The Earth's Elements

The elements that make up the earth and its inhabitants were created by earlier generations of stars

by Robert P. Kirshner

Matter in the universe was born in violence. Hydrogen and helium emerged from the intense heat of the big bang some 15 billion years ago. More elaborate atoms of carbon, oxygen, calcium and iron, out of which we are made, had their origins in the burning depths of stars. Heavy elements such as uranium were synthesized in the shock waves of supernova explosions. The nuclear processes that created these ingredients of life took place in the most inhospitable of environments.

Once formed, violent explosions returned the elements to the space between the stars. There gravitation molded them into new stars and planets, and electromagnetism cast them into the chemicals of life. The ink on this page, the air you breathe while reading it—to say nothing of your bones and blood—are all an inheritance from earlier generations of stars. Walking down the corridors of an observatory, you see collections of carbon atoms hunched over silicon boxes, controlling distant telescopes of iron and aluminum in an attempt to trace the origin of the very substances of which they are made.

Matter was created in a violent explosion, known as the big bang, some 15 billion years ago. Within a minute fraction of a second, newborn quarks coalesced into protons. These fused further into the nuclei of helium atoms. Gravitational forces amplified ripples in this primordial soup, pulling the densest regions together into a giant cosmic tapestry of galaxies and voids. Inside galaxies, thick clouds of gas spawned stars. Traces of those early ripples can be seen in the cosmic microwave radiation, which still bears traces of the structure in the infant universe.

The large-scale unfolding of the universe was accompanied by a parallel change in the microscopic structure of matter. Carbon and nitrogen and other elements essential to life on the earth were synthesized in the interiors of stars now long deceased. Within the Milky Way galaxy, in the familiar stars of the night sky, astronomers can study these processes of microscopic change. In the early 1900s, such studies led to the first of several paradoxes regarding the ages of planets and stars.

The study of natural radioactivity on the earth provided clues about the ages of the elements. Geophysicists looking at the slow decay of uranium into lead computed an age for the earth of a few billion years. But astrophysicists of the early 20th century, not knowing about nuclear processes, computed that a sun-powered by chemical burning or gravitational shrinking could shine only for a few million years.

The discrepancy mattered. An age of billions of years for the earth provides a much more plausible calendar for biological and geologic evolution, where humans often find that change is imperceptibly slow. Even though the rug in most astronomy departments is lumpy from all the discrepancies that have been swept under it, a factor of 1,000 demands attention.

Curiously, the key to the problem was found in the processes of nuclear physics that, in the form of radioactivity, had first posed it. If stars live for billions of years instead of millions, they must have a continuing source of energy 1,000 times larger than chemical energy. Ordinary chemical changes involve the electrical force rearranging electrons in the outer regions of atoms. Nuclear changes involve the strong force rearranging neutrons and protons within the nucleus of an atom. The products of the reaction sometimes have less mass than the ingredients; the excess mass is converted to energy according to the well-known formula $E=mc^2$.

In nuclear reactions the energy yield is extremely large, typically a million times the energy produced by chemical reactions. Even the terminology for nuclear weapons reflects this factor. The unit of nuclear energy is a megaton—the energy of a million tons of chemical explosive.

A star that burns hydrogen, such as the sun, has an ample supply of energy for a lifetime of 10 billion years. Estimates for the current age of the sun are in the vicinity of five billion years (so we can safely contract for long-term mortgages).

The nuclear reactions within stars provide more than the energy that allows life to flourish. The ashes of nuclear burning—the elements of the periodic table—are the materials out of which living things are made. Perhaps most important, nuclear fusion, occurring steadily over the lifetime of a star, ensures a continuous supply of energy for billions of years and allows time for life and intelligence to develop.

Stars, after all, are not such ordinary places in the universe. A star is a ball of gas nearly balanced between the inward pull of gravity and the outward pressure of the gas. The hydrogen of the core fuses into helium, releasing energy in the process. Stars, like the sun, obey the same laws of physics as are found in the absence of gravity. Matter in the universe was born in the first moments of the big bang. By the time it coalesced into stars, it was race.
STAR CRADLE is found in the Great Nebula in Orion, 1,500 light-years away (above). This picture from the Hubble Space Telescope codes the presence of nitrogen (red) and oxygen (blue). At least half the young stars are surrounded by disks of gas and dust from which young planets are believed to form. The magnified image of the outlined part above shows four young stars (right). Protoplanetary disks that are lit by hot stars are bright. The cool star, shown magnified (far right), has one-fifth the mass of the sun; its disk contains seven times the material of the earth.

pull of its own gravitation and the outward pressure of the hot gas within. The compressed hydrogen gas usually has the density of the water in Boston Harbor, some $10^{10}$ times higher than the norm in the universe. And in a universe with a typical temperature of three kelvins (-270 degrees Celsius), the center of a star is at 15 million kelvins.

