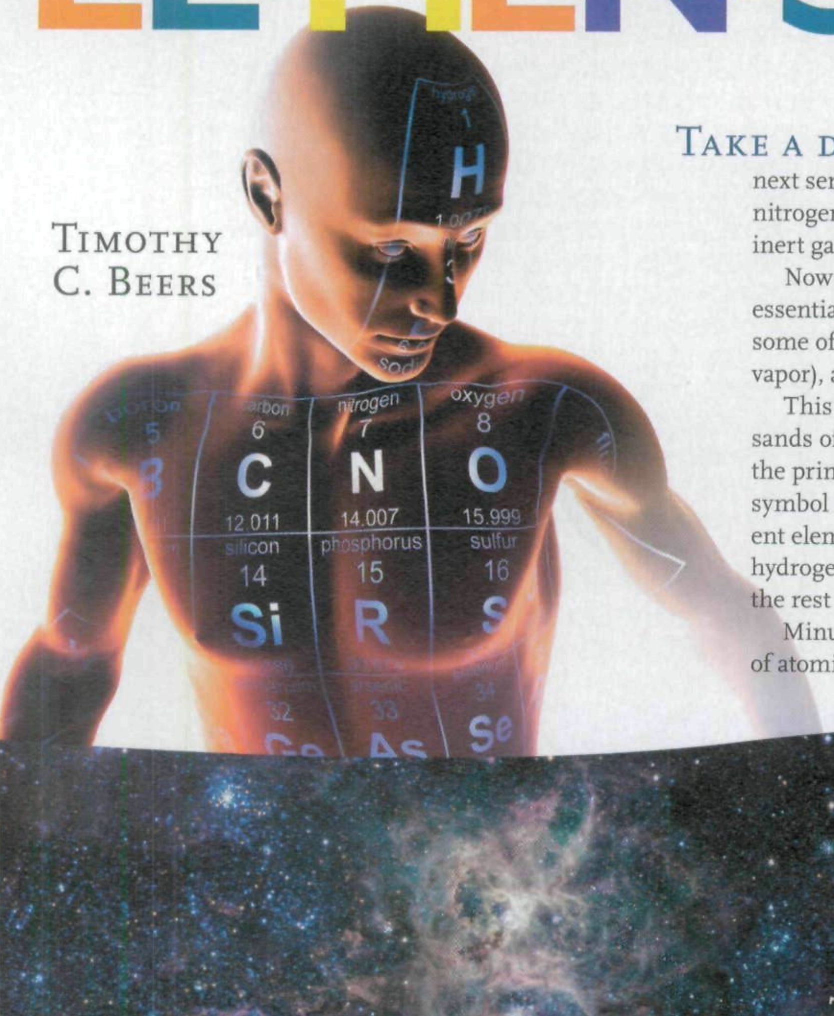
Origin of the ELEMENTS of Life



TIMOTHY C. BEERS

TAKE A DEEP BREATH, and hold it long enough to read the next sentence. You've just provided your body with a large dose of nitrogen (78% by mass) and oxygen (21%), a small amount of the inert gas argon (1%), and a trace of carbon dioxide (0.03%).

Now exhale slowly. You've just provided the atmosphere with essentially all the nitrogen (78%) and argon (1%) you took in, some of the oxygen (16%, most of it bound with hydrogen in water vapor), and a whole lot more carbon dioxide (4%).

This simple experience, repeated unconsciously tens of thousands of times each day, links your body's tissues with three of the primary ingredients of life as we know it: carbon (chemical symbol C), nitrogen (N), and oxygen (O). In terms of its constituent elements, your body's mass is 61% oxygen, 23% carbon, 10% hydrogen, and 3% nitrogen. (To learn about the 3% that makes up the rest of you, see "Where Did You Come From?" on page 32.)

