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Precious fossils of the infant universe

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PRECIOUS FOSSILS of the infant universe

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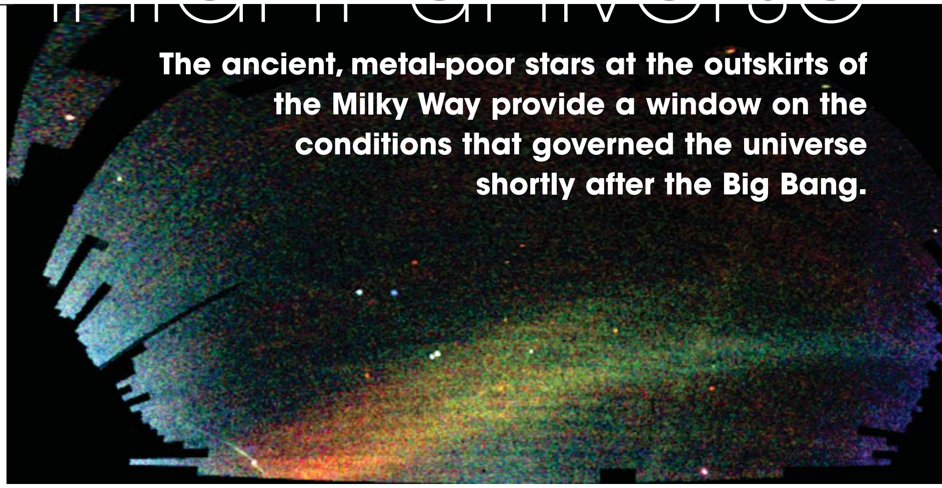
The ancient, metal-poor stars at the outskirts of the Milky Way provide a window on the conditions that governed the universe shortly after the Big Bang.



VASILY BELOKUROV

Cosmologists have created a highly successful model of the universe, in which the cosmic energy budget is dominated by a cosmological constant Λ and cold dark matter. Perhaps more remarkable, observations have enabled the fundamental parameters of the ΛCDM model to be determined with extremely high precision. However, crucial gaps remain in our understanding: We have yet to figure out how and when the first stars and galaxies formed, or how they affected subsequent cosmic history[1] (see also the article by Tom Abel in PHYSICS TODAY, April 2011, page 51).

In particular, the complex formation history of our own galaxy is unknown. Observations reveal a galaxy full of stars, gas, and intricate substructures. Surrounding it all is a spherical halo largely composed, presumably, of dark matter. Inhabiting the outer parts of the Milky Way are a variety of star streams, remnants of accretions of smaller "dwarf" galaxies. The image above prominently shows one of them (orange-yellow), the Sagittarius stream.

If we are to interpret all of that galactic structure, we need to trace the almost 14-billion-year process of cosmic evolution. Part of the challenge is to identify the basic galactic building blocks and how they are related to the initial stages of galaxy formation.[2] Another aspect is to understand both the major processes that governed the formation of the Milky Way and the time scales on which they operated. The traditional approach is to probe the early cosmos directly, with in situ observations at high redshifts; today's telescopes can see back in time to about 1 billion years after the Big Bang. NASA's *James Webb Space Telescope* (*JWST*), planned for launch later in the decade, and the next generation of extremely large ground-based telescopes will be able to significantly push back current boundaries to reach farther into space and hence further back toward the epoch of the first galaxies.

A second approach, stellar archaeology, explores the ancient past by scrutinizing fossil stars located at the outskirts of the Milky Way. The chemical surface composition of those roughly 13-billion-year-old stars reveals the conditions in the early universe just a few hundred million years after the Big Bang and before the emergence of our galaxy.[3] The fossils contain only traces of what astronomers call metals—elements heavier than hydrogen, helium, and lithium—produced in stars and supernova explosions. The chemical fingerprints of those old, metal-poor stars provide unique constraints on the nucleosynthesis inside the first stars and supernovae and on the chemical evolution of the Milky Way. In contrast to the traditional far-field approach that relies on high-redshift studies, stellar archaeology is a near-field cosmology, enabled through the study of local stars.

