Even if we can't see the first stars, we could detect their impact on the first galaxies

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Population III stars were the universe's first stars. They were extremely massive, luminous stars, and many of them exploded as supernovae. How did they shape the early galaxies? Credit: DALL-E

For a long time, our understanding of the universe's first galaxies leaned heavily on theory. The light from that age only reached us after traveling for billions of years, and on the way, it was obscured and stretched into the infrared. Clues about the first galaxies are hidden in that messy light. Now that we have the James Webb Space Telescope and its powerful infrared capabilities, we've seen further into the past—and with more clarity—than ever before.

The JWST has imaged some of the very first galaxies, leading to a flood of new insights and challenging questions. But it can't see individual stars.

How can astronomers detect their impact on the universe's first galaxies?

Stars are powerful, dynamic objects that wield a potent force. They can fuse atoms together into entirely new elements, an act called nucleosynthesis. Supernovae are especially effective at this, as their powerful explosions unleash a maelstrom of energy and matter and spread it back out into the universe.

Supernovae have been around since the universe's early days. The first stars in the universe are called Population III stars, and they were extremely massive stars. Massive stars are the ones that explode as supernovae, so there must have been an inordinately high number of supernovae among the Population III stars.

New research examines how all of these supernovae must have affected their host galaxies. The paper "How Population III Supernovae Determined the Properties of the First Galaxies" has been accepted for publication by *The Astrophysical Journal* and is posted to *arXiv*. The lead author is Ke-Jung Chen from the Institute of Astronomy and Astrophysics, Academia Sinica, Taiwan.

Stellar metallicity is at the core of this work. When the universe began, it was comprised of primordial hydrogen, helium, and only trace amounts of lithium and beryllium. If you check your periodical table, these are the first four elements. Elements heavier than hydrogen and helium are called "metals" in astronomy, and metallicity in the universe increases over time due to stellar nucleosynthesis.

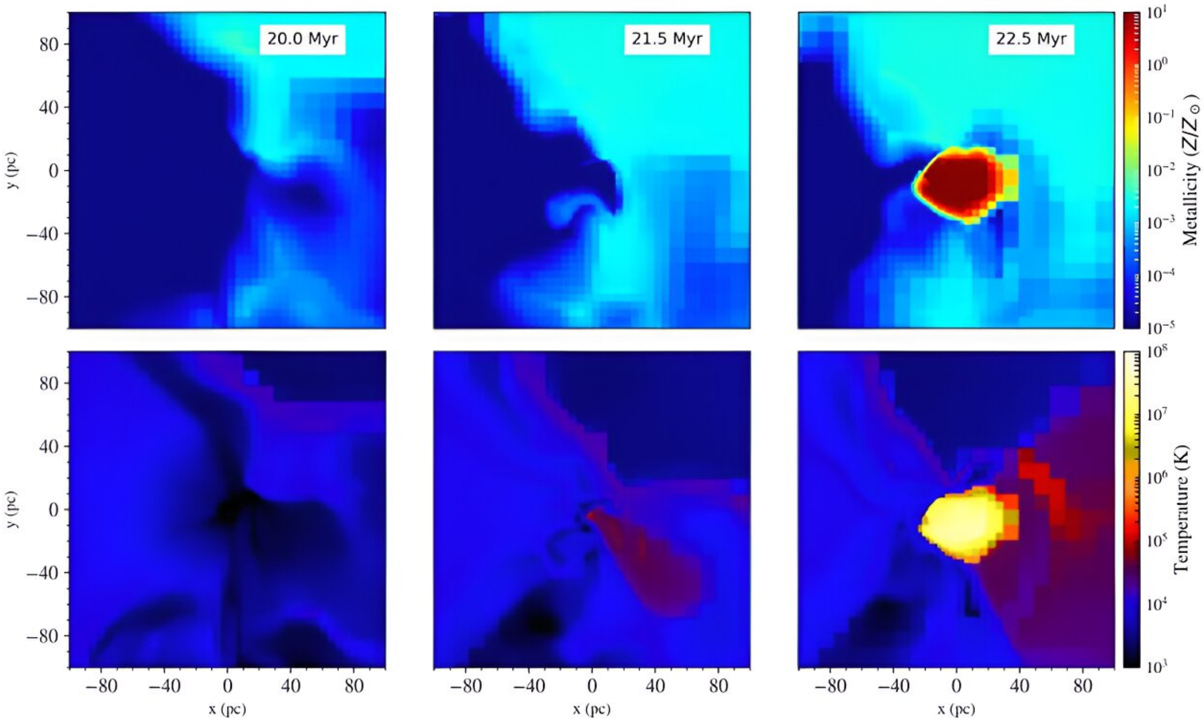
But hydrogen dominated the universe then as it does now. Only once the first stars formed and then exploded did other elements start to play a role.