Minutes after the Big Bang, there were basically only two kinds of atomic nuclei in the universe, both in two *isotopes* — varieties

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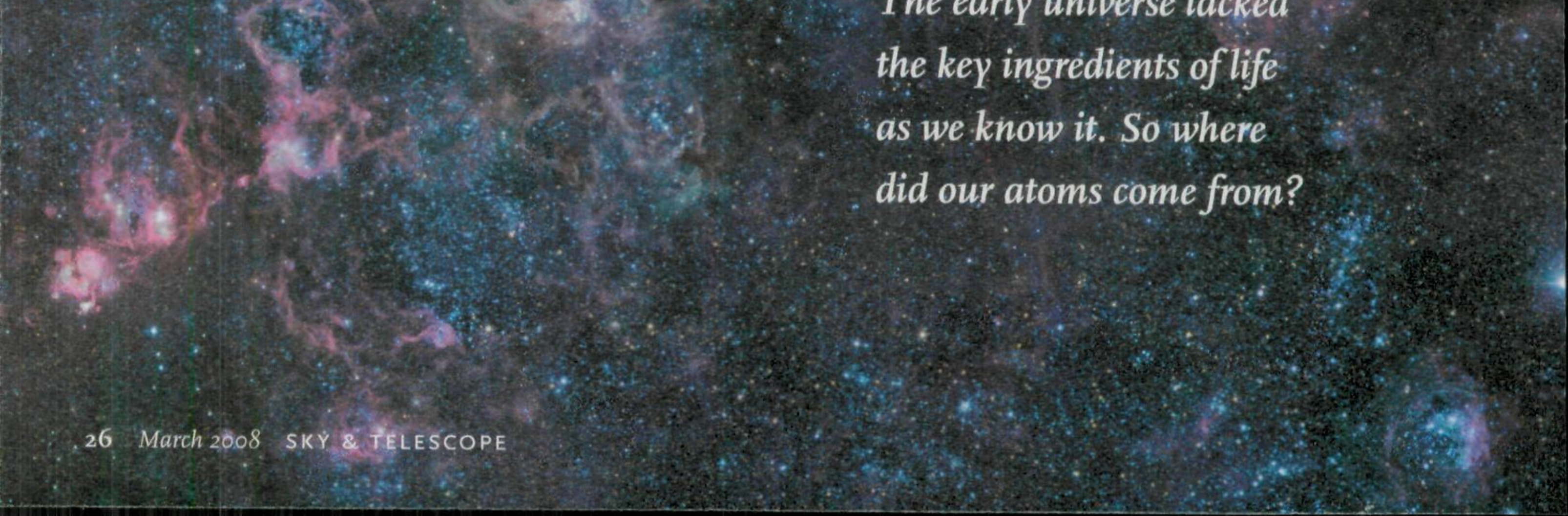


The early universe lacked the key ingredients of life as we know it. So where did our atoms come from?

with equal numbers of protons but different numbers of neutrons. There was normal hydrogen (^{1}H), with just a single proton, and "heavy" hydrogen, or deuterium (^{2}H, often denoted D), with a proton and a neutron. And there was "light" helium (^{3}He), with two protons and one neutron, and normal helium (^{4}He), with two of each.

There were also trace amounts of the next element in the periodic table — lithium, mainly as ^{7}Li — but none of the carbon, oxygen, or nitrogen needed for life. The universe simply thinned out and cooled too quickly for *nucleosynthesis*, the buildup of new elements, to continue.

Some other mechanism had to exist that could achieve high enough pressures and temperatures to form heavier elements. One of the great triumphs of 20th-century astrophysics was the discovery that, aside from the nuclei created in the Big Bang, virtually all the naturally occurring elements in the cosmos — and therefore in us — were forged by stars (*S&T:* August 2007, page 102).

It's clear from stellar-evolution theory and observations of the Sun that our solar system formed from material already enriched with carbon, nitrogen, and oxygen. So to understand where the elements of life arose, we have to look back in time to before the Sun was born. Only then can we begin to assemble a clear picture of the first steps in how you became you.