Still, the creation and evolution of the Milky Way is a complicated puzzle with many interconnected pieces; observations alone cannot provide a

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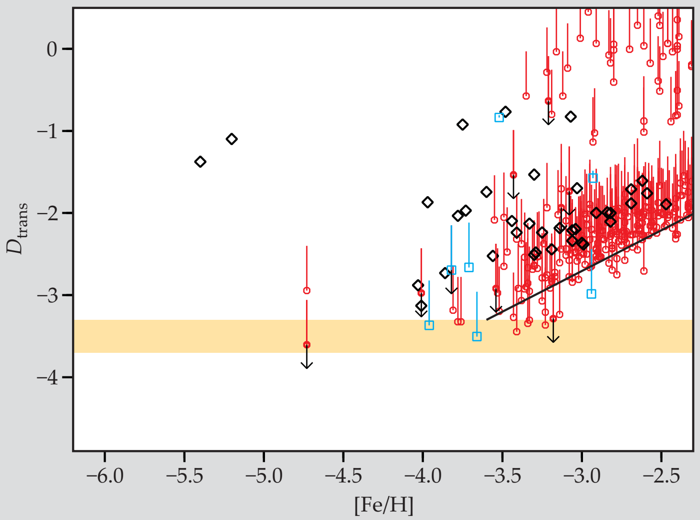

Figure 1. Stars that have survived to the current day were born from gas that could cool enough to form low-mass stars. According to one model,[7] that environment had to contain enough carbon and oxygen that a function of the two, called the transition discriminant D_{trans}, lies above the critical value of −3.5. The *x*-axis label [Fe/H] denotes the log of the iron-to-hydrogen abundance, normalized to solar values. The shaded swath is centered at the critical value of D_{trans}; its width represents theoretical uncertainty. The diagonal black line gives D_{trans} obtained with the solar abundance ratio of Fe to C to O. Data points are for metal-poor stars in the halo of the Milky Way (black and red) and for dwarf galaxies accompanying the Milky Way (blue). Vertical lines and arrows indicate a possible range of D_{trans} for those cases in which we have incomplete knowledge of the C and O abundances. Most, but not all, stars lie comfortably above the critical threshold. (Adapted from ref. 9.)

complete picture. In combination with cutting-edge theory, though, high-resolution spectroscopy can help constrain the properties of the infant universe and the early assembly of the Milky Way while duly taking into account the roles played by the first stars, chemical enrichment, and feedback processes.

The first stars

According to ΛCDM-based cosmological simulations of hierarchical structure formation, the first stars came into being a few hundred million years after the Big Bang, in small minihalos with a total mass of about a million solar masses ($M_\odot$). Until recently, simulations have predicted that those first stars were very massive; the reason for the large mass is that the primordial gas lacked effective cooling agents, so the stars needed a lot of material to overwhelm thermal pressure. Those early stars, which formed in isolation from primordial, metal-free gas, constitute a still-elusive class called Population III (Pop III). Their high masses are in stark contrast to the low masses of the stars, including our sun, that dominate today's universe. New simulations and corroborating observations suggest that those early behemoths were rapidly rotating.[4]

A different set of recent simulations, however, is challenging the old paradigm. Benefiting from improved numerical techniques, they show ubiquitous fragmentation in the disks that build up around the initial protostars. As a result, small multiples of Pop III stars—binary systems, for example—reside inside a given minihalo.[5] Even in the new paradigm, most Pop III stars are quite massive. But whether a small number of low-mass Pop III stars could also have formed as a result of the fragmentation is a topic of active debate.

