energy injected by stellar winds and supernovae, both of which can dramatically alter the dynamics of the surrounding material and remove large portions of the gas reservoir otherwise available for stellar mass growth. It also includes the dispersal of enriched material and its mixing into the pristine ambient gas. It is now well accepted that primordial star formation exhibits a similar level of complexity as the birth of new stars in the solar vicinity or elsewhere in the Galaxy. It may even be a more challenging problem when considering the potential effects of dark matter annihilation and the presence of streaming velocities between gas and dark matter.

State of the field

The current models suggest that primordial gas was highly susceptible to fragmentation and that Population III stars formed as members of multiple stellar systems, with separations as small as the distance between Earth and the Sun, as illustrated in Figure 2. The mass distribution of primordial stars was most likely logarithmically flat, ranging from sub-solar values up to several tens, or possibly hundreds, of solar masses. There are even speculations that, under highly extreme conditions, stars with masses up to several hundred thousand solar masses may have formed. The remnants of these so-called supermassive stars could be the seeds of the supermassive black holes observed in high-redshift quasars with highly sensitive telescopes.

Observational constraints

There are no direct and unambiguous detections of genuine Population III stars in the early Universe, and with the telescopes available today and those becoming operational soon, this will likely remain the case for the foreseeable future. All current constraints on the nature and properties of the first stars are highly indirect. They either come from nearby stellar archaeological surveys of the Milky Way and its satellite galaxies, or they are inferred from observations of the early Universe with the James Webb Space Telescope, from measurements of the global 21cm signal, or from the detection of gravitational waves from merging binary black hole or neutron star systems.

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