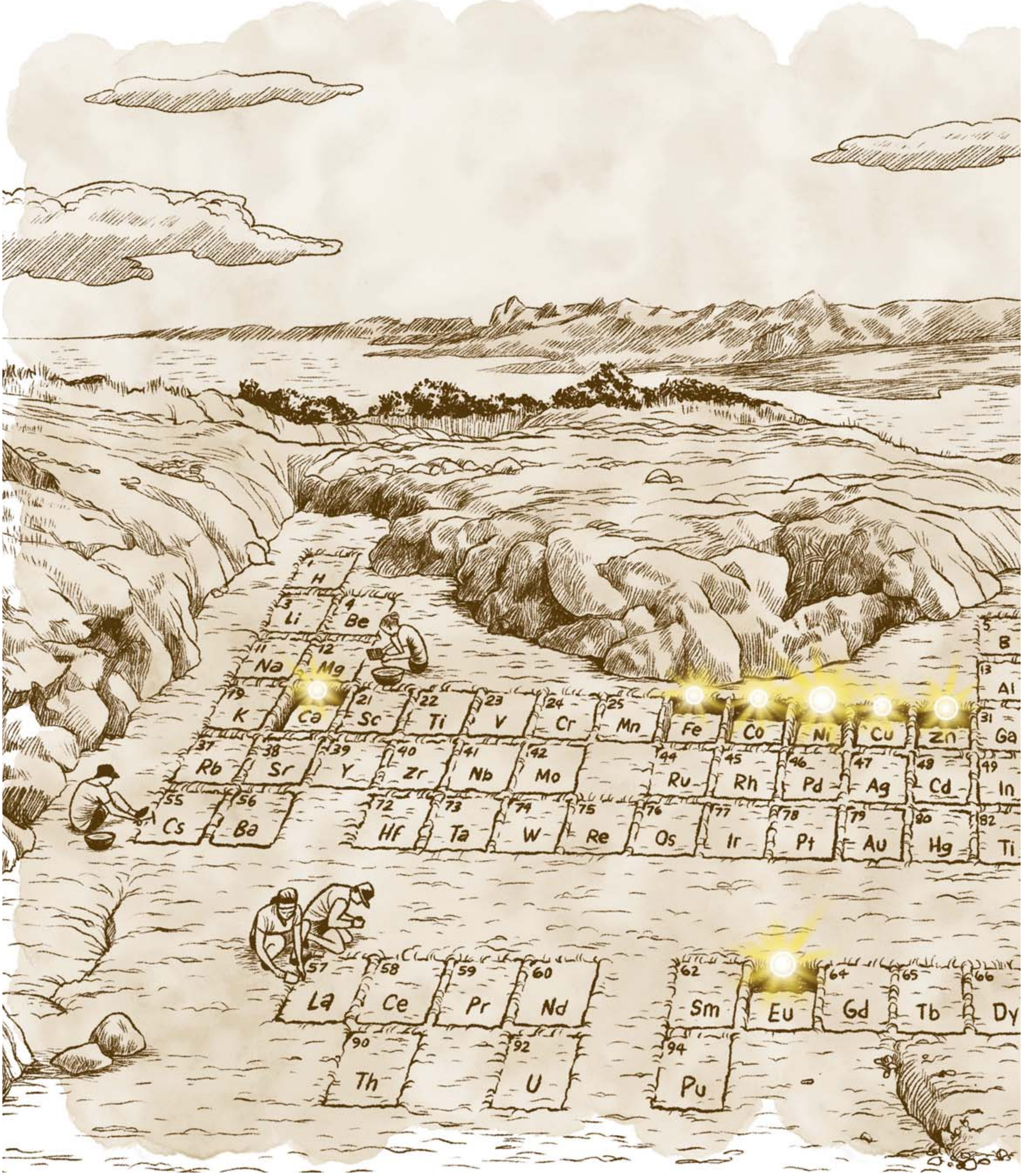