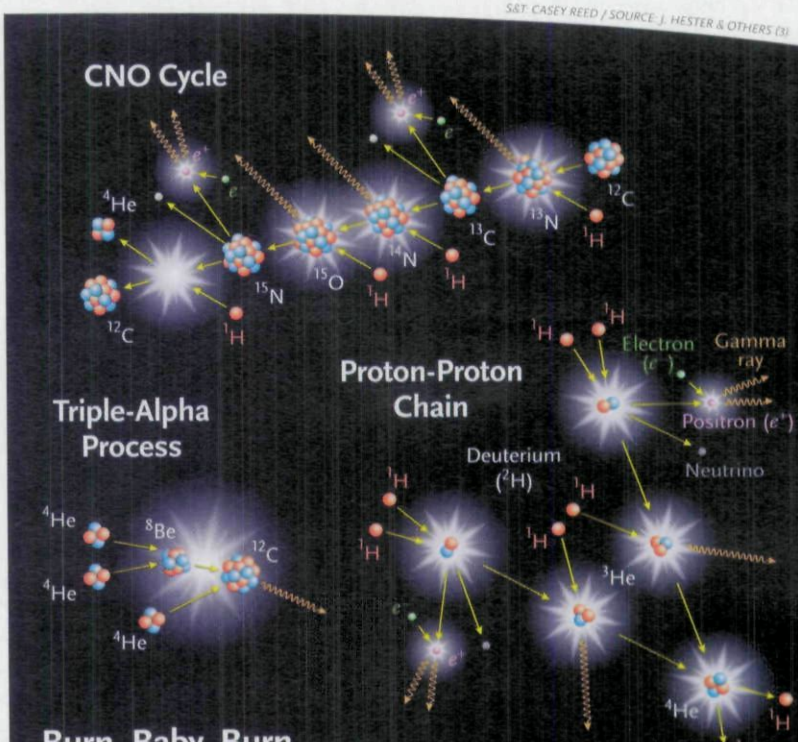
Early Stellar Generations

Computer simulations suggest that when the universe was just a few million years old, vast clouds of the hydrogen and helium created in the Big Bang began to collapse due to their own gravity. These subsequently fragmented into dense clumps that spawned the first stars, a race of giants with masses tens to hundreds of times larger than the Sun's (*S&T:* May 2006, page 30).

Deep inside these behemoths, protons fused to form helium nuclei, adding to the ones produced in the Big

COSMIC KITCHEN The portrait (at left) of the Tarantula Nebula in the Large Magellanic Cloud, a satellite galaxy of our own Milky Way, captures many stages in the life cycles of stars. Hot, young stars — some in sparkling clusters — glow in blue light. Older and cooler stars appear yellow. Irregular wisps of pink nebulosity are the placental clouds of future suns, while discrete ovals are the remnants of massive stars that exploded as supernovae. As stars form, evolve, and die, they cook light elements into heavier ones — including those we need for life.

S&T: CASEY REED / SOURCE: J. HESTER & OTHERS (3)



Burn, Baby, Burn

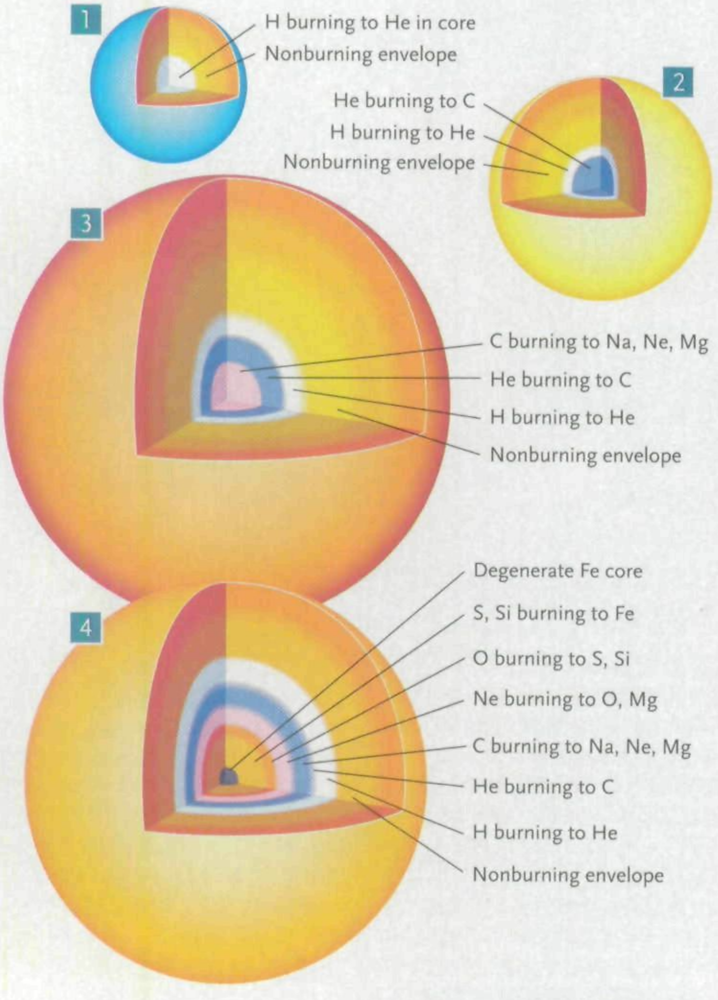
Stars are powered by nuclear fusion: the merging of light elements to form heavier ones under extremely high temperatures and pressures. Often called nuclear burning, fusion releases energy — much of it in the form of gamma rays — that holds a star up against the force of its own gravity.