After a few million years, the Pop III stars exploded as supernovae or, if they were extremely massive, directly collapsed into black holes. The exploding stars dispersed the first heavy chemical elements. The conditions for subsequent star formation in the neighborhood of the remnants were thus changed forever. The metals introduced there acted as coolants and may have enabled the second generation of stars to be less massive than the first, perhaps including some with even less mass than the Sun. Stars that formed from slightly metal-enriched material are called Population II stars. As a consequence of their low mass, they live for more than 10 billion years and are thus still observable. The Sun and the other metal-rich stars that make up Population I formed later, in environments much richer in metals than those that spawned Pop II stars.

The pattern of chemical elements in the most metal-poor Pop II stars suggests that some of them are true second-generation stars. Iron is the commonly used tracer for a star's overall metallicity (the fraction of material made of all metals). Abundance ratios are given on a logarithmic scale normalized to solar abundances: The notation is $[A/B] \equiv \log(N_A/N_B) - \log(N_A/N_B)_\odot$ for N_A atoms of element A and N_B atoms of element B. Thus a star with a metallicity of [Fe/H] = −3.0 contains 1/1000 of the solar relative Fe abundance. Stars with [Fe/H] < −3.0 are classified as extremely metal poor and are of particular interest for stellar archaeology. The current record for the lowest Fe abundance is a tiny 1/250 000 of the solar value; in absolute terms, that's about 1/100 of the Fe in Earth's core.[6]

Stars with $[Fe/H] \lesssim -3.5$ may teach us about how the first low-mass stars formed. At least according to the currently accepted paradigm, one necessary ingredient is sufficient cooling to induce fragmentation of the near-primordial gas. Turbulence, magnetic fields, and other phenomena might have played a role as well. According to some theories, gas fragmentation is induced once the interstellar medium includes a threshold abundance of heavy-element coolants. One particular refinement identifies singly ionized carbon and neutral oxygen as the main cooling agents facilitating low-mass star formation;[7] those two elements were likely produced in vast quantities in rotating Pop III stars. The cooling mechanism, called fine-structure line cooling, is a process by which thermally excited species radiate away the excitation energy as photons. The theory of the Pop III to Pop II transition is highly complex, however, and many important details remain unknown. A competing class of models posits that cooling through dust grains might have been the dominant effect in bringing about the transition.[8] In light of such uncertainties, guidance from stellar archaeology is crucial.