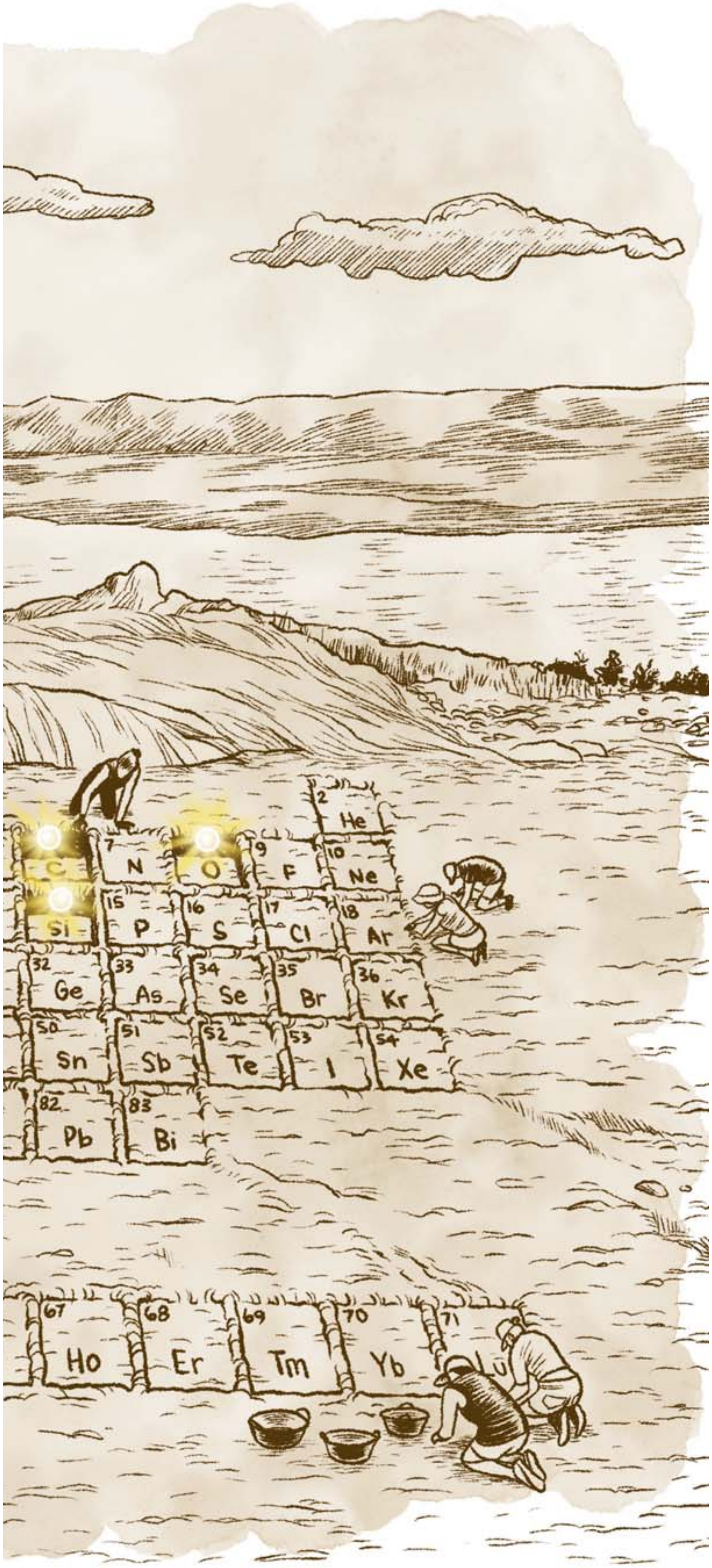
THE FIRST STARS by Brian Ventrudo





