REVIEW

Populating the periodic table: Nucleosynthesis of the elements

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Elements heavier than helium are produced in the lives and deaths of stars. This Review discusses when and how the process of nucleosynthesis made elements. High-mass stars fuse elements much faster, fuse heavier nuclei, and die more catastrophically than low-mass stars. The explosions of high-mass stars as supernovae release elements into their surroundings. Supernovae can leave behind neutron stars, which may later merge to produce additional heavy elements. Dying low-mass stars throw off their enriched outer layers, leaving behind white dwarfs. These white dwarfs may also later merge and synthesize elements as well. Because these processes occur on different time scales and produce a different pattern of elements, the composition of the Universe changes over time as stars populate the periodic table.

In the 15 min after the Big Bang, the Universe produced the first chemical elements: hydrogen, helium, and trace amounts of lithium (*1*). When the Universe contained just the Big Bang elements, very little chemistry could occur, and no complex molecules were produced. Almost 14 billion years later, 2% of the hydrogen and helium in the Galaxy has been transformed into the wide array of elements on the periodic table (*2*, *3*). This transformation of the Universe's composition is a prerequisite for complex chemistry and, ultimately, biology.

The process of producing new elements is called nucleosynthesis. Stars are responsible for the nucleosynthesis beyond helium (*4*). There is a qualitative difference between Big Bang nucleosynthesis, which is confined to the first few minutes when the entire Universe was hot enough to participate, and the slow but steady contributions of stellar nucleosynthesis over billions of years. Astronomers therefore use a single term for all elements heavier than helium: metals. This terminology is perhaps not ideal because it includes elements such as chlorine, neon, and argon as well as iron, copper, and gold. The metallicity of a star is the proportion of metals to hydrogen in its atmosphere. For most types of star, this reflects the composition of the gas from which it formed.

Some forms of nucleosynthesis, such as the fusion of hydrogen into helium, provide the energy that keeps the star from collapsing and generate its luminosity. Others do not, such as the transformation of gold into mercury by adding a neutron. Some elements, once fused, remain locked in the dead cores of stars and are not released into the surrounding galaxy. In this Review, we concentrate on the nuclei that are expelled from stars, enriching the surrounding gas, where it can be incorporated into the next generation of stars. Over the past century, astronomers have shown that the Universe's composition changes with time. The periodic table shown in Fig. 1 summarizes the origin of the elements in the Solar System that we see today.

The Big Bang

Big Bang nucleosynthesis occurred in the presence of copious amounts of free neutrons, produced in collisions between high-energy protons and electrons when the Universe was at a temperature of 10 billion K (*5*). When the temperature of the Universe fell to 1 billion K, those free neutrons fused easily with protons to make deuterium (^{2}H). Two deuterium nuclei quickly combined to make helium (^{4}He). Side reactions between protons, neutrons, ^{3}He, and ^{4}He produced some ^{7}Li, but nucleosythesis did not proceed to heavier elements because the expanding Universe was cooling rapidly, halting fusion. In addition, the free neutrons were decaying. Free neutrons are radioactively unstable; any that are not bound into nuclei with protons decay into a proton, electron, and antineutrino with a half-life of just over 10 min (*6*, *7*). Therefore, a mixture of only hydrogen and helium was available to make the first stars.

> ***"…2% of the hydrogen and helium in the Galaxy has been transformed into the wide array of elements on the periodic table."***

The first stars

The first star formed ~100 million years after the Big Bang (*8*, *9*). Before this time, gas was not cold enough for gravity to overcome thermal pressure and collapse the gas into stars. The formation of the first stars is unlike that of all other stars. Because the gas composition reflects Big Bang nucleosynthesis, it is devoid of carbon and oxygen. Today, those elements allow gas to radiate heat away through atomic and molecular transitions, cooling it to ~10 K, the temperature observed in nearby star-forming regions. In the early Universe, the lack of metals and their associated cooling means that gas can only reach ~100 K. The higher thermal pressure requires gas clumps to have larger mass before they collapse into stars. This was the only period in the Universe's history that overwhelmingly favored the production of stars more massive than the Sun (*10*). This has consequences for the composition of the Universe because the lifetime, nucleosynthesis, and ultimate fate of stars is determined mainly by their mass.