Stars like the Sun produce most of their energy deep inside via the *proton-proton chain*, the simplest fusion pathway. Pairs of protons (^{1}H) hook up, and one of them converts itself into a neutron to form deuterium (^{2}H). More protons merge with deuterium to produce "light" helium (^{3}He), and pairs of these nuclei — each containing two protons and one neutron, combine to form normal helium (^{4}He), liberating two protons that can serve as fuel for subsequent reactions.

Where conditions are even more hellish, helium nuclei — also known as alpha particles — can be converted into more complex elements, beginning with carbon, via the *triple-alpha process*. Two ^{4}He nuclei fuse to form beryllium (^{8}Be), which is so unstable that it tends to disintegrate in less than a trillionth of a second. But it never gets a chance, because it's immediately struck by another alpha particle to produce a nucleus of carbon (^{12}C), with six protons and six neutrons. Depending on the mass and evolutionary state of the star, it might fuse helium with carbon to make oxygen, helium with oxygen to make neon, and so on to heavier and heavier nuclei.

Another crucial reaction is the *CNO cycle*, through which normal stars more massive than about 1½ Suns produce most of their energy. Here carbon acts as a catalyst in the production of helium and energy through a sequence of proton captures that yields nitrogen and oxygen along the way, as illustrated above. The fusion of ^{14}N and ^{1}H to produce ^{15}O is by far the slowest reaction in this sequence. As a result, the abundance of nitrogen inside these stars tends to build up over time. Eventually it gets blown into space, where it can be incorporated into future generations of stars and planets — and living creatures like us.

PUMPING IRON Many of the chemical elements were forged inside massive stars, which begin life by fusing hydrogen into helium in their cores *(1)*. After exhausting its core hydrogen fuel, a massive star begins burning helium into carbon in its core and hydrogen into helium in a thin layer farther out *(2)*. At the same time, it begins to swell into a red giant. As the star continues to evolve, the ash of one reaction becomes the fuel for the next, and the star — now pulsating as it adjusts to each new source of energy — becomes layered like an onion *(3)*. The process ends when the core, shown vastly exaggerated in relative size here, burns into iron *(4)*.



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A WEIGHTY SUBJECT

How a star evolves depends first and foremost on its mass. More massive stars have stronger gravity pressing inward, so they have to burn their nuclear fuel more furiously to generate enough energy to hold themselves up. As a result, the more massive the star, the faster it evolves and the sooner it burns itself out. Stars like the Sun shine for more than 10 billion years. But stars just a few times more massive, like Vega in the constellation Lyra, shine for only a few hundred million years.

Bang itself. But massive stars live fast and die young, going out in a blaze of glory. Before the first stars could achieve the temperatures required to trigger the fusion of helium into still heavier elements, they disintegrated in catastrophes similar to what we observe today as supernovae, only much more energetic.

The explosive deaths of the first stars produced the highest temperatures and pressures seen since the Big Bang. These conditions surely ignited the fusion of some helium into oxygen and perhaps other heavy elements, adding new squares to the infant universe's periodic table. But those early stars were relatively few in number, so they enriched the cosmos only slightly. It was enough, though, to alter the chemistry and physics of starbirth so that future stars would form with masses more like what we observe around us today: from less than 1 Sun's worth up to perhaps 50 to 80 Suns.