LEAH TISCIONE / S&T

Stellar Archaeology

Astronomers are illuminating the universe's early days by studying chemical patterns in the oldest stars.

The first stars must have been a magnificent sight. Far brighter, hotter, and more massive than most stars that currently light the sky, they emerged after a period of relative darkness — about 100 million years after the Big Bang, aided by the gravitation of countless halos of dark matter. No large galaxies existed yet, nor did elements heavier than helium, save for a trace of lithium. But when the first stars ended their lives as immense supernova explosions a few million years later, they released heavier elements that helped form the next generation of stars.

These heavy elements, such as carbon, calcium, and iron, astronomers collectively call *metals*. Metals helped radiate away heat from collapsing clouds of hydrogen and helium gas, fostering the creation of less massive and longer-lived stars. The smallest of these second-generation *Population II* (Pop II) stars still exist in the Milky Way and in nearby dwarf galaxies. Their outer layers harbor traces of metals produced in the first stars, called (counterintuitively from a chronologist's view) *Population III*.

This presents astronomers with an opportunity to do archaeology — stellar archaeology. No current telescopes can look back more than 13 billion years to directly study the first stars. But astronomers can study the abundances and relative proportions of metals left behind by the first stars in the outer layers of the oldest surviving Pop II stars, much as earthbound archaeologists learn about ancient cultures by studying the artifacts they left behind. Using this approach, astronomers hope to increase our understanding of how the first stars evolved, how they generated the first elements heavier than lithium, and how the first galaxies formed.

Finding the Oldest Stars

Population II stars are not hard to find. A peek through a telescope at a bright globular cluster such as M13 presents the combined light of hundreds of thousands of these ancient stars. Many stars in the Milky Way's central bulge and immense but sparsely populated halo are also Pop II stars that formed some 10 billion to 13 billion years ago. Only a fraction of them formed immediately after the demise of the first stars.

Much younger *Population I* stars, by contrast, lie in the Milky Way's disk. They are relatively rich in elements such as iron and carbon, because they formed from interstellar material seeded by many generations of earlier stars. Our Sun is a Pop I star. It formed about 9 billion years after the Big Bang, time enough for heavy elements to enrich its natal cloud. Today about 1.5% to 2% of the Sun's mass comprises elements heavier than helium.

This fraction may sound low, but it's high compared with Pop II stars: Metals are less than a tenth as abundant in Pop II stars as they are in the Sun. The oldest Pop II stars have the lowest levels. This is the key assumption of stellar archaeology: The abundances of metals in the atmosphere of a star are a proxy for its age. The lower the abundance of metals such as carbon, iron, and calcium, the more likely it is that the very first stars produced these trace metals. Pop III stars, if they are ever observed, would have virtually no elements heavier than helium.

The first metal-poor stars were found by chance. In 1951, Joseph Chamberlain and Lawrence Aller (both University of Michigan) found the stars HD 140283 and HD 19445 had surprisingly low iron and calcium abundances. Astronomers often use a star's iron abundance as a gauge for its overall metal content. Subsequent studies of HD 140283 revealed an iron abundance about $\frac{1}{300}$ that of the Sun. Sometimes called the Methuselah Star, this 7th-magnitude star is easily visible in the constellation Libra with a pair of binoculars.

Later sky surveys revealed hundreds of metal-poor stars. The HK and Hamburg/European Southern Observatory projects in the 1980s and 1990s recorded low-resolution spectra directly onto photographic plates, which astronomers then analyzed to find two absorption lines from calcium — the H and K lines at 397 nm and 393 nm.

The HK survey detected the first star with an iron abundance $\frac{1}{10,000}$ solar, while astronomers found another star, HE 1327-2326 — until recently the most iron-poor star known — with the Hamburg/ESO survey. It has an iron abundance 500,000 times lower than the Sun's, which suggests it is one of the oldest stars yet discovered.

The more recent Sloan Digital Sky Survey and the SkyMapper survey of the southern sky have resulted in the discovery of many more metal-poor stars. Based at Siding Spring Observatory, SkyMapper uses a fully automated 1.35-meter modified Cassegrain telescope with six photometric filters to estimate the color and brightness of millions of stars. One of the filters overlaps with the Ca H and K lines to make a rough estimate of overall metallicity. Less absorption at these violet wavelengths suggests a metal-poor star, and astronomers measure higher-resolution spectra of such stars using larger telescopes. Detailed numerical models render the abundance of a particular metal from the measured strength of the absorption line, along with an estimate of the star's effective temperature and surface gravity. Screening excludes stars cooler than 4000K, because they have evolved to a stage in which convection dredges up metals from the core and contaminates the outer layers of the star.

▲ **M13** Astronomers estimate that 20% of the stars in the globular cluster M13 are primordial Population II stars.

NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA)

Despite extensive searching, results to date show only about 30 stars with iron content less than $\frac{1}{10,000}$ that of the Sun. "Finding these stars is like searching for a needle in a haystack," says Anna Frebel (MIT) who discovered the low metallicity of HE 1327-2326 and other metal-poor stars. "An automated survey like SkyMapper gives us a bigger magnifying glass to look for these stars, but it's still hard work."