Indeed, stellar archaeology has already tested

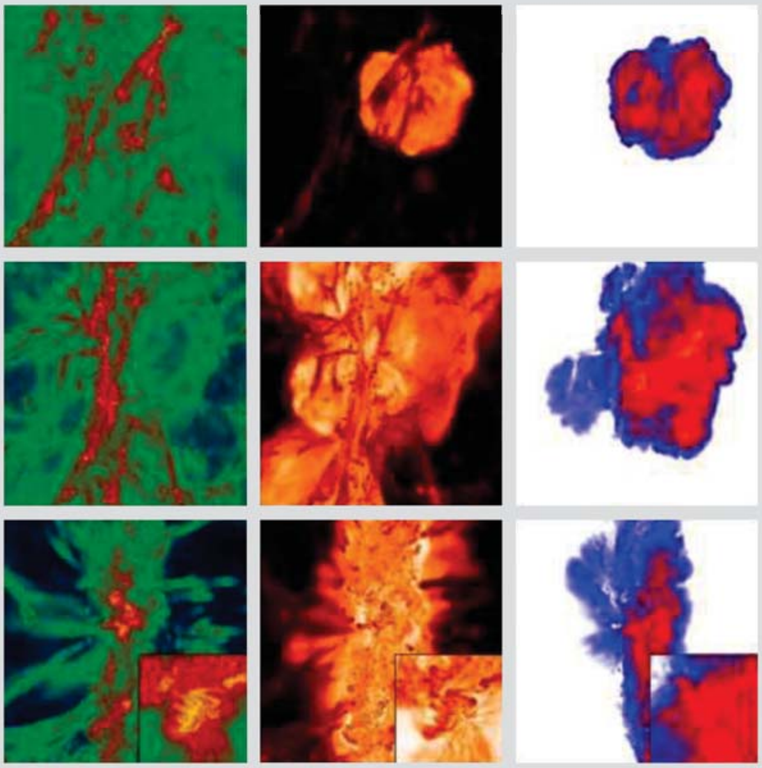

Figure 2. A supernova explosion of a Population III star distributes matter into the intergalactic medium; eventually that matter recollects at the center of a primordial galaxy. This supercomputer simulation shows, from left to right, gas density (green low, orange high), temperature (dark low, bright high), and metallicity (blue low, red high). Panels from top to bottom are for times 15 million, 100 million, and 300 million years after the explosion. The inset panels in the bottom row zoom into the center of the emerging first galaxy. The high-metallicity environment there is conducive to the formation of Population II stars. (Adapted from ref. 13, T. H. Greif et al.)

the line-cooling theory.[9] Any star that has survived since the dawn of the universe must have a mass of about 0.8 $M_\odot$ or less, and thus C and O abundances would be above predictable threshold values. (More precisely, the transition discriminant, a function of the two abundances, is what must be above a critical value.) As figure 1 shows, almost all of the known lowest-metallicity stars have discriminants above the critical threshold, which is consistent with the line-cooling theory. But some stars have values very close to or even slightly below critical.[10] At least in some cases, the lesson may be that cooling from dust grains in high-density condensations drives low-mass star formation.

The fine-structure line-cooling model may shed light on observations of metal-poor objects with [C/Fe] > 1.0. About ⅕ of metal-poor stars with [Fe/H] < −3.0 exhibit such a C overabundance, as do ¾ of the stars with [Fe/H] < −4.5. Those relatively large C concentrations could reflect conditions in the early star-forming regions. Moreover, if fine-structure line cooling is the dominant process for low-mass star formation, stars that will later be discovered with [Fe/H] ≲ −4.0 should also have large C or O overabundances with respect to Fe. Observations of high-redshift giant gas clouds called damped Lyman-α systems show them to be rich in C. Those early clouds may have been hosts for carbon-rich metal-poor stars.[11] The statistics of the observations need to be improved, however, if theorists are to be adequately guided in their modeling of early-universe cooling.

Empirical constraints from stellar archaeology can be incorporated in large-scale simulations that take into account such environmental influences as specific abundance patterns, dust-to-gas ratios, and radiation fields. But to really understand the cosmological origin of the most metal-poor stars and their journey from their birth clouds into the halo of today's Milky Way requires a detailed examination of the hierarchy of structure formation—from the basic building blocks to the present-day Milky Way.

Building a galaxy

The first stars formed in isolation or as members of a small multiple-star system. Unfortunately, individual Pop III stars are beyond our observational reach: Despite their large luminosities, even the *JWST* won't be able to see them. The only chance to catch one is at the moment of its explosive death when, theory predicts, it is extremely bright. We therefore turn to the next stage in the hierarchy of cosmic structure formation, which results in potentially observable stellar systems.

In time, gravity merged the minihalos that hosted the first stars into more massive structures. Theory suggests[12] that the second round of star formation occurred in dark-matter-dominated halos with a mass of about 10^8 $M_\odot$. Such halos emerged roughly 500 million years after the Big Bang, as deep gravitational potential wells collected the material that had previously been heated by the very first stars and blown out into the intergalactic medium. The gas that thus assembled into the first galaxies was likely already enriched with heavy elements to 0.1% of solar levels (see figure 2). According to state-of-the-art ΛCDM simulations, the metal-enriched environment of the first galaxies gave rise to the first low-mass stars. Those stars have survived for virtually the entire age of the universe and form the basis for stellar archaeology.[13]