The gravitational collapse of gas into a star releases a large amount of potential energy, heating the gas until it is hot enough for the gas pressure to counteract gravity; the star settles into equilibrium. At the temperatures reached in the cores of stars—millions of kelvin—nuclear reactions are possible. When the first stars form, only hydrogen and helium nuclei are available as fuel, with no free neutrons. Fusion in stars therefore proceeds by means of different mechanisms to those that operated during Big Bang nucleosynthesis. Fast-moving protons can overcome the electric repulsion between like charges, getting close enough for the reaction $^1\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + e+ + v_e$ to happen through quantum tunneling (*11*). Because this reaction requires conversion of a proton into a neutron by means of the weak nuclear force, it is unlikely to happen. Direct proton-proton fusion is so slow that it cannot provide enough power to support high-mass stars. Instead, the star contracts and heats up to high-enough temperatures that any helium produced through proton fusion is quickly converted to carbon by further fusion reactions (*12*). Once carbon is present, it acts as a catalyst for the fusion of hydrogen to helium through a series of reactions known as the CNO cycle (for carbon–nitrogen–oxygen) (*13*). This cycle provides enough power to halt the collapse; nitrogen and oxygen are produced as intermediate products.

The conversion of four protons (hydrogen nuclei) into two protons and two neutrons in a helium nucleus increases the neutron:proton ratio by more than any other process in stellar nucleosynthesis. This is a necessary step before heavier nuclei can be produced because they have neutron:proton ratios ≥1. The electromagnetic repulsion between protons means that fusion of hydrogen (informally called hydrogen burning) proceeds slowly, leading to the long lifetimes of stars. Fusion of hydrogen into helium in the core of the star continues until the core's hydrogen is exhausted. Higher-mass stars burn through the hydrogen in their cores more quickly than lower-mass stars, with the larger fuel reserves insufficient to make up for the higher reaction rate. This makes high-mass stars more luminous and shorter-lived than low-mass stars. Hydrogen burning in a 1-solar-mass ($M_\odot$) star lasts 10 billion years; in a 10-$M_\odot$ star, 25 million years; and in a 30-$M_\odot$ star, 6 million years (*14*).

The highest-mass stars among the first generation therefore run out of core hydrogen first.

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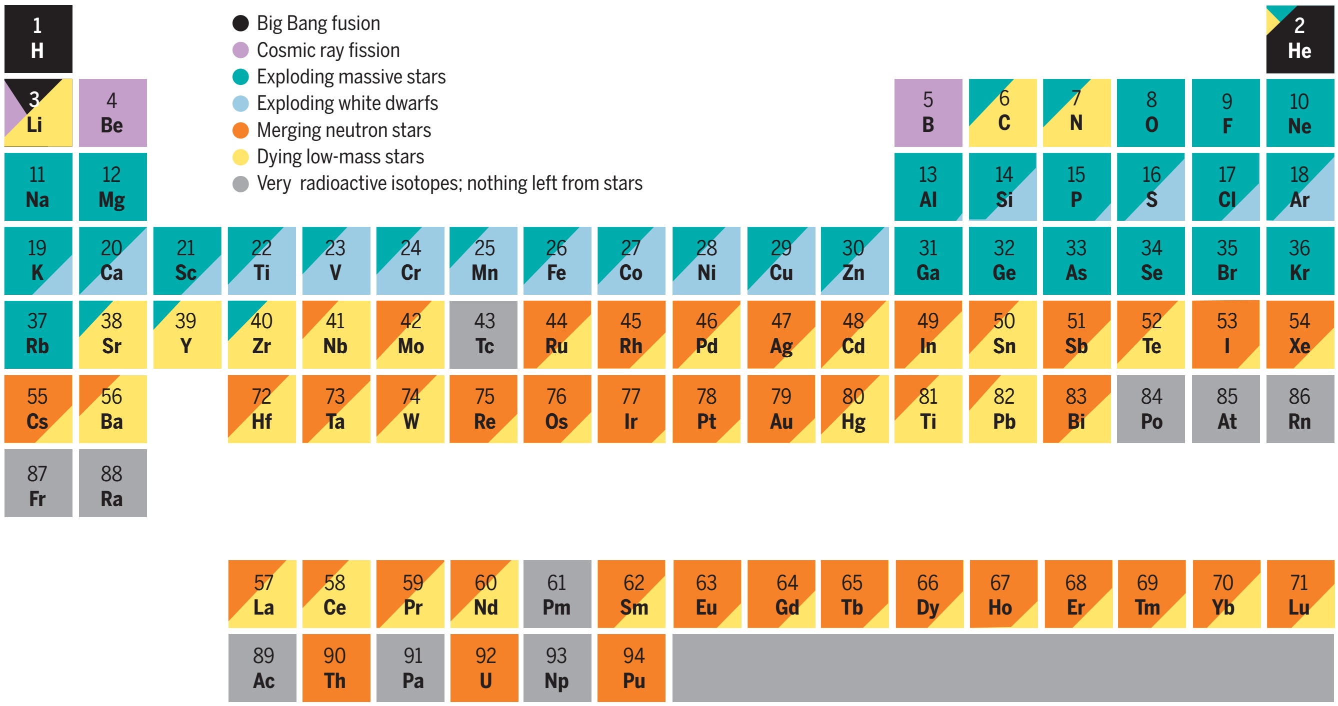
The evolving composition of the Universe