"The birth of primordial (Pop III) stars at z ~ 20 ~ 25 marked the end of the cosmic dark ages and the onset of the first galaxy and supermassive black hole (SMBH) formation," the authors of the new paper write. But their role as creators of astronomical metals is at the heart of this research.

The researchers used computer hydrodynamical simulations to examine how Pop III stars shaped early galaxies. They looked at core-collapse supernovae (CCSNe), pair-instability supernovae (PISNe), and Hypernovae (HNe.)

Stars can only form from cold, dense gas. When gas is too hot, it simply isn't dense enough to collapse into protostellar cores. The researchers found that when Pop III stars exploded as supernovae, they produced metals and spread them into the surrounding gas. The metals cooled the star-forming gas quickly, leading to faster formation of more stars. "Our findings indicate that SNRs from a top-heavy Pop III IMF (initial mass function) produce more metals, leading to more efficient gas cooling and earlier Pop II star formation in the first galaxies."

The simulations showed that the supernova remnants (SNR) from the Pop III SN fall towards the center of the dark matter haloes they reside in. "These Pop III SNRs and the primordial gas are dragged by the halo gravity toward its center," the authors explain. These SNRs sometimes collide and produce turbulent flows. The turbulence mixes the gas and the metals from the SN and "creates filamentary structures that soon form into dense clumps due to the self-gravity and metal cooling of the gas."