Large-scale simulations have also yielded detailed insight into formation and evolution of large galaxies like the Milky Way.[14] Indeed, the hierar-

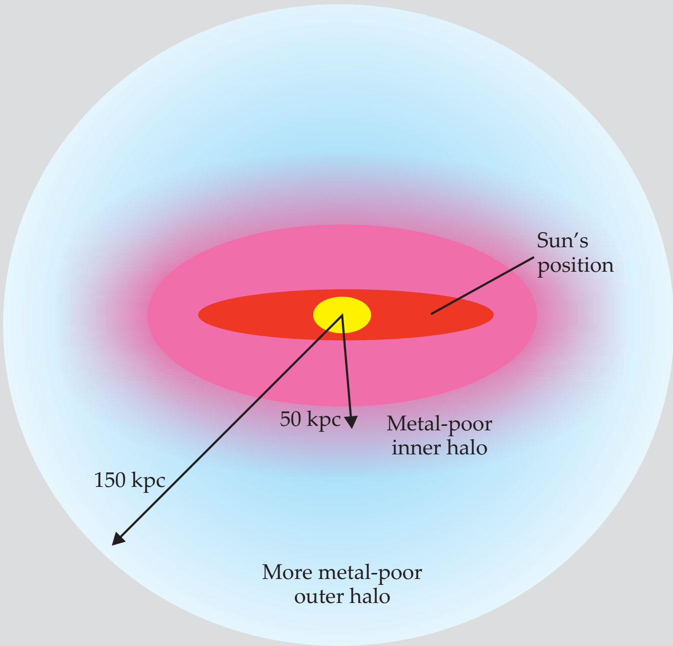

Figure 3. A galactic halo surrounds most of the luminous matter of the Milky Way. This schematic view of the galaxy shows the galactic bulge (yellow), the galactic disk (red), the inner halo (pink), and the outer halo (light blue). A distance of 1 kiloparsec (kpc) corresponds to 3260 light-years. The inner parts of the galaxy are not to scale. In particular, the Sun is about 8 pc from the galactic center.

chical assembly of any large galaxy is an ongoing process. Our own galaxy's continuing accretion of matter has led to a variety of streams and substructure. Key questions remain, however. Within the hierarchical picture, how many smaller systems did the Milky Way devour and at what times? Do some of the first galaxies survive as low-mass members of the so-called Local Group of galaxies, or have they all been merged into larger systems? Did the inner and outer parts of our galaxy form at different times?

Chemical abundances of stars in the galactic halo and in dwarf galaxies provide clues to the answers of those and related questions. The armada of dwarf galaxies orbiting our Milky Way is an obvious place to look for such clues.

Ancient, metal-poor stars

Known stellar metallicities range from greater than solar down to [Fe/H] = −5.4. The extremely metal-poor stars are the most interesting to those of us who study the early universe, but unfortunately, the number of stars decreases rapidly with decreasing metallicity. Individual metal-poor stars have been discovered primarily in the old halo of the Milky Way, where the stellar density is much lower than in the inner regions of the disk and bulge (see figure 3).

Absorption-line spectroscopy, in combination with atmospheric modeling, serves to determine the chemical composition of a star's surface. Typically, the spectra achieve a resolution $\lambda/\Delta\lambda$ of 20 000 in the optical wavelength regime. Figure 4 shows representative spectra and, in particular, illustrates the qualitative changes in absorption-line strength that accompany decreasing metallicity. Many metal-poor stars show an astonishing range of elements. That variety illustrates that all of the elements were already produced in the first generations of stars and supernovae, albeit in tiny amounts. Indeed, the most metal-poor stars provide important empirical constraints on the nucleosynthetic yields of the first supernovae in the universe.