Iron-Poor Stars and the First Supernovae

As SkyMapper was commissioned, Frebel and her collaborators in 2014 discovered SMSS 0313-6708, a 15th-magnitude red giant with no detectable iron absorption. The missing signal

Understanding Stellar Populations

Astronomers, like most scientists, love to classify things. It was in this spirit that Walter Baade introduced the idea of stellar populations in the 1940s. He noticed bluer stars, which he called Population I, congregate in the spiral arms of the Milky Way and other galaxies, while redder Population II stars were found in and around the bulge of the galaxy, in the halo, and in globular clusters. Population I stars stay in the disk as they orbit the galactic center along fairly circular paths, while Population II stars in the bulge and halo can in some cases follow highly elliptical orbits around the center of the Milky Way and can shoot through the disk as well.

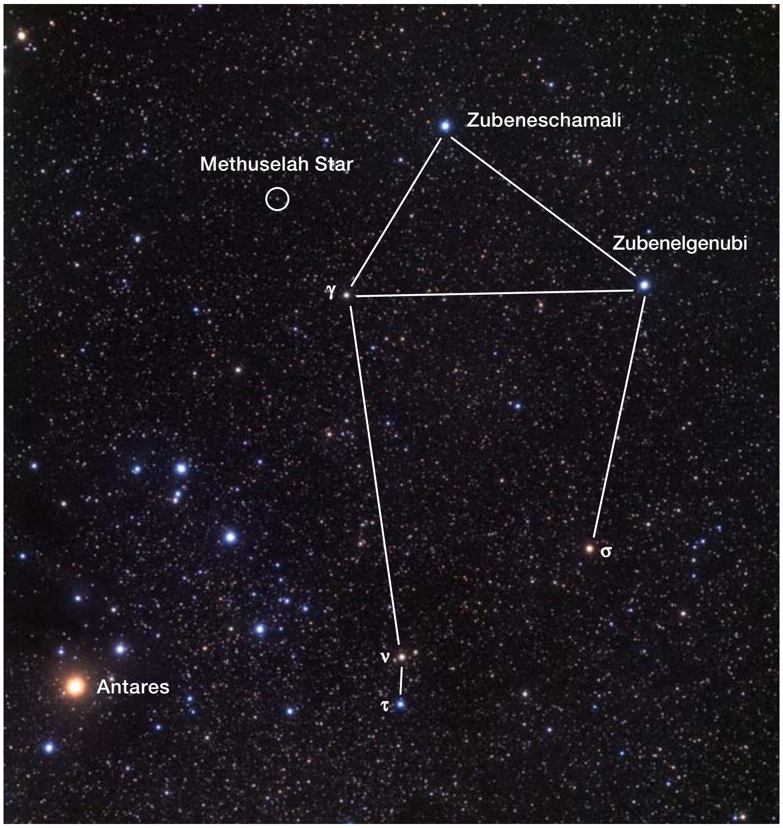
In the early 1950s, astronomers found Population I stars had much larger abundances of elements heavier than helium compared to Population II stars. That's suggested the star's iron fraction is at most 1⁄13 million that of the Sun. Spectroscopy also revealed weak absorption lines of carbon, magnesium, and calcium in this ancient halo star.

In 2019, Frebel's team found another iron-poor star, SMSS 1605-1443. It has the lowest measured iron abundance, at 1.6 million times less than solar. This star also has 100,000 times less calcium and magnesium compared to the Sun.

While these stars have just traces of iron, they feature a surprising overabundance of carbon. In the case of SMSS 1605-1443, for example, carbon is nearly 10,000 times more abundant than iron compared to the same ratio in our Sun. More recent observations of the iron-poor halo star J0815+4729 reveal a similar overabundance of oxygen compared to iron. These results surprised astronomers, because massive Pop III stars should die in spectacular supernovae explosions that eject large amounts of iron as well as lighter elements such as carbon, oxygen, magnesium, and calcium, all of which should find their way into the first Pop II stars.

So where did the iron go? One possibility suggests *mixing-fallback supernovae*. In this scenario, which might affect relatively small Pop III stars of 10 to 20 solar masses, mixing inside the collapsing core transports some heavy elements to the core's outer layers, where they are ejected in the explosion along with lighter elements such as carbon. But most of the heaviest end products of nuclear fusion in the core — such as iron, nickel, and zinc — would fall back into the black hole or neutron star formed at the star's core, explaining the relative lack of iron. A 2017 study by Ke-Jung Chen (National Astronomical Observatory of Japan) and colleagues made detailed computer simulations of mixing-fallback supernovae for Pop III stars. Using stars of 10 to 60 solar masses, they successfully explained the observed metal abundances in stars such as SMSS 1605-1443 and SMSS 0313-6708.