At such extreme temperatures the hydrogen atoms are stripped of their electrons. The naked protons undergo frequent, jarring collisions as they buzz furiously in the star’s dense interior. Near the center the temperature and density are highest. There the protons, despite the electrical repulsion between them, are pushed so close together that the strong and the weak nuclear forces can come into play.

In a series of nuclear reactions, hydrogen nuclei (protons) fuse into helium nuclei (two protons and two neutrons), emitting two positrons, two neutrinos and energy. If the elements synthesized were limited to helium (which is also made in the big bang) and if it stayed locked up in the cores of stars, this would not be quite such an interesting story—and we would not be here to discuss it. After a long and steady phase of hydrogen fusion, which leads to helium accumulating in the core, the star changes dramatically.

The core shrinks and heats as four nucleons are locked up in each helium nucleus. The temperature and density of the core increase to maintain the pressure balance. The star as a whole becomes less homogeneous. While the core becomes smaller, the outer layers swell up to 50 times their previous radius. A star the size of the sun will swiftly transform into a cool, but luminous, red giant. From the parochial viewpoint of earth dwellers, this will be the end of history and of human creations. Commodity future options, the designated-fitter rule and call waiting will all be vaporized with the earth.

But interesting events take place inside red giants. As the core contracts, the central furnace grows denser and hotter. Then nuclear reactions that were
previously impossible become the principal source of energy. For example, the helium that accumulates during hydrogen burning can now become a fuel. As the star ages and the core temperature rises, brief encounters between helium nuclei produce fusion events.

The collision of two helium nuclei leads initially to an evanescent form of beryllium having four neutrons and four protons. Amazingly enough, another helium nucleus collides with this short-lived target, leading to the formation of carbon. The process would seem about as likely as crossing a stream by stepping fleetingly on a log. A delicate match between the energies of helium, the unstable beryllium and the resulting carbon allows the last to be created. Without this process, we would not be here.

Carbon and oxygen, formed by fusing one more helium with carbon, are the most abundant elements formed in stars. The many collisions of protons with helium atoms do not give rise to significant fusion products. Lithium, beryllium and boron—the nuclei of which are smaller than those of carbon—are a million times less abundant than carbon. Thus, abundances of elements are determined by often obscure details of nuclear physics. A star of the sun’s mass endures as a red giant for only a few hundred million years. The last stages of burning are unstable: the star pushes off its outer layers to form a shell of gas called a planetary nebula. In some stars, carbon-rich matter from the core is dredged up by convection. The freshly synthesized matter then escapes, forming a sooty cocoon of graphite. Eventually fuel runs out, and the inner core of the red giant congeals into a white dwarf.

A white dwarf is protected from total gravitational collapse not by the kinetic pressure of gases: the carbon and oxygen in its interior are in an almost crystalline state. The star is held up by the quantum repulsion of its free electrons. Quantum mechanics forbids electrons from sharing the lowest energy state. This restriction forces most electrons to occupy higher energy states even though the gas is relatively cold. These electrons provide the pressure to support a white dwarf. There is no more generation of nuclear energy, and no new elements are synthesized.

Many white dwarfs in our galaxy come to this dull end, slowly cooling, dimming and slipping below the edge of detection. Sometimes a too-generous neighboring star may supply gas that streams onto a white dwarf, provoking it into a type I supernova and a sudden synthesis of new elements.

The most significant locations for the natural alchemy of fusion are, however, stars more massive than the sun. Although rarer, a heavy star follows a shorter and more intense path to destruction. To support the weight of the star’s massive outer layers, the temperature and pressure in its core have to be high. A star of 20 solar masses is more than 20,000 times as luminous as the sun. Rushing through its hydrogen-fusion phase 1,000 times faster, it swells up to become a red giant in just 10 million years instead of the sun’s 10 billion.