Fig. 1. Nucleosynthetic sources of elements in the Solar System. Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources, scaled to the time of Solar System formation. Only elements that occur naturally in the Solar System are shown; artificially made elements and elements produced only through radioactive decay of long-lived nuclei are shown in gray. The data plotted in this figure are available in table S1.

The exhaustion of fuel means that the core can no longer support its own weight. It contracts and heats up, until helium burning provides enough power to again support the core. This process happens repeatedly, with each contraction halting when the products of the previous cycle begin burning in the core. After hydrogen burning, the fusion proceeds in multiple layers, with different elements burning in a series of shells around the core.

The most massive stars reach the highest core temperatures because they can release the most gravitational potential energy. Stars with masses greater than ~8 $M_\odot$ get hot enough to produce the iron-peak elements, such as iron and nickel. The series of burnings proceed in this order: Hydrogen fuses to helium. Helium ignites at $\sim 10^8$ K, fusing to carbon and oxygen. When carbon ignites, the nuclear reactions become more varied because $^{12}\mathrm{C}+^{12}\mathrm{C}$ not only forms $^{24}\mathrm{Mg}$ but also $^{23}\mathrm{Na}+^{1}\mathrm{H}$, $^{20}\mathrm{Ne}+^{4}\mathrm{He}$, and other related nuclei (*15*). At the next stage, some neon nuclei are ripped apart by energetic photons and react with other $^{20}\mathrm{Ne}$ to produce $^{24}\mathrm{Mg}$. The oxygen left over from helium burning is inert at the temperatures of carbon and neon burning, but at 1 billion K, it too ignites (*11*, *15*). As with carbon burning, the fusion of two oxygen nuclei can lead to several different daughter products, and even more elements are produced from side reactions. After oxygen is exhausted, the core contracts and heats up to 3 billion K, at which point the final set of nuclear reactions during the star's life begins.

The electric repulsion between two silicon nuclei is so large that even at 3 billion K, they cannot get close enough to fuse. Instead, high-energy photons rip particles off existing nuclei, then these lighter particles fuse with silicon, sulfur, and other nuclei to reach the iron peak. The relative abundances of the nuclei produced in silicon burning depend on their nuclear binding energies and the neutron-to-proton ratio (*15*). $^{56}\mathrm{Fe}$ is the most tightly bound of the nuclei produced in this process, so its production is favored, but not exclusively.

Each stage of these burnings takes less time than the previous one because less energy is released per reaction, and more energy is carried away from the core by neutrinos. The reaction rates must be higher to support the star, consuming the available fuel more rapidly. For a 15-$M_\odot$ star, core hydrogen burning millions of years, carbon burning lasts a few thousand years, oxygen burning lasts a few weeks, and silicon burning lasts a few days (*16*). Near the end of its life, the star has a 1.4-$M_\odot$ silicon-burning core surrounded by a series of shells where hydrogen, helium, carbon, neon, and oxygen burning flicker on and off. Each shell (except neon) contains ≥0.5 $M_\odot$ of material that could contribute to the enrichment of the Universe if ejected from the star. Whether that happens depends on how the star dies.