METHUSELAH STAR: AKIRA FUJII; GALAXY DIAGRAM: GREGG DINDERMAN / S&T

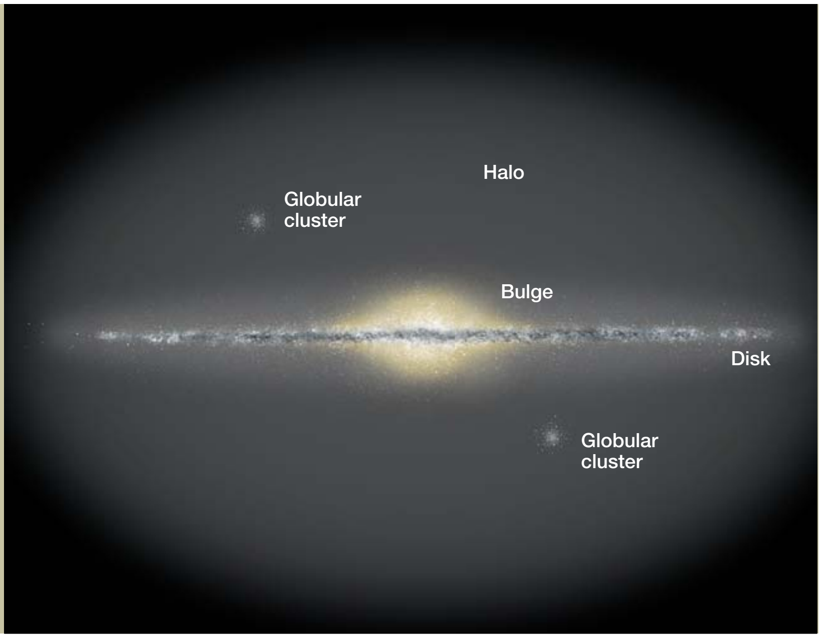


▲ **METHUSELAH STAR** Astronomers realized in the 1950s that the 7th-magnitude star HD 140283 in Libra has a surprisingly low level of iron.

Another explanation involves *pulsational pair-instability supernovae*, which would afflict Pop III stars of 100 to 140 solar masses. According to Stan Woosley (University of California, Santa Cruz), who has extensively modelled these supernovae, such stars first lose mass to stellar winds that might themselves be rich in carbon, nitrogen, and oxygen. Then they pulse violently as the dense soup of nuclei and gamma rays in their cores form pairs of electrons and

because Pop I stars, which are younger, formed from gas in the interstellar medium that was enriched by heavy elements ejected from many generations of dying stars. The Sun is a Pop I star, as are most other bright stars visible to the unaided eye. The older Pop II stars have far lower metal abundances than the Sun because they formed from less enriched material, earlier in the history of the universe. The 7th-magnitude star HD 140283 in Libra (see image above) is an example of a Pop II star.

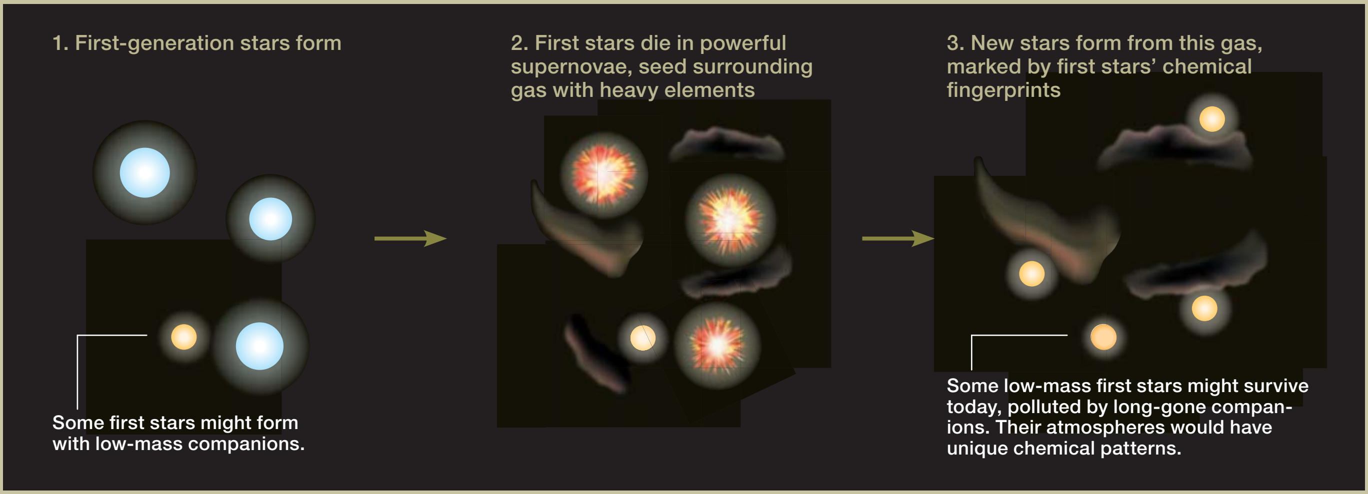
Astronomers introduced Population III stars as a concept in the 1960s. These stars have yet to be observed, but they would have no heavy elements because they formed out of primordial hydrogen, helium, and tiny traces of lithium only 100 to 200 million years after the Big Bang, before heavier elements existed.



