

Reconstructing the Cosmic Evolution of the Chemical Elements

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Abstract: The chemical elements are created in nuclear fusion processes in the hot and dense cores of stars. The energy generated through nucleosynthesis allows stars to shine for billions of years. When these stars explode as massive supernovae, the newly made elements are expelled, chemically enriching the surrounding regions. Subsequent generations of stars are formed from gas that is slightly more element-enriched than that from which previous stars formed. This chemical evolution can be traced back to its beginning soon after the Big Bang by studying the oldest and most metal-poor stars still observable in the Milky Way today. Through chemical analysis, they provide the only available tool for gaining information about the nature of the short-lived first stars and their supernova explosions more than thirteen billion years ago. These events set in motion the transformation of the pristine universe into a rich cosmos of chemically diverse planets, stars, and galaxies.

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One beautiful afternoon I went for a run along the river. I was breathing plenty of fresh air, my face was all flushed, and I felt my heart pounding and blood flowing through my body. As air was filling my lungs, I was reminded of Carl Sagan's saying: "We are all made from star stuff." Indeed we are. When quenching my thirst with water, I was consuming hydrogen and oxygen in the form of H₂O. When breathing, I had been taking in air made from nitrogen, oxygen, and tiny traces of other elements such as argon and neon. The red liquid of life owes its color to iron, which is embedded in our hemoglobin. But these elements do not just circulate within our carbon-based bodies: before they became part of humans, each of these atoms was created in a grand cosmic cycle called chemical evolution that took place long before biological evolution led to life on Earth.

Most of the universe's iron, for example, is the end result of a binary star system in which one star acquires enough material from its companion that it reaches a critical mass and erupts in a huge thermonuclear explosion, forging new elements in the pro-

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cess. On the other hand, the hydrogen atoms that make up water are probably nearly fourteen billion years old and were created as part of the Big Bang. And all the carbon upon which life as we know it is based was synthesized in evolved stars near the end of their lives.

The fact that all elements except hydrogen, helium, and lithium are made in stars and their subsequent explosions has only been known for less than sixty years. A seminal paper from 1957, often referred to as “B²FH” following the initials of the authors, provided the first comprehensive summary of “the synthesis of the elements in stars.”¹ This came after decades of work directed at finding the energy source of stars. With the elucidation of how and where the chemical elements are forged in stars came the realization that there is a chemical evolution in the universe, causing a net increase in the amount of elements over time. Most important, this model provided observationally testable support for the Big Bang theory and the theory of a time-dependent chemical evolution of the universe.

While the nature of chemical evolution of galaxies is now well established, many details of the complex circle of nucleosynthesis in stars, later chemical enrichment of interstellar gas, and subsequent star formation remain poorly understood and thus continue to be subject to ongoing research. Many questions center around what the exact abundance yields of individual supernova explosions may be, as well as how the nature of the exploding stars themselves and the astrophysical environment influences nucleosynthesis and the production of the elements throughout the periodic table. Because old stars that formed in the early phases of chemical evolution can help with this quest, we will start the tale of the origin of the elements from the very beginning of the universe.

Immediately after the Big Bang 13.8 billion years ago, there was a time without stars and galaxies. The hot gas left over from the Big Bang had to cool enough before the first cosmic objects were able to form. This process took a few hundred million years, but eventually the very first stars lit up the universe. The universe at that time was made from just hydrogen and helium: heavier elements did not exist yet. As a consequence of a variety of gas chemistry and cooling processes that govern star formation, the first stars are thought to have been rather massive. Recent computations suggest these behemoths may have had up to one hundred times the mass of the sun.² In comparison, most stars today are low-mass stars with less than one solar mass.

Stars are powered by the nuclear fusion taking place in their cores; it is the energy source that sustains their enormous luminosities. In the first and by far the longest burning phase, hydrogen is fused into helium. At about ten million degrees F, four protons (or hydrogen nuclei) are fused together in a series of nuclear reactions to make a helium nucleus. Subsequent burning stages, which occur only in the last ten percent of stars' lives, result in three helium nuclei (“ α -particles”) being converted to beryllium, which then captures another particle to become carbon in the so-called triple- α process.