Exploding massive stars

With the end of core silicon burning, the star approaches the "iron catastrophe." Once again no longer able to produce enough fusion power to support itself against gravity, the core initially contracts slowly, but two processes rapidly remove energy from it. First, some iron-peak nuclei absorb high-energy photons and disintegrate. Second, when the temperature reaches 10 billion K, protons and electrons have enough energy to make neutrons, as they did in the Big Bang. What starts as a slow contraction becomes a freefall when the gas pressure plummets far below the amount needed to support the core. As the density of the falling material increases, it briefly exceeds that of an atomic nucleus. The strong nuclear force pushes back against this excessive density, causing the infalling material to bounce back and launching an expanding shock wave. In at least some massive stars, the shock wave, in combination with additional physical effects that are currently under debate (*17*–*19*), causes much of the material beyond the original iron core to be ejected in an explosion of neutrinos, photons, and kinetic energy that we observe as a core-collapse supernova.

These supernovae enrich the Universe in three ways. First, they eject the products of nucleosynthesis built up over the star's lifetime (Fig. 2). Most carbon, oxygen, and magnesium, for example, are made before the core collapse, and the explosion simply distributes these elements into space (*20*). Second, the extreme temperatures and densities caused by the shock wave drive additional nucleosynthesis. In particular, the iron ejected by core-collapse supernovae comes not from the core but from

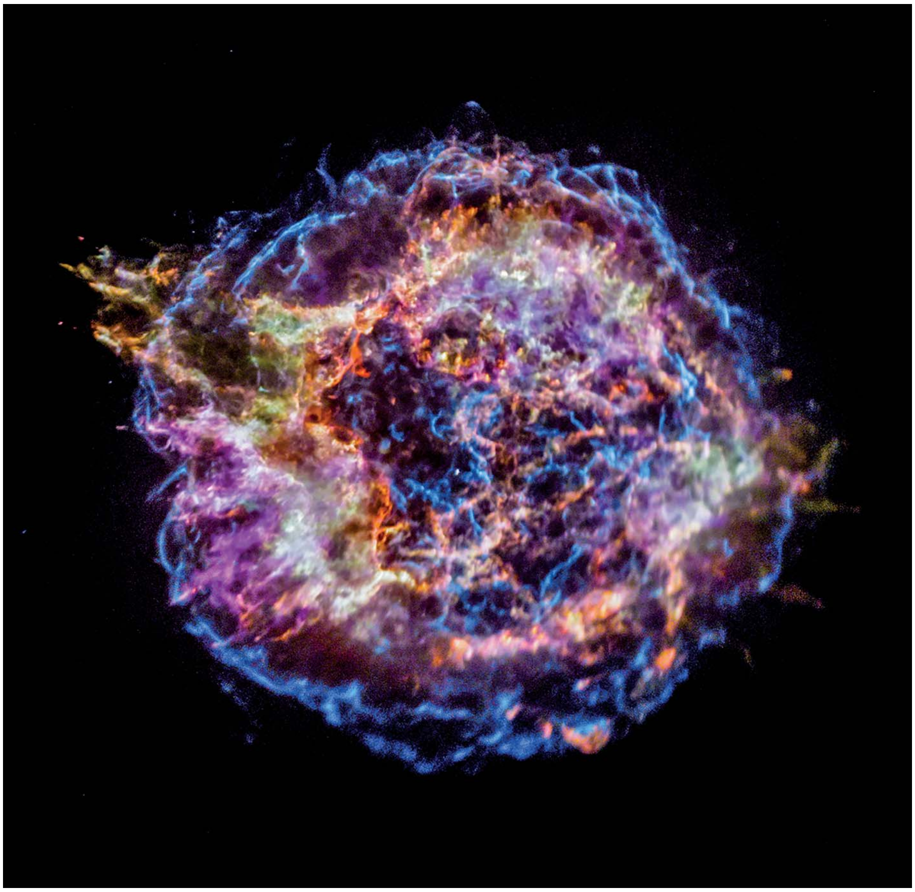

Fig. 2. Nucleosynthesis in a core-collapse supernova. The Cassiopeia A supernova remnant glows with x-ray light emitted by silicon (red), sulfur (yellow), calcium (green), and iron (purple). The boundaries of the blast wave appear blue (*53*).