Among the elements found in every metal-poor star are α elements like magnesium-24 and calcium-40 that are multiples of the helium-4 α particle. Determining α-element abundances enables astrophysicists to establish a rough chemical-enrichment time scale for the system that hosted the metal-poor stars. At early times, type II supernovae, which manifest the core collapse of massive stars, established a characteristic [α/Fe] ratio. After about 1 billion years, the first lower-mass stars in a system began to explode as type Ia supernovae—white dwarf stars that accreted too much mass from a companion in a binary system—and added fresh Fe to the interstellar medium. As a consequence, [α/Fe] should be lower in late generations of stars. Such a decrease has been observed in halo stars at higher metallicities of [Fe/H] > −1.5 and in dwarf galaxies, and it indicates that not all systems have the same enrichment time scale.

Metal-poor stars also contain heavy elements, such as strontium and europium, that are formed as a result of neutron capture. Those elements, though, are less common than the lighter elements with atomic number Z less than 30 or so. Neutron-capture nucleosynthesis processes are highly sensitive to local environmental conditions and progenitor masses, and theoretical predictions are still subject to huge uncertainties. The slow (s-) neutron-capture process, which produces about half the isotopes of heavy elements ($Z > 30$), operates in the pulsing, bloated atmospheres of evolved stars before they end their lives as white dwarfs. It may also occur in rapidly rotating, massive Pop III stars (reference 4, C. Chiappini et al.). But at least in the canonical picture, the process occurs a few hundred million years after the first lower-mass stars begin to reach the ends of their lives. Hence the characteristic s-process signature can be found in metal-poor stars only if the metallicity [Fe/H] is at least −2.6 or so.

Other metal-poor stars show a near-perfect chemical signature of the rapid (r-) neutron-capture process—the process responsible for the other half of isotopes with $Z > 30$ (see the article by John Cowan and Friedrich-Karl Thielemann, Physics Today, October 2004, page 47). It is not known exactly where the r-process operates, but the current best candidates are massive supernova explosions and the emerging neutron stars that can provide the strong neutron flux required to build up the heaviest known elements.

The radioactive elements thorium and uranium are among those made by the r-process; they have actually been observed in a handful of metal-poor stars that must have formed close to the location of

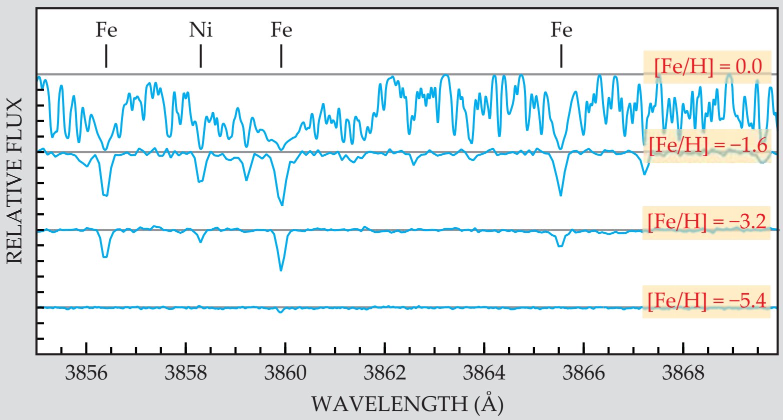

Figure 4. HE 1327–2326, the most iron-poor star yet discovered (as measured by the logarithmic abundance ratio [Fe/H]), has just a tiny absorption-line bump visible in the lowest of the four absorption spectra shown here. The stars generating the other three spectra are, from top to bottom, the Sun, G66–30, and G64–12. Evidently, the variations in line strength reflect the decrease in stellar metallicities. Four neutral elemental absorption lines are indicated near the top of the plot. (Adapted from ref. 18.)

a previous r-process supernova. In combination with modeling of r-process nucleosynthesis, the measured abundances of such long-lived radioactive species enable us to tell how old the stars are. If the radioisotope-containing stars were born shortly after the corresponding supernovae, an assumption justified by the stars' low metallicity, then they are roughly 13 billion years old.[15] Metal-poor stars are ancient—older than the Milky Way itself. But where did they form, and how did they end up in our galaxy?