After that, through additional particle captures, carbon nuclei are converted to oxygen; through yet more nucleosynthesis processes, all elements in the periodic table up to iron are built up. The fusion of lighter elements into heavier ones results in a conversion of a small amount of mass into energy. For example, a helium nucleus is 0.7 percent lighter than four individual hydrogen nuclei. It is this mass difference that, as described by $E = mc^2$, fuels the star and sustains its luminosity for long periods of time. However, once the

star has created an iron core at its center, nucleosynthesis stops. No more energy can be gained by fusing iron into even heavier nuclei: the star's energy source has ceased for good. As a consequence, the star can no longer maintain equilibrium and begins to collapse due to its own gravity. As a result of the huge pressures, the iron core is converted into an extremely dense neutron star. The collapsing mass of the star bounces off the hard neutron star and leads to a gigantic supernova, leaving the neutron star behind. This was also the fate of the massive very first stars. To sustain their great luminosities, massive stars (those with more than ten solar masses) require large amounts of nuclear energy. Consequently, they burned through the hydrogen and subsequently created heavier-element fuel much more quickly than stars with lower masses, therefore limiting their lifetimes to just a few million years.

During the explosion of a star, all the newly created elements are released into the surrounding gas. The death of the first stars marked an important milestone in the evolution of the universe: it was not pristine anymore, but "polluted" with carbon, oxygen, nitrogen, iron, and other elements. Thus, over time, the universe became more and more enriched in the elements heavier than hydrogen and helium, which are collectively called "metals" by astronomers. In contrast, the very first stars were the only ones that formed from completely metal-free gas. All stars in subsequent generations would then form from gas clouds that contained some metals provided by at least one previous generation of stars exploding as supernovae.

The sudden existence of metals in the early universe following the death of the first stars changed the conditions for subsequent star formation. Gas clouds can cool down more efficiently when metals or dust made from metals are present, leading to the collapse of smaller clouds, and thus the

formation of smaller stars. Lower-mass stars like the sun could therefore form for the first time. The first low-mass stars (those with 60 to 80 percent of the mass of the sun) have long lifetimes of fifteen to twenty billion years due to their sparse consumption of the nuclear fuel in their cores. Born soon after the Big Bang as second- or third-generation stars, they are still shining today. Many of these ancient survivors are suspected to be hiding in our Milky Way galaxy and, indeed, astronomers have discovered dozens of them over the past three decades. What makes these extremely rare objects so valuable is that they preserve in their atmospheres information about the chemical composition of their birth cloud, which existed soon after the Big Bang. Hence, studying their chemical composition allows astronomers to reconstruct the early era of their births.

In the earliest stages of the universe's development, massive stars exploding as supernovae dominated the production of iron in the universe. However, this changed after about a billion years. Through the existence of the first lower-mass stars with longer lifetimes, a different pathway for iron production emerged. At the end of their long lives, low-mass stars turn into compact white dwarf remnants. If a star and a white dwarf are in a binary system and enough mass is transferred from the star to the white dwarf, the latter will undergo a thermonuclear explosion. Given the dominance of low-mass stars in the universe today, iron is thus mainly produced by this process rather than by exploding massive stars, as was exclusively the case in the early universe.

After about nine billion years of this chemical evolution, driven by different types of stars at different times, our sun, together with its planets, finally formed. Its birth gas had been enriched by perhaps a thousand generations of stars and supernova explosions. That evolution pro-

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vided the gas with enough metals to enable the formation of planets – something that may not have been possible much earlier on in the universe. Consequently, when astronomers look for extrasolar planets, they focus their search on stars that are close in age to or younger than the sun.