The next stellar generations incorporated the extra helium and other debris blasted into space by the short-lived first-generation stars. Inside these slightly enriched new stars, temperatures could reach 100,000,000° C or more, and stable helium fusion could take place. For the first time in the history of the universe, carbon (with six protons and six neutrons) began to appear in significant amounts. It was forged from trios of helium nuclei by the so-called *triple-alpha process*, illustrated in the box on the previous page.

Once a star is synthesizing carbon, it doesn't take a lot more heat and pressure to generate oxygen (eight protons and eight neutrons) by adding another helium nucleus. Still more oxygen is produced when the most massive of these stars explode as supernovae.

What about nitrogen? Even though it's lighter than oxygen (with one less proton and neutron), it forms in stars at a slower rate via a reaction sequence called the *CNO cycle*, also described on the previous page. Thus its cosmic concentration builds up only gradually.

Most of the nitrogen in the universe was probably contributed by intermediate-mass stars (those of about 1 to 8 solar masses), where the CNO cycle predominates. In their turbulent late stages of evolution, when they're called asymptotic giant branch (AGB) stars, these objects dredge up large amounts of nitrogen from their interiors and blow it into space via energetic winds.

Star Witnesses

Having laid out the basic pathways for the origin of carbon, oxygen, and nitrogen, let's ask where and when conditions were just right for these elements of life to appear for the first time. It's like an elaborate detective game where we already know who the culprits are, but we need to find their hideouts and deduce the timelines of the execution of their crafty plans.

This forensic astronomy begins with the search for clues that might still be available from the early epochs

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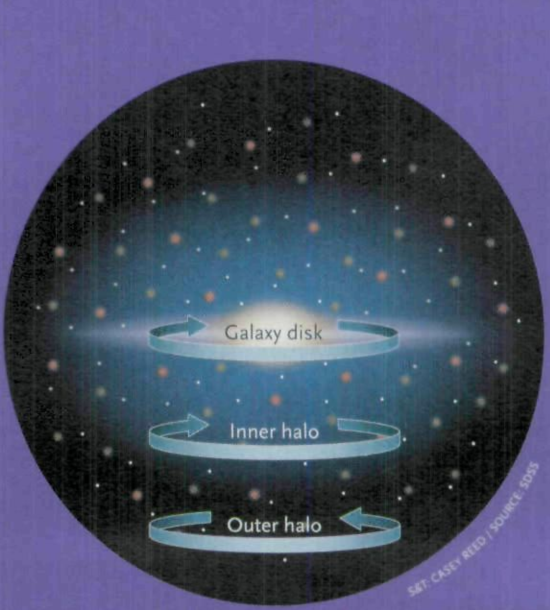
Learn more about the SEGUE project at www.sdss.org/dr6/start/aboutsegue.html.

SKY SURVEYOR This odd-looking device is the 2.5-meter (98-inch) telescope of the Sloan Digital Sky Survey (SDSS) at Apache Point, New Mexico. A real workhorse, it has recorded images and spectra of stars, galaxies, and quasars by the millions. When not in use, it's protected by a shed that rolls into place on rails.



S&T: CASEY REED / SOURCE: SDSS

A New View of the Milky Way's Halo

For the past six years, astronomers with the Sloan Digital Sky Survey (SDSS) have been systematically measuring the brightnesses and colors of stars, galaxies, and quasars. They've compiled the world's largest body of such data, now encompassing more than 200 million objects over nearly half the northern sky. The project has also acquired medium-resolution spectra for more than 1.2 million objects.

The original survey, now known as SDSS-I, formally came to an end in July 2005. Since then SDSS scientists have continued their journey of discovery with the first extension of the survey, known as SDSS-II. This is scheduled to run through July 2008 and includes a project called SEGUE, the Sloan Extension for Galactic Understanding and Exploration. It's the first dedicated SDSS effort to collect spectroscopy for a large number of stars in the Milky Way's disk and halo. Among other things, SEGUE has already determined the metallicities of more than 200,000 stars. That's by far the largest such data set ever assembled in the history of stellar astronomy — and it's still growing.