positrons that self-annihilate, causing the core to partially collapse and rebound. They eject what was left of their hydrogen envelope and the outer part (maybe up to 5 to 10 solar masses) of their helium, along with appreciable C, O, Ne, and Mg. After the pulsations, the remainder of the star collapses to a black hole, capturing the iron remaining near the core. Very little of the iron — if any — escapes, and very little silicon and calcium.

Explaining the overabundance of carbon in iron-poor stars got more complicated in 2019, when Rana Ezzeddine (then at MIT) and her collaborators measured UV absorption lines of zinc in HE 1327-2326 using the Cosmic Origins Spectrograph on the Hubble Space Telescope. In HE 1327-2326, zinc is not only present but six times more abundant than iron. Zinc is created from iron during supernova explosions, but standard mixing-fallback and pulsational pair-instability supernovae cannot produce such large amounts. Instead, the study suggests a significantly asymmetric supernova of a fast-rotating 25 solar-mass star would be energetic and unstable enough to power a pair of jets that would emerge from the core itself. The jets would pull up zinc from deep inside and eject it, even as most of the iron falls into the newly made black hole.

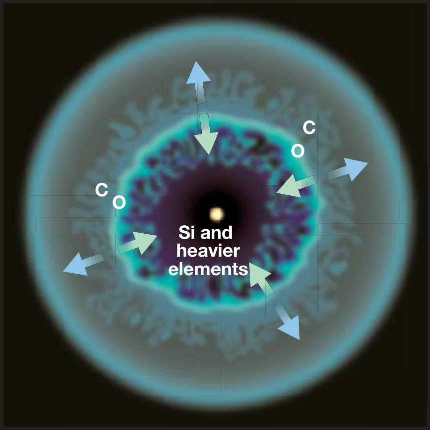
MAKING THE OLDEST STARS



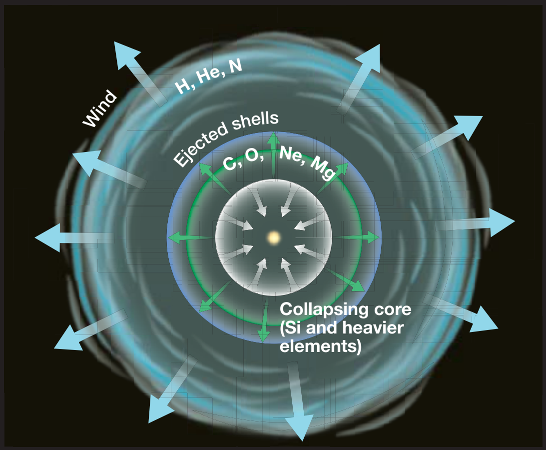
GREGG DINDERMAN / S&T (2)

THE FIRST SUPERNOVAE

Based on the chemical patterns in the oldest Population II stars, astronomers have suggested several possible ways the universe's first stars died.



MIXING-FALLBACK: As the core explodes, the gravity of the newly formed neutron star/black hole drags on expanding ejecta, causing it to fall back and mix. The star ejects large amounts of carbon and oxygen, but elements heavier than silicon mostly end up in the compact remnant.



PULSATIONAL PAIR-INSTABILITY: Stars lose their outer layers over time and in a series of pulses, ejecting carbon, oxygen, and elements of similar atomic mass. Heavier elements are trapped in the core when it collapses.