The high central temperature leads as well to a more diverse set of nuclear reactions. A sunlike star builds up carbon and oxygen that stays locked in the cooling ember of a white dwarf. Inside a massive star, carbon nuclei fuse further to make neon and magnesium. Fusion of oxygen yields silicon as well, along with sulfur. Silicon burns to make iron. Intermediate stages of fusion and decay make many different elements, all the way up to iron.

The iron nucleus occupies a special place in nuclear physics and, by extension, in the composition of the universe. Iron is the most tightly bound nucleus. Lighter nuclei, when fusing together, release energy. To make a nucleus heavier than iron, however, requires an expenditure of energy. This fact, established in terrestrial laboratories, is instrumental in the violent death of stars. Once a star has built an iron core, there is no way it can generate energy by fusion. The star, radiating energy at a prodigious rate, becomes like a teenager with a credit card. Using resources much faster.

SPECTRUM OF THE SUN shows dark absorption lines that coincide with the bright lines in the spectrum of iron (bottom). Cool iron atoms absorb the same wavelengths of light that iron atoms emit when hot. The matching lines prove that the sun’s relatively cool surface, or photosphere, contains iron, which could have come only from an ancestral star.
RELATIVE ABUNDANCES OF ELEMENTS in the universe reveal the processes that synthesized heavier elements out of the hydrogen (H) and helium (He) of the big bang. Fusion in stars created more helium, skipped over lithium (Li), beryllium (Be) and boron (B) to carbon (C) and generated all the elements up to iron (Fe). Massive stars can synthesize elements heavier than oxygen (O); these stars eventually explode as supernovae. Elements heavier than iron are made in such explosions. The chart has a logarithmic scale, in which abundance increases by a factor of 10 for each unit of height. Elements heavier than zinc (Zn) are too rare to be displayed.

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So what happens? For the star, at least, the disaster takes the form of a supernova explosion. The core collapses inward in just one second to become a neutron star or black hole. The material in the core is as dense as that within a nucleus. The core can be compressed no further. When even more material falls into this hard core, it rebounds like a train hitting a wall. A wave of intense pressure traveling faster than sound a sonic boom thunders across the extent of the star. When the shock wave reaches the surface, the star suddenly brightens and explodes. For a few weeks, the surface shines as brightly as a billion suns while the emitting surface expands at several thousand kilometers per second. The abrupt energy release is comparable to the total energy output of the sun in its entire lifetime.

Such type II supernova explosions play a special role in the chemical enrichment of the universe. First, unlike stars of low mass that lock up their products in white dwarfs, exploding stars eject their outer layers, which are unburned. They belch out the helium that was formed from hydrogen burning and launch the carbon, oxygen, sulfur and silicon that have accumulated from further burning into the gas in their neighborhood.

New elements are synthesized behind the outgoing shock wave. The intense heat enables nuclear reactions that cannot occur in steadily burning stars. Some of the nuclear products are radioactive, but stable elements heavier than iron can also be synthesized. Neutrons bombard iron nuclei, forging them into gold. Gold is transformed into lead (an alchemist’s nightmare!), and lead is bombarded to make elements all the way up to uranium. Elements beyond iron in the periodic table are rare in the cosmos. For every 100 billion hydrogen atoms, there is one uranium atom each made at special expense in an uncommon setting.

This theoretical picture of the creation of heavy elements in supernova explosions was thoroughly tested in February 1987. A supernova, SN 1987A, exploded in the nearby Large Magellanic Cloud. Sanduleak -69° 202, which in 1986 was noted as a star of 20 solar masses, is no longer there. Together the star and the supernova give dramatic evidence that at least one massive star ended its life in a violent way.

Neutrinos emitted from the innermost shock wave of the explosion were detected in Ohio and in Japan, hours before the star began to brighten. Freshly synthesized elements radiated energy, making the supernova debris bright enough to see with the naked eye for months after the explosion. In addition, satellites and balloons detected the specific high-energy gamma rays that newborn radioactive nuclei emit.

Observations made in 1987 with the International Ultraviolet Explorer and subsequently with the Hubble Space Telescope supply strong evidence that Sanduleak -69° 202 was once a red giant star that shed some of its outer layers. Images taken this year with the newly acute Hubble revealed astonishing rings around the supernova.