IMAGE: NASA/CXC/SAO

explosive burning of material in the silicon shell during the supernova. Last, the additional shocks that occur as the ejected material plows into surrounding ambient gas accelerates some particles to close to the speed of light, making cosmic rays (*21*). Cosmic rays are energetic enough to break apart heavier nuclei, producing new elements through fission. This is responsible for large fractions of the lithium, beryllium, and boron seen in the Universe. Cosmic ray fission also produces elements such as carbon and oxygen, but the abundance of those elements is dominated by other modes of production.

In some cases, not enough energy is released to eject the envelope, and a black hole forms (*22*). There will be no large explosion or ejection of material; the star appears to simply disappear (*23*). If there is not enough mass to cause the formation of a black hole, a supernova occurs and leaves behind a neutron star as the remnant of the collapsed core (*22*).

The supernovae of the first generation of stars released the first metals into the Universe. Their presence strongly modified star formation, allowing the formation of low-mass stars that survive for billions of years. Some of those second-generation stars are expected to live long enough that they are still around today, providing a fossil record of the composition of the Universe (Fig. 3). Searching for these stars is a topic of current research (*24*–*26*).

Neutron star mergers

Core-collapse supernovae are spectacular releases of metals but probably do not make every element. The vast majority of elements heavier than nickel are made through various forms of neutron capture. Because neutrons carry no electric charge, they are not repulsed by nuclei, and thus heavier elements can be made at much lower temperatures than occur during silicon burning. After Big Bang nucleosynthesis, neutron capture is not the dominant process in nucleosynthesis because a sufficient flux of free neutrons occurs only in certain situations. At least 100 neutron captures are required to traverse the periodic table from the iron peak to rare earth elements. The production of neutrons in material expelled by a supernova can drive some neutron capture (*27*). However, the majority of neutrons are trapped in the collapsing core and do not participate in nucleosynthesis in the supernova, so it is unclear whether supernovae contribute measurable amounts to elements beyond the iron peak (*28*).

The neutrons in a neutron star can eventually participate in nucleosynthesis. Tidal forces during double–neutron star or neutron star/black hole mergers can pull the neutron star apart, leading to many neutron captures in a few seconds and the ejection of the processed material (*29*). This series of rapid neutron captures, called the *r*-process, produces nuclei with atomic masses beyond 250, but elements beyond plutonium have such short half-lives that none born in stars are present in the Solar System today. Neutron-star mergers are rare events because two massive stars must explode as supernovae, and the remnants form a sufficiently close binary system to merge within the age of the Universe (*30*). As a result, the Solar System abundance of elements formed in the *r*-process is one-millionth that of carbon and oxygen (*2*, *31*).

The emission of gravitational waves by orbiting neutron stars is critical for draining energy from the system and bringing the remnants together. For the closest systems, mergers are possible within ~10 million years after star formation begins (*32*). Therefore, the Universe will be enriched by the *r*-process before the first low-mass stars die and add their contributions.

Dying low-mass stars

Stars less massive than ~8 $M_\odot$ do not experience the iron catastrophe. Before cores of low-mass stars can heat up enough to produce the iron-peak elements, their contraction is halted by degeneracy pressure, a source that is not based on maintaining a high temperature. Degeneracy pressure is an effect of quantum mechanics related to the Pauli exclusion principle. At high-enough densities, the requirement that subatomic particles avoid sharing quantum states means that many particles must have high speeds. In these stars, nucleosynthesis ceases after the production of carbon and oxygen, or sometimes magnesium and neon. These elements are tightly gravitationally bound into a white dwarf, a stellar remnant supported by electron degeneracy pressure. Low-mass stars eject large amounts of helium, carbon, and nitrogen produced in the shell burnings. The process is more gradual than for high-mass stars; the ejection of the stellar envelope lasts more than 100,000 years, compared with a few seconds for a core-collapse supernova. The Sun will gently waft away its envelope, not explode. Stars of 8 $M_\odot$ live for ~30 million years, so nucleosynthesis from these stars appears before the Universe is very old. The lower-mass stars in the second generation enrich the Universe over a period of ~10 billion years (*33*), more than half the Universe's present age.