Through spectroscopic observations, astronomers can determine which elements are present in a star's outer layers and what their respective abundances are. Spectroscopy is a technique in which starlight is split up into its components, just as sunlight is split when we see a rainbow. The different elements (hydrogen, helium, and metals) in the star's atmosphere absorb light at very specific colors, or wavelengths. When carrying out high-resolution spectroscopy, the starlight is significantly stretched out over all visible wavelengths to enable the detection of even very weak absorption lines left behind by all the elements in the stars. The existence and strength of absorption lines corresponding to specific elements are measured and analyzed with computer programs that reconstruct the stellar atmosphere. This way, astronomers can calculate how many atoms of a given element are present in the star.

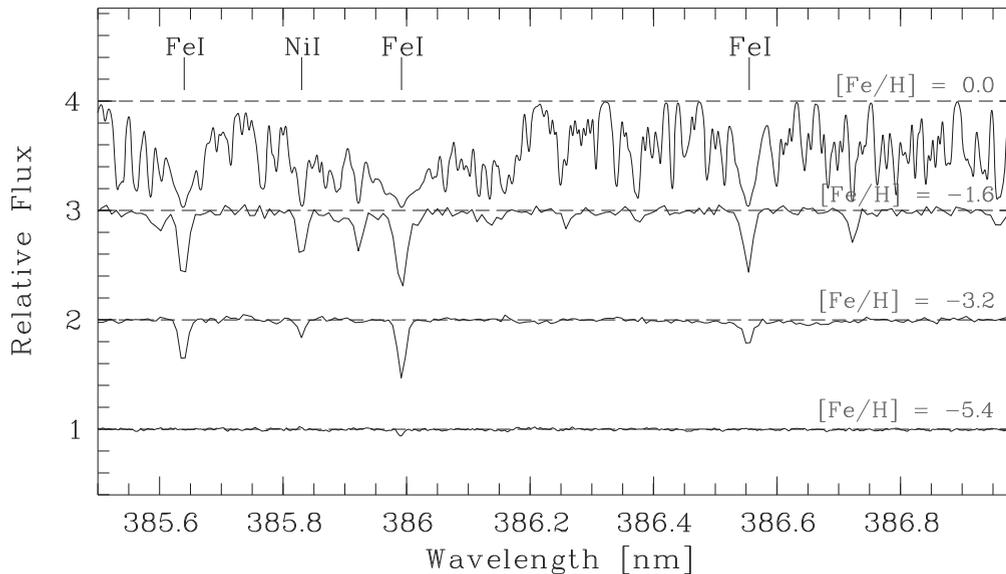
High-resolution spectroscopy, especially for fainter stars, requires the largest telescopes that observe the visible wavelength range. Telescopes like the Magellan-Clay Telescope at Las Campanas Observatory, located in Chile's Atacama desert, are equipped with high-resolution spectrographs. Thanks to its large 6.5-meter-diameter mirror, the Magellan Telescope is capable of collecting enough light from faint stars to enable high-resolution spectroscopic measurements. Chemical analysis then shows how much of each type of metal is present in a star, which indicates the star's formation time. So-called metal-poor stars are assumed to be old because

they formed from gas enriched with only a trace amount of heavy elements, created by the first few stellar generations after the Big Bang.³ In contrast, "metal-rich" stars like the sun must have formed at a much later time when the universe was significantly enriched with metals by many stellar generations.

Our study of early star formation and chemical evolution relies on our ability to measure stars' metallicity, or metal content. The main indicator used to determine stellar metallicity is iron abundance, which, with few exceptions, reflects a star's overall metallicity fairly well. Absorption lines of iron (Fe) can be found throughout stellar spectra, often covering large wavelength ranges from 350 to 900 nanometers, which makes measuring iron abundance relatively straightforward. The iron abundance of a star is given as $[Fe/H]$, which is used in the logarithm of the ratio of iron atoms to hydrogen atoms in comparison to that of the sun. The formal definition reads $[Fe/H] = \log_{10}(N_{Fe}/N_H)_* - \log_{10}(N_{Fe}/N_H)_{\odot}$ with N being the number of Fe and H atoms, respectively, and * and \odot representing the star being evaluated and the sun, respectively. The consequence of this logarithmic definition is that metal-poor stars will have negative $[Fe/H]$ values, as those stars have a lower concentration of Fe atoms than the sun. Stars containing higher concentrations of metals than the sun will show a positive $[Fe/H]$ value.