Not to scale

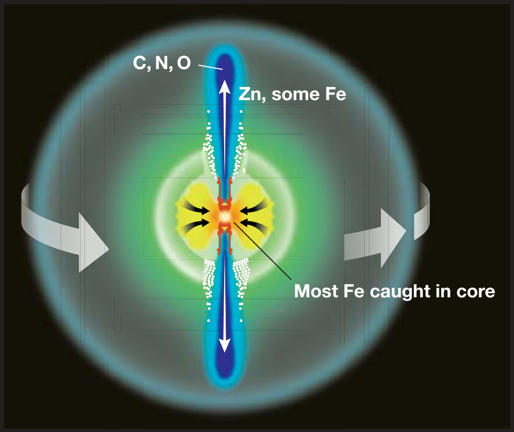
According to Frebel, a coauthor on the study, "In some ways, an asymmetric core-collapse supernova is a more natural explanation than mixing-fallback supernovae, while also explaining the zinc abundances in HE 1327-2326." In a press release after the study's publication, Ezzeddine suggested this result changes our understanding of how the first stars exploded. "This is the first observational evidence that such an asymmetric supernova took place in the early universe," she said.

The Origin of the Milky Way's Metal-Poor Stars

Most metal-poor stars discovered so far lie in the vast halo around the disk of the Milky Way. These 13-billion-year-old stars almost certainly predate the formation of the Milky Way as we know it today. But how did these stars come to arrive in our galaxy's halo, and where did they initially form?

Stellar archaeology suggests the answers to these questions lie in the kinematics of the dozens of dwarf spheroidal galaxies that surround the Milky Way. These tiny galaxies contain just a few thousand to a few million stars embedded within a more massive halo of dark matter that holds them together. They also have virtually no gas or dust, which means new star formation ended billions of years ago.

While computer simulations suggest the Milky Way has ingested many dwarfs in the past 10 to 12 billion years, it's been challenging to verify this observationally. However, stellar archaeologists have measured high-resolution spectra of a handful of the brightest stars in the closest dwarf galaxies. Results show the faintest galaxies, the so-called *ultra-faint dwarfs* (UFDs), have the lowest metallicities and the oldest Pop II stars. Metal-poor stars in UFDs such as Ursa Major II, SEGUE I, Boötes I, and Leo IV have abundances of Ca, Ti, Cr, and Zn remarkably similar to the most metal-poor stars in the halo of the Milky Way, suggesting they formed in a similar environment. "The chemical signatures in old stars in ultra-faint dwarf galaxies compared to those in the Milky Way halo is strong evidence that at least some of these stars in the halo came from ingested dwarf galaxies," says Frebel.



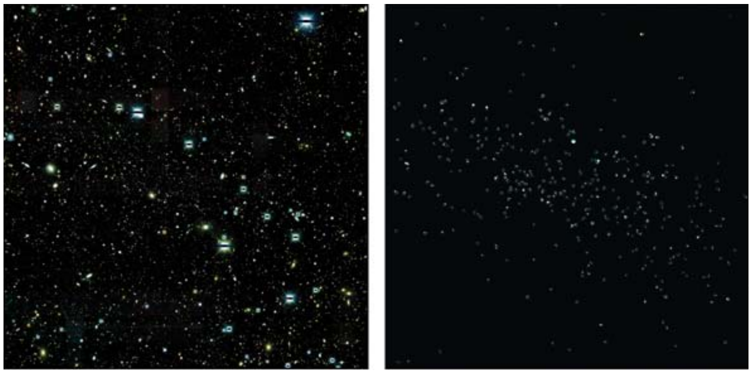
ASYMMETRIC, ROTATING: A rapidly spinning star explodes, and the energy and spin power jets that emerge from the core. The jets carry zinc and some iron up into the exploding star's outer layers, but much of the iron falls into the black hole.

UFDs also serve as sites for stellar archaeologists to investigate how Pop III stars generated the first elements heavier than iron. Massive stars create all the metals up to iron by fusion in their cores, but they only make small amounts of elements slightly heavier than iron — cobalt, nickel, copper, and zinc — before fusion shuts down and the star dies. Yet these elements clearly pollute the next generation of stars in significant amounts, so they must have been made somehow, along with even heavier elements.