The inner ring is material that the star lost when it was a red giant, excited by the flash of ultraviolet light from the supernova. The outer rings are more mysterious but are presumably related to mass lost from the pre-supernova system. The products of stellar burning are concentrated in a central dot, barely resolved with the Hubble telescope, which is expanding outward at 3,000 kilometers per second. No neutron star has yet been observed in SN 1987A.

The supernova has provided dramatic confirmation of elaborate theoretical models of the origin of elements. Successive cycles of star formation and destruction enrich the interstellar medium with heavy elements. We can identify the substances in interstellar gas: they absorb particular wavelengths of light from more distant sources, leaving a characteristic imprint [see illustration at bottom of preceding page]. The absorption lines tell us as well the abundance of the element—its amount compared with that of hydrogen.

In a spiral galaxy like the Milky Way, interstellar gas is associated with the
spiral arms. Optical studies of the galaxy are hampered by the accompanying dust, which absorbs much of the light passing through. But the dust also shields the hydrogen atoms from ultraviolet light, allowing them to combine chemically and form molecules (H₂). In these hidden backwaters of the galaxy, other molecules such as water (H₂O), carbon monoxide (CO) and ammonia (NH₃) all assemble. The chemical variety is quite surprising: more than 100 molecules have been found in interstellar clouds.

In May of this year Yanti Miao and Yi-Jehong Khan of the University of Illinois reported finding the smallest amino acid, glycine, in the star-forming cloud near the center of our galaxy, Sagittarius B2. It is amusing to speculate that amino acids and other biologically interesting chemicals could be present in the protoplanetary disk that accumulates near a forming star. Such chemicals, if on a young planet, would almost certainly be destroyed by heat. But after the planet had cooled, they could reach its surface by way of meteorites. Indeed, complex hydrocarbons were found last year on microscopic dust particles that originated in interplanetary space.

We can learn much about the materials from which the earth was formed by the simple act of picking up a pen. Made of carbon compounds and metals, the pen—and indeed the earth itself—is typical of the cosmic pattern of abundances. Except for hydrogen and helium, which easily slip the gravitational grip of a small planet, the elements of the earth are the elements of the universe: formed by stars and dispersed throughout the galaxy. (The jury is still out on the question of whether ordinary matter, composed of known subatomic particles, is a small fraction of the total mass in the universe. If so, then we are truly made of uncommon stuff.)

Whereas the sun is 99 percent hydrogen and helium, the 1 percent of more complex nuclei includes traces of iron and other heavy elements. Thus, the solar system must have formed from elements synthesized by previous generations of stars. Like silver candlesticks from your grandmother (but much more valuable), we have inherited the carbon and oxygen produced by ancestral stars.

Astronomers can begin to trace a family tree for the solar system by examining massive stars within the Milky Way. If the massive stars in a star cluster are just now becoming red giants, the cluster must be young. If the stars currently headed toward the red giant phase have the mass of the sun, the cluster must be old enough for its sun-like stars to begin that change: about 10 billion years. The oldest clusters in our galaxy are the globular clusters, which appear to have an age of 12 to 18 billion years when measured in this way.

We recognize the globular clusters as an early generation of stars. The oldest of these are significantly different from the sun: the abundances of elements such as iron are often 100 or even 1,000 times lower. Yet even these ancient stars contain a pinch of heavy elements. Thus, they evince the presence of a complete-
ly unseen generation of stars, which has no members left.

Given that the universe itself is only about 15 billion years old (see box below), the initial chemical enrichment of the Milky Way must have been very rapid. (Even quasars, extragalactic beacons from a time when the universe was only a fifth of its current age, contain carbon and nitrogen.) There has been much less change in recent times. The present-day chemical abundances in interstellar gas are about the same as in the sun, locked in five billion years ago. This is the raw material for future stars and planets.

In neighboring gas clouds such as the Orion nebula, astronomers can study intimate scenes of stellar birth. New infrared detectors are lifting the shroud from these cradles. (Although it blocks visible light, interstellar dust is transparent to infrared or radio waves.) We can see infant stars as they condense, even before they ignite hydrogen fuel in their cores (see illustration on pages 60 and 61). In addition, large telescopes such as the eight-meter Gemini

Supernova 1987A and the Age of the Universe

Supernova 1987A led to an unexpected, and stringent, test of our ability to measure cosmic distances. Remote stars and galaxies appear to be moving away from the earth, sharing the cosmic expansion that began with the big bang. If we can measure the distance to a receding galaxy, then by combining this information with how fast the galaxy is moving, we can determine for how long it has been receding. Thus, we gain a measure of the age of the universe.