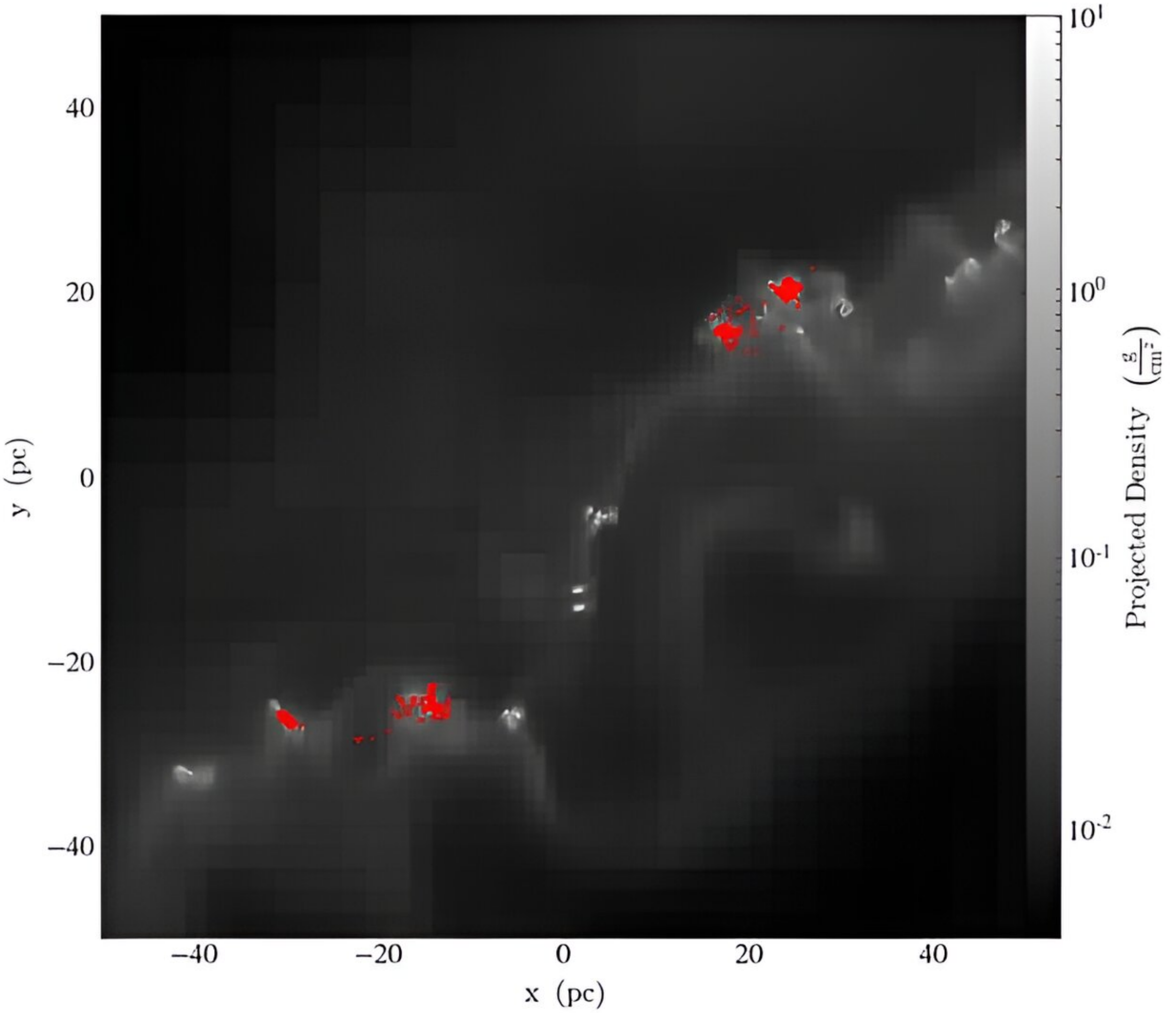


This figure from the research shows metallicity (top) and temperature (bottom) slices from the simulations, showing a 200 solar mass star forming, living a very short life, and then exploding as a supernova. The explosion creates feedback into the next stars. The left panels are right before the star forms, the middle panels are 1.5 myr after the formation, and the right panels show 0.5 myr after the star’s death. After it exploded, it formed a supernova remnant of hot and metal-rich ejecta. The metals in the ejecta would’ve contributed to cooling the gas, encouraging more rapid formation of the next generation of Pop II stars. Credit: Chen et al. 2024

This leads to more star formation, though at this point, they're still Pop III stars. These aren't enriched by the earlier Pop III supernovae and are still made of primordial gas. Some of these later Pop III stars form before the initial ones reach the center of the halo. That creates a complicated situation.

The second round of Pop III stars then "impose strong radiative and SN feedback before the initial Pop III SNRs reach the halo center," the authors write.

The Pop III stars heat the surrounding gas with their powerful UV radiation, as shown in the figure above, inhibiting star formation. But they're massive stars, and they don't live very long. Once they explode, they spread metals out into their surroundings, which can cool gas and trigger more star formation. "After its short lifetime of about 2.0 Myr, the star dies as a PI SN, and its shock heats the gas to high temperatures (> 105 K) and ejects a large mass of metals that enhance cooling and promotes a transition to Pop II SF," the authors explain.



This is Figure 6 from the research. It shows how Pop II stars have lower masses than Pop III stars and form in clusters in the fragmented clouds. “Due to the metal cooling and turbulence, these Pop II stars form into clusters along the dense filaments around the halo center,” the authors write. Image Credit: Chen et al. 2024

This is where the Pop III stars shaped the earliest galaxies. By injecting metals into the clouds of star-forming gas, they cooled the gas. The cooling fragmented the clouds of star-forming gas, making the following generation of Pop II stars less massive. "Due to the effective metal cooling, the mass scale of these Pop II stars shifted to a low mass end and formed in a cluster, as shown in the right panel of Figure 6."

Pop III stars existed mostly in dark matter haloes. However, the research shows how they shaped the succeeding Pop II stars, which populated the early galaxies. One question astronomers have faced regarding the first galaxies is whether they were filled with extremely metal-poor (EMP) Pop II stars. But this research shows otherwise. "We thus find that EMP stars were not typical of most primitive galaxies," the authors conclude.

More information: Ke-Jung Chen et al, How Population III Supernovae Determined the Properties of the First Galaxies, *arXiv* (2022). DOI: 10.48550/arxiv.2211.06016

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