To illustrate the difference between younger metal-rich and older metal-poor stars, Figure 1 shows spectra of the sun and three metal-poor stars. Their decreasing metallicities are listed. The corresponding number of absorption lines detectable in the spectra decreases with increasing metal-deficiency. In star HE 1327–2326 (bottom spectrum), only very few metal absorption lines are left to observe. Their weakness is such that determining their metal-

Figure 1
Spectral Comparison of the Sun with Three Metal-Poor Stars with Different Metallicities Indicating the Course of Chemical Evolution from the Early Universe (Bottom) to the Sun's Birth ~4.5 Billion Years Ago (Top)



Source: Anna Frebel, "Stellar Archaeology: Exploring the Universe with Metal-Poor Stars," *Astronomische Nachrichten* 331 (2010): 474.

licity requires extremely high-quality data that can only be obtained with large telescopes.⁴

If one wishes to identify the oldest stars, the task is to find stars with the lowest metallicities and thus the earliest formation times. It is those stars that allow astronomers to look back in time and reconstruct the formation and evolution of the chemical elements and the involved nucleosynthesis processes that created them. While very distant galaxies are often used for observational studies of galaxy formation and cosmology, metal-poor stars are the local equivalent of the distant universe and thus the object of "near-field" cosmology. Both approaches to cosmology complement each other in providing detailed information and observational constraints

that push us toward understanding the onset of star and galaxy formation in the early universe some thirteen billion years ago. Metal-poor stars are, however, the only tool we have available to learn about the nature of the first stars and their supernova explosions. Our study of these stars therefore provides unique constraints on various theoretical concepts regarding the physical and chemical nature of the early universe.

Past sky surveys for metal-poor stars have shown that these ancient objects can be systematically identified in a three-step process that involves the selection of candidates from the survey data and subsequent follow-up of the best targets with medium- and high-resolution spectroscopy.⁵ This technique has identified large numbers of

metal-poor stars on the outskirts of the Milky Way, the so-called halo of the galaxy. Work done over the last few decades has shown that stars with low metallicity are much fewer in number compared to more metal-rich stars, reflecting not only the chemical evolution of the universe but also the overwhelming number of stars that have formed since its early stages.

The most metal-deficient stars, in particular, are extremely rare and difficult to find. Only about fifty stars are known to have metallicities of $[\text{Fe}/\text{H}] < -3.5$, which corresponds to $\sim 1/30000$ th of the solar metallicity. Of those, only six have $[\text{Fe}/\text{H}] < -4.0$ or $< 1/10,000$ th of the solar value. The current record holder is the star SMSS 0313-6708, with $[\text{Fe}/\text{H}] < -7.0$. No iron lines could be detected, so only an upper limit on the iron abundance could be determined, which corresponds to less than $\sim 1/10,000,000$ th that of the sun. The next most iron-poor star, HE 1327-2326, has an iron abundance of $[\text{Fe}/\text{H}] = -5.4$ ($\sim 1/250,000$ th of the solar iron abundance). This translates into an actual iron mass of just 1 percent of the iron mass present in the Earth's core. This is a very small amount, considering that the star is approximately 300,000 times more massive than the Earth and about one million times larger in size. It also reveals that in the early universe, iron and other elements were rare commodities.

Thus, the few stars with $[\text{Fe}/\text{H}] < -4.0$ have opened a new and unique observational window to the time shortly after the Big Bang when only the very first stars had enriched the universe. They are frequently employed to constrain theoretical studies about the formation of the first stars, element production and chemical evolution, and supernova yields. The elemental-abundance patterns (chemical abundances as a function of atomic number of the respective element) of these stars appear to be highly individual, but in fact

can be successfully reproduced by scenarios in which a massive first supernova explosion provided the elements to the gas cloud from which the observed object later formed. In fact, the most metal-poor stars all display the “fingerprint” of one single massive first supernova, which allows astronomers to ascertain the mechanisms and details of the supernova itself and the nature of the long-extinct progenitor star.