Large surveys always yield surprises, and this one's no exception. The SDSS-II team, with members in Japan, Australia, Italy, and the US, reported something unexpected in the December 13, 2007, issue of *Nature:* our galaxy's halo contains two chemically and dynamically distinct stellar populations.

In the somewhat flattened inner halo, out to about 50,000 light-years from the galactic center, stars on average rotate in the same sense as the disk and spiral arms. In the more spheroidal outer halo, beyond 65,000 light-years or so, they tend to move in the opposite direction, and about twice as fast. Stars in the outer halo also have substantially lower heavy-element abundances than those in the inner halo.

All this suggests that the halo was assembled from multiple components as the nascent Milky Way collided with smaller star systems, tearing them apart and dispersing their stars. But the most likely sequence of events is hard to pin down.

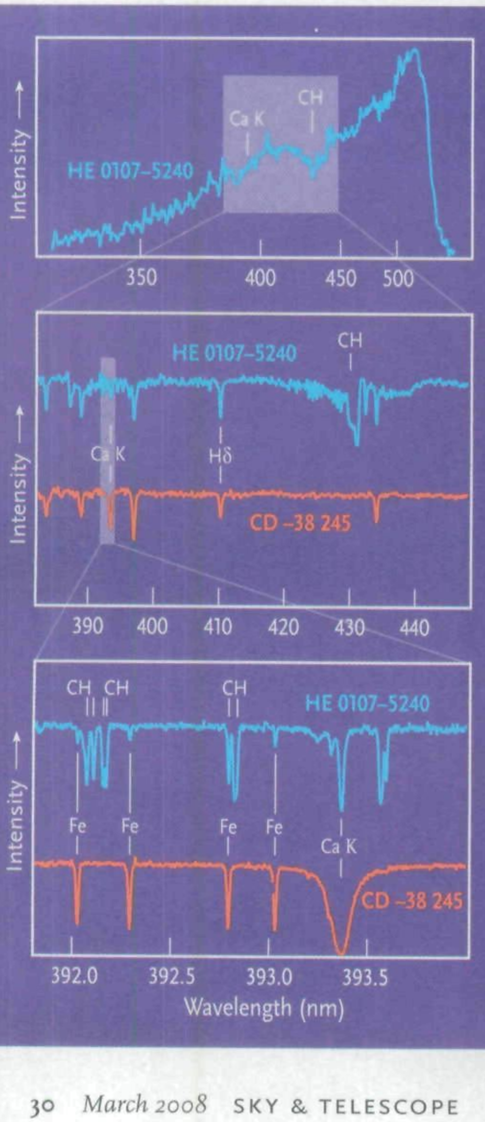
The dual nature of the halo was determined from measurements of 20,000 stars. SEGUE will extend that data set by a factor of 10 or more. This means there are bound to be more surprises in store!

when all the action was taking place. Unfortunately, the first generations of massive stars burned out quickly, so no matter how diligently we might look for them, we have no hope of finding any.

By contrast, stars with masses of 0.8 Sun or less can shine for more than 13.7 billion years — longer than the universe itself has been here. Did significant numbers of low-mass stars form at the time when C, N, and O were first produced in the universe? If so, they should still be around, and they should exhibit the element-abundance patterns they inherited from the relative handful of stellar generations that preceded them.

Specifically, these stars should have a paucity of heavy elements, such as iron (Fe), that require many stellar life cycles to form in substantial amounts. Astronomers often refer to such atoms — everything beyond hydrogen and helium — as "metals," and to a star's concentration of them, compared with the Sun's, as its *metallicity*.

The challenge, then, is to find these witnesses to the emergence of the elements of life in the early universe: the low-mass, low-metallicity stars.



Zeroing In

Finding the lowest-metallicity stars in the galaxy requires a multistep procedure. The top panel shows a low-resolution spectrum of one candidate, HE 0107-5240, selected from the Hamburg/ESO objective-prism survey. It's a cool, low-mass star, as evidenced by the presence of the CH molecule in its atmosphere. The so-called K absorption line from ionized calcium (Ca), often quite prominent, is undetectable, suggesting that the star's overall heavy-element abundance is very low.