These low-mass stars cannot burn oxygen or silicon and therefore do not contribute to the iron-peak elements. However, they do make a substantial fraction of the heavier elements in the Universe (Fig. 4). This is possible because the temperatures only need to be high enough for nuclear reactions that release neutrons, not for nuclei with large numbers of charged particles to merge. The released neutrons readily fuse with iron and other seed nuclei formed in previous generations of stars. These reactions do not supply enough energy to support the star; they proceed slowly as a by-product of stellar evolution.

The source of neutrons in dying low-mass stars is atomic nuclei, not the proton-electron collisions at 10 billion K in high-mass stars. A specific series of nuclear reactions must happen to cause a neutron excess and then a free neutron. Dying low-mass stars produce free neutrons in their helium-burning shells because of specific circumstances (*15*, *33*). The outer parts of the star experience convection, moving fresh material from the unburned hydrogen-rich envelope into the helium-burning shell. The presence of ^{4}He, protons, and newly produced ^{12}C in helium-burning temperatures leads to reactions that convert ^{12}C to ^{16}O while releasing a neutron. Neutron-releasing reactions can happen in higher-mass stars as well, but the slower evolution of low-mass stars means that substantially more neutrons per seed nucleus are available. Convection also causes low-mass stars to release some nitrogen and lithium (Fig. 1) because convection brings these nuclei to the cooler surface, preventing these elements from being burned into other nuclei (*33*).

Neutron-star mergers and dying low-mass stars do not make heavy elements in equal proportions (Fig. 1). Most xenon is produced in neutron-star mergers, whereas lead is primarily from low-mass stars. In the *r*-process, neutron captures proceed more rapidly than radioactive decay. Only when nuclei are close to the neutron-drip line do they cease capturing additional neutrons. The most abundant atomic masses produced by the *r*-process are therefore those with small neutron-capture reaction rates near the neutron-drip line. In dying low-mass stars, a seed nucleus typically captures a neutron every few weeks to months (*34*). If a neutron capture produces an unstable nucleus, radioactive β-decay of a neutron to a proton will usually happen before the next neutron capture. This slow neutron-capture process (*s*-process) therefore produces nuclei close to the valley of β-stability, preferring almost-stable nuclei with small neutron-capture reaction rates. The *r*- and the *s*-processes therefore favor nuclei with very different proton-to-neutron ratios. When the unstable nuclei produced in the *r*-process subsequently decay, the abundance of elements in the Solar System from the two processes differ in atomic mass (*4*).

The actinide elements (Fig. 1, bottom row) have no contribution from the *s*-process. This is because the gradual build-up to ever heavier nuclei is halted by the nearly stable nucleus ^{210}Bi (atomic number 83), which decays by releasing a helium nucleus, not an electron (*15*). Although subsequent neutron captures can build back up to ^{210}Bi, the *s*-process never reaches thorium and uranium.

Because of the longer lifetimes of lower-mass stars, their nucleosynthesis products are only released when stars just below the mass required for core collapse reach the end of their lives. The first contributions appear when stars of 8 $M_\odot$ die 30 million years after the first core-collapse supernovae. However, the total contribution of all low-mass stars is negligible until ~1 billion years after star formation begins (*35*). Their lower masses mean that each star enriches the Universe with fewer metals than do high-mass stars. However, after the first generation there are many more low-mass stars than high-mass stars (*11*), so their collective contribution substantially populates the periodic table.

Exploding white dwarfs

White dwarfs that form in close binary systems, like binary neutron stars do, can be the sites of additional nucleosynthesis. Their individual evolution was halted by electron degeneracy pressure, preventing the release of additional gravitational potential energy to heat the gas and ignite additional burning. However, if an additional energy source can be supplied by transferring mass from the white dwarf's binary companion, then the carbon and oxygen can explosively burn all the way to the iron peak (*36*). The details of how this process occurs are the subject of current research, and it appears that multiple mechanisms contribute (*37*–*39*). In one model, helium deposited on the surface can start to burn and detonate the whole white dwarf. A more energetic event occurs if enough additional material, either from a normal star or another white dwarf, adds enough mass that the white dwarf exceeds the Chandrasekhar limit (*40*), the maximum mass that can be supported by electron degeneracy pressure. The white dwarf then collapses, releasing enough additional energy to restart fusion.