With the exception of hydrogen and helium, all elements up to iron are created through nuclear fusion during lifetimes of stars. But these elements (with atomic number $Z \leq 30$) make up less than one third of the periodic table. So where do the other elements with higher atomic masses, such as silver ($Z = 47$) and gold ($Z = 79$), or more exotic rare earth elements, such as lanthanum ($Z = 57$) and europium ($Z = 63$), come from?

The study of metal-poor stars has greatly advanced our understanding of this topic. As we now know from nuclear physics, elements heavier than iron are created not through fusion processes but through neutron-capture by seed nuclei (for example, iron nuclei). In an astrophysical environment that provides a constant flux of neutrons, heavy elements can thus be built up. Such conditions are thought to occur during certain kinds of supernova explosions in which a strong neutron flux develops above the newly formed central neutron star. For example, if iron nuclei are extremely rapidly bombarded with many neutrons before the nuclei β -decay, their nuclei capture more neutrons, creating heavy, neutron-rich, and unstable isotopes. Once these have β -decayed to stability, new and heavier elements remain.⁶ Beta decay is a spontaneous decay of one element into another through the conversion of a neutron into a proton accompanied by the emission of an electron and a neutrino. Due to the rapid bombardment,

this process is called the *r*-process. About half of all stable isotopes of elements heavier than zinc are made this way.

The other half of the isotopes of heavy elements are created in the so-called *s*-process, where a slower neutron bombardment (over a longer timescale than the β -decay process) leads to the successive build-up of heavy elements. This process occurs in the pulsing outer shells of evolved red giant stars with masses of less than eight solar masses and metallicities of $[\text{Fe}/\text{H}] > -3.0$ (indicating that the star formed from gas already containing a small amount of iron atoms that could function as seed nuclei). Through stellar winds, these elements are eventually released into the surrounding gas.

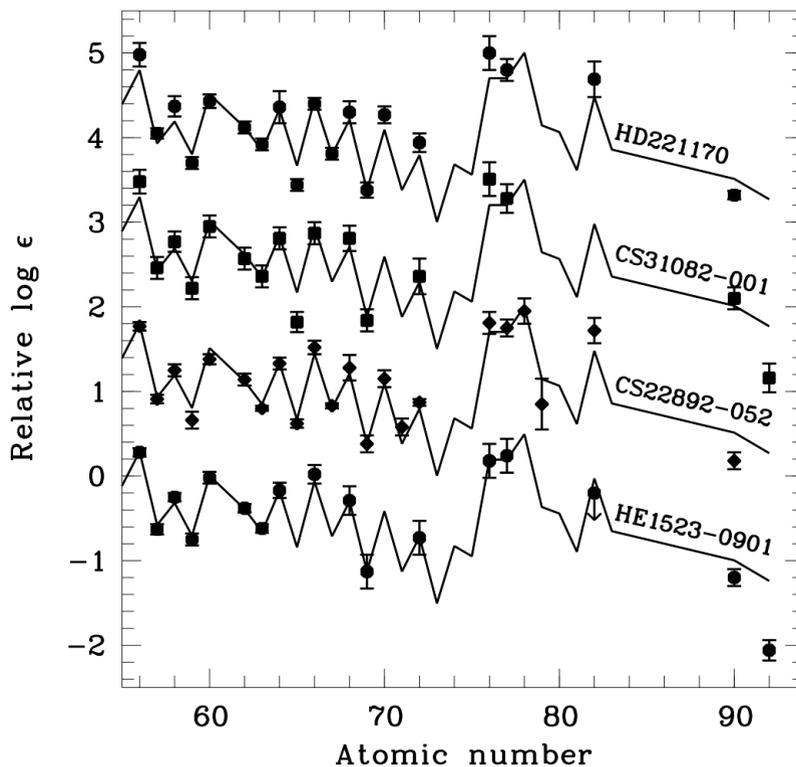
In 1995, a low-mass, metal-poor star, CS 22892-052, was discovered to possess a very high abundance of numerous neutron-capture elements (including the rare earth elements) compared to lighter elements such as iron. Indeed, the star has a metallicity of $[\text{Fe}/\text{H}] \sim -3.0$ (or $\sim 1/1000$ th of the solar iron abundance), but the neutron-capture material is about forty times more abundant. The various neutron-capture elements detected in this star are likely the result of an *r*-process event that took place prior to the star's birth. When the star formed, it inherited the chemical signature of this particular nucleosynthesis event. For the 4.5-billion-year-young sun, which formed from gas enriched by many generations of stars, it is possible to infer how much of each observed element may have been produced by *r*-process events prior to the sun's formation. The resulting solar *r*-process pattern can be compared to that of other, more metal-poor stars. A comparison between the sun and the metal-poor CS 22892-052, for example, revealed that both stars have the exact same relative pattern of neutron-capture abundances (see Figure 2). It appears that at any time and place in the