Theory indicates that half the elements heavier than iron are produced through neutron capture in the so-called *r-process*, in which seed nuclei such as iron are bombarded by a huge flux of neutrons (roughly 10^{24} per cubic centimeter), then transmute into heavier elements in a cascade of energetically favorable nuclear reactions. The r-process happens in a matter of seconds, producing gold, rare earths like europium, and actinides such as uranium. It likely occurs in supernovae during the collapse and explosive re-expansion of the core, or during the cataclysmic merger of two neutron stars. In the present day, neutron star mergers may be a dominant source of r-process elements. But since many metal-poor stars have relatively low abundances of these elements, astronomers suspected that neutron-star mergers were irrelevant in the earliest days of star formation, possibly because of the long time it takes for such a merger to happen.

This view changed in 2016, when Alexander Ji (then at MIT) and his collaborators examined metal-poor stars in Reticulum II, a nearby UFD. They found very high abundances of r-process elements such as europium in seven of the nine stars observed, more than 100 to 1,000 times the abundance of these elements compared to stars in other UFD galaxies. It would take 1,000 supernovae to create these levels — an unlikely scenario in this tiny galaxy. Or they could be explained by a single merger of two neutron stars that polluted the environment. The neutron stars could have been the remnants of mid-sized, metal-free Pop III stars or very old Population II stars.

Coincidentally, Ji's study showed evidence of a neutron-star merger just before the Laser Interferometer Gravitational-Wave Observatory (LIGO) began to find gravitational waves from similar events (*S&T:* Feb. 2018, p. 32). "This is a really fantastic little galaxy that has changed our understanding of the field of nuclear astrophysics," Frebel says of Reticulum II. "It's a perfect example of how stellar archaeology plays at the top levels of astrophysics."



▲ **RETICULUM II** Ultra-faint dwarf galaxies (UFDs) contain so few stars that they're difficult to spot. Foreground stars mask the UFD Reticulum II in a Dark Energy Camera image *(left, with brightest stars blacked out by bars)*. Only after blacking out all other visible matter can we see the stars that belong to the tiny galaxy *(right, stars' bubble appearance is a consequence of the image processing)*.

A Faint Hope

While most models of Pop III stars suggest they should have expired long ago, there remains a lingering uncertainty. Computer simulations in 2014 by Athena Stacy (then at University of California, Berkeley) and Volker Bromm (University of Texas, Austin) suggest that not all Pop III stars formed big and died quickly. Some less massive than the Sun may have formed in conjunction with a much higher-mass companion. If so, slow-burning and low-mass Pop III stars might remain nearby, although they would likely be quite rare and possibly contaminated by heavy elements from the interstellar medium or a companion star.

Would current techniques of stellar archeology allow us to find them? "These stars, if they exist locally, would be freaks of nature," says Frebel. "But we cannot yet exclude the possibility of their existence. I think we could recognize these stars if we measured them."

Bromm also believes we could recognize Pop III stars. It's unlikely such stars could masquerade as low-mass Pop II stars, he says — the chemical signature of the contamination they had experienced would be different. Yet he is not optimistic about finding them. "The chances to find these stars are fading because survey sizes are so large that, if low-mass Pop III stars existed, we should have found them by now," he says.

New projects such as the Canada-France-Hawaii Telescope's Pristine survey and results from larger ground-based telescopes will likely find even more metal-poor stars with interesting chemical signatures. The European Space Agency's Gaia mission is also helping link the chemistry of these ancient stars with their motions through the galaxy. Astronomers are already using such data to identify large groups of stars that are the likely remains of destroyed dwarfs (*S&T:* Mar. 2020, p. 34).

Like its earthbound counterpart, stellar archaeology is a challenging field. But when it comes to the night sky, the deeper you dig, the more you find.

■ An erstwhile laser physicist and longtime stargazer with degrees in astronomy and applied physics, **BRIAN VENTRUDO** now observes and writes about stars of all ages from his home in Calgary, Canada.

▼ **ORIGINS OF THE ELEMENTS** The solar system's elements have different cosmic origins, with many of the heaviest made in neutron-star mergers (dark blue). Those in black are either artificially made or unstable on long time scales.

RETICULUM II: FERMILAB / DARK ENERGY SURVEY (2); PERIODIC TABLE: LEAH TISCIONE / *S&T*, SOURCE: JENNIFER JOHNSON / *SCIENCE* 2019