Whatever the ignition source, the carbon and oxygen burn to produce nuclei from silicon to the iron peak. This nucleosynthesis takes just a few seconds, explosively destroying the white dwarf as a type Ia supernova and ejecting its entire mass into the surrounding galaxy. Because this type of supernova does not produce free neutrons, they do not synthesize any elements beyond the iron peak.

Type Ia supernovae require first the complete evolution of a low-mass star to produce the white dwarf, followed by either mass transfer or spiraling together through release of gravitational waves. They are the last nucleosynthesis event to contribute to the composition of the Solar System. The death of 8-$M_\odot$ stars after 30 million years provides the first opportunity for white dwarfs to appear. Although in extremely rare cases such a white dwarf might quickly accrete enough material to exceed the Chandrasekhar mass, a more realistic calculation shows that exploding white dwarfs contribute substantial amounts of material after 1 billion years (*35*). At that stage, the Universe has experienced all the major sources of nucleosynthesis. However, the relative importance of the different sites and the absolute amount of gas in metals continues to change.

The evolving composition of the Universe

Once star formation starts, the periodic table is rapidly populated because core-collapse supernovae and merging neutron stars probably make all elements (but not all isotopes) between them. The short delay between the first core-collapse supernovae and the first neutron-star mergers means that the Universe contains

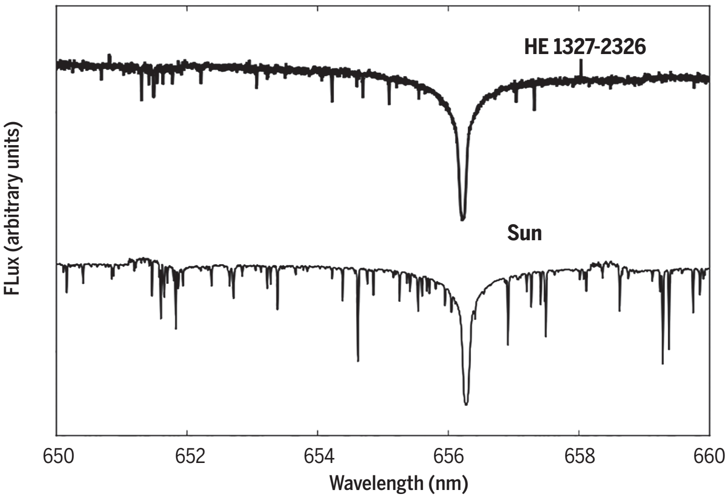

Fig. 3. The record of nucleosynthesis from the first stars. The star HE 1327-2326 has an atmosphere that is extremely deficient in most metals (*52*). It is close to Big Bang composition, but with enhanced carbon and oxygen. The low metallicity of this star can be seen by comparing its spectrum with that of the Sun, around the hydrogen-α absorption line at 656.3 nm. HE 1327-2326 has considerably fewer absorption lines from atoms other than hydrogen. Its atmosphere has less than 1/100,000th of the Sun's abundance of iron. No stars with only hydrogen and helium in their atmospheres have been found, suggesting that no low-mass, long-lived stars were produced in the first generation of star formation.