universe, the *r*-process creates its heavy elements in the exact same ratios, indicating that the *r*-process is a universal process. Since most neutron-capture elements are too heavy to be created and studied in accelerator laboratories on Earth, this has been an important empirical finding based on stellar astronomy.

The elements produced in the *r*-process include thorium and uranium, which are very long-lived radioactive isotopes: ^{232}Th has a half-life of 14 billion years while ^{238}U has a half-life of 4.5 billion years (they are thus decaying very slowly and are near-stable on Earth). Measuring thorium and uranium abundance in metal-poor stars whose birth gas cloud was enriched by only one or few supernova events enables astronomers to carry out cosmochronometry: dating the oldest stars with a method analogous to dating archaeological finds through radiocarbon analysis. In the latter technique, the initial ratio of ^{12}C (the typical stable form of carbon) to ^{14}C (an unstable isotope) must be estimated and then compared to the ratio at the time of discovery. Cosmochronometry requires astronomers to know the initial amount of the heaviest elements, which were presumably produced together in a massive supernova explosion (obtaining such information is extremely challenging, but detailed calculations of *r*-process nucleosynthesis have yielded estimates). The estimated initial ratios of unstable and stable rare earth elements (such as thorium to europium, uranium to osmium, and thorium to uranium) can then be compared with the currently observed ratios, and the degree of decay of the unstable isotopes thus provides the age of the star.

While thorium is often detectable, uranium poses a great challenge. Only one extremely weak absorption line of uranium is available in the optical spectrum, making its detection difficult, if not impossible,

Figure 2
Elemental Abundances in Four Metal-Poor Stars with a Relative Overabundance of *r*-Process Elements (Various Symbols) Compared with the Scaled Solar *r*-Process Pattern (Solid Line)



All patterns are arbitrarily offset to allow a visual comparison. Note the remarkable agreement of the metal-poor star pattern and that of the sun for elements heavier than barium ($Z \geq 56$). Source: Anna Frebel and John E. Norris, "Metal-Poor Stars and the Chemical Enrichment of the Universe," in *Planets, Stars and Stellar Systems*, vol. 5, ed. Gerard Gilmore (Amsterdam: Springer, 2012), doi:10.1007/978-94-007-5612-0_3.

in most cases. In an ideal scenario, both radioactive elements are detected so that many ratios of the thorium and/or uranium abundance to those of stable rare earth elements can be compared to model predictions for the yields of the *r*-process event. Indeed, several *r*-process metal-poor stars with metallicities of roughly 1/1000th of the solar value were found to be about 14 billion years old. These include HE 1523-0901, which is only the third metal-poor star in which uranium can reliably be detected. Moreover, HE 1523-0901 can be

dated with seven different "cosmic clocks"; that is, abundance ratios containing either thorium or uranium and different rare earth elements. The average age obtained through this analysis is 13.2 billion years; this is consistent with the universe's age of 13.8 billion years, which has been deduced from observations of the cosmic background radiation interpreted with the latest cosmological models. Unfortunately, the range of uncertainty with respect to stellar age is often several billion years. Regardless, cosmo-chronometry

confirms that HE 1523–0901 and all other metal-poor stars are ancient and formed soon after the Big Bang during the early phases of chemical evolution.