The middle panel shows a medium-resolution spectrum of the same star from the 2.3-meter (90-inch) telescope at Siding Spring Observatory in Australia. It resolves the Ca K feature but confirms that it is indeed quite weak as compared with the same line in another metal-poor star, CD –38 245.

The bottom panel shows high-resolution spectra of both stars from one of the 8-meter reflectors of Europe's Very Large Telescope in Chile. Not only is there little calcium in HE 0107-5240, but now it's also clear that the star contains only a minuscule amount of iron (Fe). This object turns out to be one of the most metal-poor stars known in our galaxy.

S&T: CASEY REED / SOURCE: T. BEERS & N. CHRISTLIEB

Finding the Metal-Poor Stars

These stars do exist, but they're quite rare. Most are in the Milky Way's halo, the vast spheroid of stars and globular clusters that predates the formation of our galaxy's disk and spiral arms.

If we had to examine these faint, distant stars one at a time to find the most metal-poor examples, it'd be painfully slow going. A more effective search strategy is the objective-prism survey.

In this technique, usually used on small telescopes, a photographic plate or large CCD camera records low-resolution spectra of thousands of halo stars at once. It's easy to pick out spectra where normally strong heavy-element absorption features are weak or nonexistent.

The next step is to obtain moderate-resolution spectra of these candidates using a bigger telescope. Any stars that still show few signs of metals can then be examined using one of the world's largest telescopes and a state-of-the-art spectrograph. Only with the utmost in sensitivity and resolution can we finally read the testimony of a truly metal-poor star.

Astronomers usually cite a star's metallicity relative to the Sun's using a logarithmic scale, often in terms of the relative abundance of iron. So, for example, if a star has 10% of the proportion of metals that the Sun does, its heavy-element abundance could be written as [Fe/H] = –1.0, where –1.0 is the base-10 logarithm of 0.10.

Until recently, two major prism surveys had unearthed most of the stars known to have metallicities below 1% of solar (that is, [Fe/H] < –2.0): the HK survey by the author and his colleagues, and the Hamburg/ESO Survey (HES) led by Norbert Christlieb.

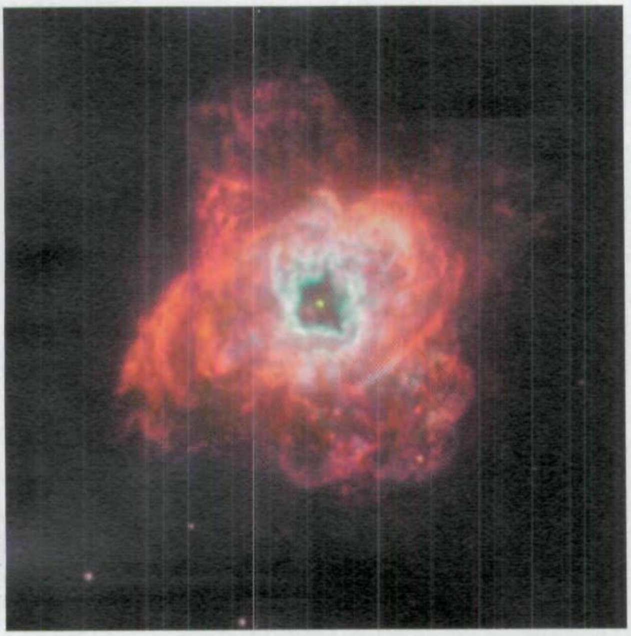
These efforts have identified more than 2,000 stars with [Fe/H] < –2.0, hundreds with [Fe/H] < –3.0, and a few with [Fe/H] < –4.0. The HES has found two stars with iron abundances approaching a millionth of the Sun's!

Over the past several years, astronomers working with the Sloan Digital Sky Survey (see page 29) have identified likely low-metallicity stars in SDSS images and obtained moderate-resolution spectra for them using an instrument capable of observing up to 640 stars at once. Not surprisingly, this approach has already surpassed the previous harvest of metal-poor stars by a factor of three.

An Embarrassment of Riches

Among the surprises from the HK and HES efforts is the discovery that about 20% of stars with less than 1% of the Sun's heavy-element abundance have anomalously large amounts of carbon in their atmospheres, relative to what you'd expect based on their iron content.