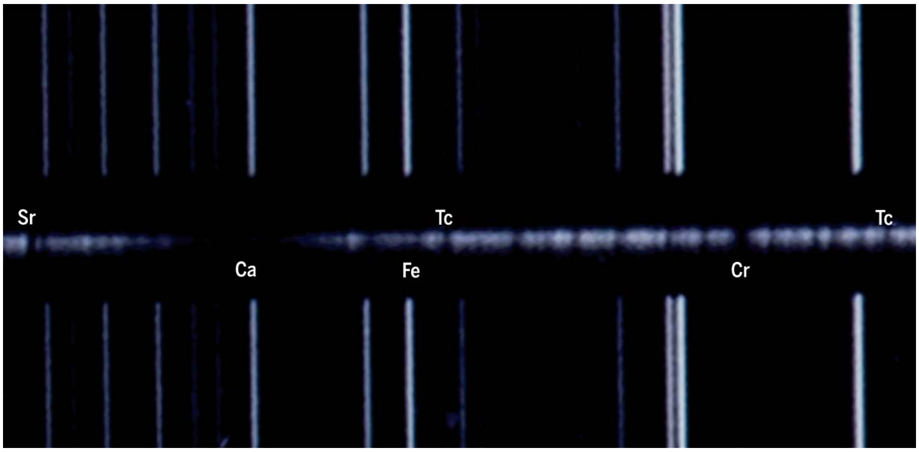

Fig. 4. Discovery of technetium in a dying low-mass star. Part of a 1951 photographic plate showing the spectrum of R Gemini, a star that has the radioactive element technetium (Tc; atomic number 43) in its atmosphere (*54*). The absorption due to technetium atoms as well as a few other elements are labeled. The bright lines above and below the spectrum are from a calibration lamp used to determine the wavelength scale. The discovery of technetium, whose longest-lived isotope has a half-life of 211,000 years, in the atmosphere of a low-mass star that lives for over a billion years is compelling evidence that R Gemini must have synthesized technetium in its interior and dredged it up to the surface through convection.

IMAGE: CYNTHIA HUNT (CARNEGIE OBSERVATORIES)

many stars whose composition reflects gas enriched by core collapse supernovae and neutron-stars but not dying low-mass stars and white dwarfs (Fig. 3) (*41*). The later contributions from low-mass stars and exploding white dwarfs alter the ratios of the elements, increasing the amount of iron as compared with magnesium, for example. As the mean metallicity of the gas increases, planet formation becomes more likely, at least for giant planets (*42*). The relative ratios of the elements that make rocky planets (O, Mg, Si, and Fe) determine the planet's mineralogy and internal structure, with implications for their geophysical properties (*43*). The existence of the Solar System demonstrates that it has been possible to produce Earth-like planets for at least the past 4.5 billion years.

Eventually, the Universe will exhaust its cold gas reservoirs (*44*). Present-day elliptical galaxies give us a preview of how all galaxies will look once star formation ceases. Not all avenues of nucleosynthesis are shut off; white dwarfs still explode, and low-mass stars still waft away their envelopes. However, the Universe will steadily become depleted in all but the lowest-mass stars, whose nucleosynthesis contributions are negligible because of their very low masses. By 10 trillion years from the Big Bang, the chemical composition of the Universe will cease to change (*44*).

Future of nucleosynthesis studies

Some of the nucleosynthesis sources shown in Fig. 1 are more certain than others. Although the broad picture of stellar nucleosynthesis has been established (Figs. 2 to 4), there are many outstanding questions to be addressed. The number and timing of neutron-star mergers—quantities which are poorly known (*45*–*48*)—affect the *r*-process elements. Ground-based gravitational wave detectors recently detected neutron star mergers and are expected to soon establish their rate. Space-based gravitational wave detectors could provide a similar constraint on the rate of white-dwarf binary mergers (*49*). The exact origin of the elements between nickel and zirconium remains under debate (*45*, *50*). These elements do not require large amounts of neutrons, so both the weak *s*-process that occurs in high-mass stars and the weak *r*-process that could happen in supernovae are likely sources. Observations of the abundances of these elements in stars with known contributions from other nucleosynthetic sources are underway (*24*–*26*, *51*).

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ACKNOWLEDGMENTS

I am very grateful to my colleagues at Ohio State University for their interest in words ending with -ium and their work on numerous topics discussed in this Review. I am also most appreciative of S. Woosley for his lectures on the advanced stages of stellar evolution and nucleosynthesis, and I thank C. Hunt for the high-resolution photographs of the original photographic plate shown in Fig. 4. **Funding:** This work was supported in part by NSF grant AST-1211853. **Author contributions:** I am responsible for the entire manuscript. **Competing interests:** There are no competing interests. **Data and materials availability:** The data used for Fig. 1 are provided in table S1. In Fig. 3, the spectrum of HE 1327-2326 was obtained from http://archive.eso.org under proposal ID 075.D-0048(A) (principal investigator, A. Frebel), and the solar spectrum was obtained from www.eso.org/observing/dfo/quality/UVES/pipeline/solar_spectrum.html. The photographic plate shown in Fig. 4 is archived at the Carnegie Observatories library.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/363/6426/474/suppl/DC1
Table S1
References (*55*–*65*)

10.1126/science.aau9540

Science

Populating the periodic table: Nucleosynthesis of the elements

Jennifer A. Johnson

Science **363** (6426), 474-478.
DOI: 10.1126/science.aau9540

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