Through individual age measurements, metal-poor *r*-process stars provide an independent lower limit for the age of the universe. This makes them vital probes for near-field cosmology. At the same time, given their rich inventory of very heavy, exotic nuclei, these stars also closely connect astrophysics and nuclear physics by acting as a “cosmic lab” for both fields of study.

Recent searches for metal-poor stars have not only focused on the old stellar halo but also on dwarf satellite galaxies orbiting the Milky Way. The ultra-faint dwarf galaxies – whose total luminosities range from 1,000 to 100,000 solar luminosities, making them the dimmest galaxies known – appear to contain almost exclusively metal-poor stars. These systems ran out of gas for additional star formation billions of year ago. Chemical evolution and star formation ceased as a result, and when we observe these systems, we can only see the leftover low-mass stars that are still shining today. They, too, tell us the story of nucleosynthesis and enrichment in the early stages of the universe.⁷ In fact, there are recent indications that these systems are nearly as old as the universe itself: some of them may be among the first galaxies that formed after the Big Bang. Studying these stars thus offers another chance to reconstruct the initial events of element creation within the first stars and their violent explosions, and the subsequent incorporation of this material into next-generation stars. Moreover, the existence of such old satellites may shed light on the existence of metal-poor stars in the halo of the Milky Way. Predating our own galaxy, these halo stars must have come from somewhere; perhaps they orig-

inated from dwarf galaxies when analogous systems were gobbled up by the Milky Way during its assembly process.

Topics like these inspire astronomers to collect additional information about the nature and structure of the galaxy. To chemically characterize the galactic halo in detail, including its streams, substructures, and satellites, wide-angle surveys with large volumes are needed. The Australian SkyMapper Telescope is already mapping the Southern sky. It is optimized for stellar work and is delivering new metal-poor star candidates for which high-resolution spectroscopy will be required. The Chinese LAMOST spectroscopic survey is providing numerous metal-poor candidates in the Northern hemisphere. Studying ever-fainter stars further out in the deep halo of the Milky Way and in far-away dwarf galaxies may become a reality with the light-collecting power of the next generation of optical telescopes, including the Giant Magellan Telescope, the Thirty Meter Telescope, and the European Extremely Large Telescope. These telescopes are currently scheduled for completion around 2020. At this point, only the Giant Magellan Telescope is scheduled to be equipped with the high-resolution spectrograph necessary to study metal-poor stars. Further, GAIA, an astrometric space mission led by the European Space Agency (ESA) that was launched in late 2013, will obtain high-precision astrometry for one billion stars in the galaxy, along with the physical parameters and the chemical composition of many of them. Together, these new data will revolutionize our understanding of the origin, evolution, structure, and dynamics of the Milky Way.

All of these new observations will be accompanied by an increased theoretical understanding of the first stars and galaxies, supernova nucleosynthesis, and the mixing of metals into gas clouds in the early universe, as well as cosmic chemical evo-

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lution. New generations of sophisticated cosmological simulations of galaxy formation and evolution will enable a direct investigation of chemical evolution (in a first-galaxy simulation, for example). Being able to trace the metal production and corresponding spatial distributions will allow astronomers to compare the results with abundance measurements of metal-

poor stars in the Milky Way's satellite dwarf galaxies. This way, studying nucleosynthesis and the products of chemical evolution will reveal whether any of the ultra-faint dwarf galaxies are surviving first galaxies and whether the metal-poor galactic halo was assembled from early analogs of today's dwarf satellites billions of years ago.

ENDNOTES

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