The study of metal-poor stars in dwarf galaxies helps to answer that question. Of particular interest are the recently discovered ultrafaint dwarf galaxies, whose total luminosity is a mere 10^3–10^5 times greater than that of the Sun. In the faintest systems, the entire galaxy is dimmer than a single massive, evolved, and thus very luminous star. Ultrafaint dwarf galaxies, as a whole, are very metal deficient, and they host some 30% of the most metal-poor stars observed to date. The average [Fe/H] of their stars may be as low as about −2.5, a value slightly less than for most metal-poor, old globular clusters. At the metal-poor end, [Fe/H] abundance ratios are as low as about −4; we have yet to see any stars in ultrafaint dwarfs with [Fe/H] > −1.0.

Surprisingly, detailed element-abundance ratios for stars in the ultrafaint dwarfs are strikingly similar to those of typical metal-poor stars in the halo of the Milky Way, as can be seen in figure 5. Observations of extremely metal-poor stars located in so-called classical dwarf galaxies echo those findings. The chemical similarity of all those stars, whether they are found in the galactic halo, in classical dwarfs, or in ultrafaint dwarfs, indicates that chemical evolution at the earliest times was a universal process. Chemical evolution proceeded beyond those earliest times, but in the ultrafaint dwarfs the evolution terminated shortly after the production of the galaxy's metal-poor stars. In the classical dwarfs, chemical evolution continued with several bursts of star formation, as manifested, for example, in those galaxies' [α/Fe] abundance records.[16]

The chemical similarity of the stars in three different types of galaxies suggests that accreted dwarf galaxies contributed at least some of the Milky Way's metal-poor halo stars and that ultrafaint dwarf galaxies or their close cousins served as the building blocks of the galactic halo. Moreover, the surprisingly low metallicity of the ultrafaint dwarf galaxies means that they themselves likely are fossil objects that will allow physicists to explore beyond the fossil record of individual metal-poor stars. Theorists are making progress investigating the nature and evolution of those galaxies.[17] The full potential of dwarf archaeology, though, has not yet been fully realized because detailed spectroscopic observations of stars in the ultrafaint dwarfs, if they are possible at all, require lots of telescope time. But what we have already learned from the ultrafaint dwarfs raises the hope that we have finally identified a Rosetta stone of cosmic chemical evolution that will enable us to connect elemental abundances to a single episode of prior enrichment.

The sky is the limit

The full picture of structure formation in the early universe is likely imprinted in its stars and gas. Fleshing out that picture will require contributions from theorists, simulators, and observers. Theorists are constantly refining their models in an effort to connect early-universe cosmology with chemical-abundance measurements in metal-poor stars. Parallel supercomputers will enable ever more realistic simulations of structure formation in the early universe. The ability of those simulations to trace early metal production and spatial distributions will be essential to our determining the extent to which the ultrafaint dwarf galaxies of today resemble the first galaxies. The simulations will also shed light on whether the ultrafaint dwarfs are indeed the building blocks of the Milky Way halo.

Ever more detailed observations of stars in the halo and of ultrafaint dwarfs will become available through new surveys such as the Australian National University's SkyMapper, a project in which a 1.35-meter telescope will map out the complete southern sky. Such observations will yield a more complete census of the chemical and dynamical history of our galaxy. With large 6- to 10-meter telescopes and a full night's observing, one can obtain a usable spectrum for the faintest stars amenable to measurement. Some spectral features, though—for example, the absorption lines due to uranium and