These *carbon-enhanced metal-poor* (CEMP) stars have from 10 to 10,000 times the Sun's ratio of carbon to iron. Often their nitrogen and oxygen fractions are greatly enhanced too — again, relative to their iron abundances. The early universe apparently was able to produce more



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

CAST AWAY How do the elements produced inside stars get dispersed into space, where they can make their way into the next stellar generation? One way is via the creation of a planetary nebula, in which an evolved intermediate-mass star gently sheds its outer layers. The planetary shown here is NGC 5315, about 7,000 light-years away in the southern constellation Circinus.

carbon, nitrogen, and oxygen than we thought!

The observed fraction of CEMP stars increases as metallicity decreases. For example, a 2005 study by the author and Christlieb found that about 40% of all stars with [Fe/H] < –3.5 are carbon-enhanced. All three known stars with [Fe/H] < –4.0 are CEMP stars.

These results are probably no coincidence. More likely, the different amounts of C, N, and O enhancement are associated with the particular astrophysical sites of these elements' manufacture.

The largest category of carbon-enhanced stars is called CEMP-s. These objects exhibit the spectral signatures of heavy elements produced by slow neutron capture. Called the *s-process* and explained more fully in the article on page 32, it occurs, for example, in intermediate-mass AGB stars at the end of their lives.

Because such stars evolve over tens of millions to at most a few billion years, the ones that produced the heavy elements we're seeing in the CEMP-s stars died and faded away long ago. Does this mean the trail has gone cold?

Not at all! Many of the long-gone AGB stars left their fingerprints behind by transferring their enriched outer envelopes onto low-mass binary companions. These long-lived stars are still around to give evidence about the formation of C, N, O, and s-process elements in their now-departed neighbors.

You can learn more than you probably want to know about every type of atom in the universe using an interactive periodic table of the elements. Here's one of the most popular: www.webelements.com.

The oddest of the carbon-enhanced metal-poor stars are the ones classified as CEMP-no. As the name suggests, these stars exhibit no evidence of neutron-capture elements. This is strange, because the synthesis of C, N, and O by AGB stars is thought always to be accompanied by the creation of s-process nuclei.

CEMP-no stars are usually found among the very lowest-metallicity stars, those having [Fe/H] < –2.7, less than 0.2% of the solar value. Perhaps the s-process simply doesn't work at such low metallicities.

Another possibility is that the CEMP-no stars hark back to the early population of ultralow-metallicity massive stars. If the effects of rapid rotation are included in models of these first-generation powerhouses, then the lowest-metallicity examples undergo mixing and rare fusion processes that produce lots of C, N, and O without any accompanying neutron-capture elements — just what the doctor ordered!

The heavy elements created inside such tumultuous stars are rapidly transported to their surfaces, where they get blown into space by strong stellar winds. Long after these massive stars died out, any low-mass stars that formed from the gas they enriched could still be around to tell their story. Are these the CEMP-no stars? We'll likely find out as we delve deeper into their testimony.

Abundances in Abundance

Slowly but surely, we're coming to understand the processes and environments that first spawned the vital elements of life in the cosmos. The discovery of the objects that provide the best evidence has really only begun — the vast majority of CEMP stars identified to date have been found in just the past 10 years.

Ambitious new surveys like SEGUE (page 29) promise to find thousands more metal-poor stars in the coming years. Such large samples are of the utmost importance, as they'll likely probe all possible outcomes of all the various element-production scenarios that took place in the early universe.

OVER THE RAINBOW

A stellar spectrum is obtained by using a prism or grating to spread the star's light into its component colors, much as cloud droplets disperse sunlight into a rainbow. Spectra are often presented as graphs of brightness versus wavelength, as in this article. The graph is notched at wavelengths where atoms, ions, or molecules near the star's surface absorb light generated deep in the interior — and these wiggles tell what the star is made of.

Blessed with this abundance of new information, and with the parallel development of ever more robust theories that can be tested with these data, astronomers will finally be able to tell a coherent tale of how, when, and where the elements that made life possible came to be. ✦

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