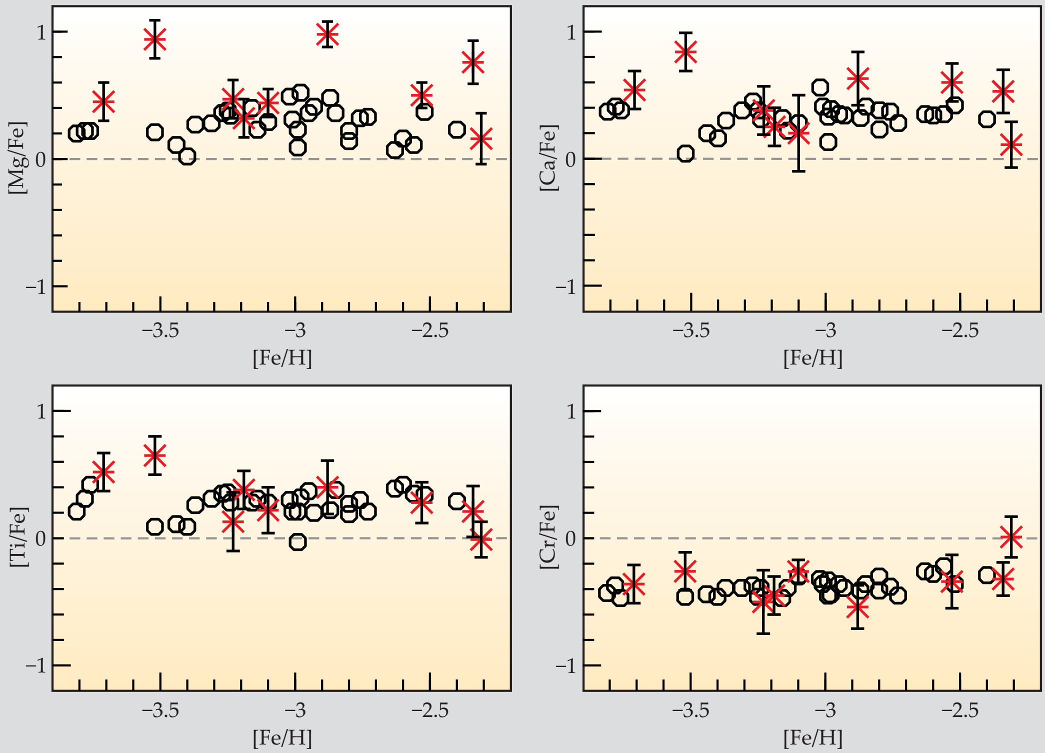

Figure 5. Relative abundance ratios are very similar for stars in the halo of the Milky Way (black circles) and stars in ultrafaint dwarf galaxies (red asterisks). (Adapted from ref. 3, A. Frebel and J. Norris.)

lead formed in the r-process—are so weak that the required data quality can only be obtained for relatively bright halo stars.

To maximize the discovery rate of extremely rare, metal-poor fossils, observers will increasingly rely on the ability to combine chemical abundances with kinematic information. However, many of the metal-poor candidate stars we seek are too faint for detailed observations with current telescopes; as a result, the outer halo is still a largely unexplored territory. The light-collecting power of the next generation of optical telescopes, including the 25-meter Giant Magellan Telescope, the Thirty Meter Telescope, and the 39-meter European Extremely Large Telescope, will enable us to reach farther out into the halo and examine the most metal-poor stars—provided that the telescopes are equipped with high-resolution spectrographs.

The exploration of the early universe is among the main scientific goals of a whole new suite of facilities. These ground- and space-based telescopes will look mostly at high-redshift galaxies and other far-field objects. Several radio facilities will shed light on the epoch during which the neutral cosmos was reionized by the emerging first generation of stars. The *JWST*'s near-IR images of the earliest star-forming regions will address many of the questions that scientists are currently trying to answer. Looking closer to home, the *Gaia* mission will soon begin to take a comprehensive census of the stars in the Milky Way to fully characterize the spatial structure of our home galaxy. Together, the new facilities promise to yield exceptional insights about cosmic evolution. Stellar archaeology and near-field cosmology will play an important role in that ongoing story of discovery.

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