Based on observations we had carried out in 1987 and 1988, my colleagues and I could time how long light took to reach the supernova’s bright inner ring. Because we know the speed of light, that time allowed us to calculate the ring’s physical size. Observations made with the imperfect Hubble Space Telescope in 1990 gave a measure of the ring’s apparent angular size, viewed from the solar system. Combining these two pieces of information yields a distance to the Large Magellanic Cloud (in which SN 1987A occurred) of about 169,000 light-years, in good agreement with classical methods.

A separate method we developed to measure the distance to SN 1987A analyzes the light emitted from the supernova shortly after the explosion. When the shock wave reached the surface, it heated the gas and blasted it outward. The velocity with which this debris is flying out is coded in the amount by which the absorption lines of known elements is shifted. Knowing this velocity and the time when the supernova exploded, we can compute how far the debris must have traveled—and therefore the current radius of the supernova. Given the radius, we know its surface area.

A key piece of information now comes into play. From the overall color of the gas we can estimate the supernova’s temperature. The latter yields the amount of light the supernova is emitting per unit area of its surface. Because we know the surface area, we can find the total amount of energy being radiated. Measuring the amount of energy received at the earth, we acquire another estimate of how far away SN 1987A is. In repeated calculations of this kind, we get a distance of about 150,000 light years—an excellent match with the previous estimate by astronomical standards.

With the confidence that this second method gives the “right” answer when used nearby, we have applied it to more distant supernova explosions. My students Ronald Eastman and Brian Schmidt and I have now measured a dozen supernova distances. When combined with the redshifts of the galaxies in which they erupted, the distances yield an age for the universe of between 12 and 16 billion years.

The estimate assumes that gravity has not slowed down the expansion significantly. Many cosmologists suspect that the universe has just enough mass to balance the energy of expansion, slowing it down until it almost stops. If this is so, the age of the universe would be only two thirds the original estimate, which assumed constant expansion. Then the age of the universe should be scaled back to between eight and 11 billion years.

Globular clusters, on the other hand, are between 12 and 18 billion years old. When future measurements determine the deceleration of the universe, I expect they will do so in the direction of avoiding a paradox. It would be embarrassing to find 14-billion-year-old globular clusters in a universe that is aged only seven billion years.
the conviction. As in cosmology, where there is one example of a universe (we are in it), there is one well-known planetary system (we are on it). A planet is difficult to sight directly. An observer would have to see a small object, shining only by reflected light, next to one about a billion times brighter.

Detecting planets by their gravitational effects is more promising. The idea is to observe the velocity changes of a visible star produced by an unseen object as the two execute a stellar do-si-do. The object, having less than a tenth of the mass of the star, would affect the motion of the star only minutely. Although there are tantalizing hints, no planet has yet been discovered by looking for the motion it produces in the luminous star it orbits. Present techniques are not quite up to the task of detecting a planet smaller than Jupiter in orbit around a star like the sun.

Yet a spinning neutron star, PSR B1257+12, was recently shown to have objects that are producing periodic shifts in its emission (see illustration on pages 62 and 63). When a neutron star forms in a supernova explosion, the core of the star contracts to a dense sphere just a few miles across. As it shrinks, any rotation of the original star ends up in the rotation of the neutron star. So neutron stars are born spinning. If the neutron star has a magnetic field, it may be a powerful source of radio waves, emitted in a sharply specific direction.

These objects actually exist: they are called pulsars. Every time the fan of radio emission sweeps by the earth, astronomers observe a pulse of radio noise. Because the emission mechanism is anchored to a dense flywheel, the pulse period is very precise. Extremely subtle variations can be measured by diligently observing the arrival times of the pulse. If the pulsar has an unseen companion, an observer will see the pulses arrive a little early, and then late, as the source approaches and recedes.

In 1992 Alexander Wolszczan, now at Pennsylvania State University, and Dale A. Frail of the National Radio Astronomy Observatory in Socorro, N.M., reported that their observations of the pulsar PSR B1257+12 had periodic changes in the pulse arrival times. The variation was only 1.5 milliseconds, stretched over months. It could be explained if the neutron star was being orbited by a pair of objects. These would have masses of 3.4 and 2.8 times the mass of the earth. This past April these workers found signs of the gravitational forces between the planets and evidence for yet a third object, having about the mass of the moon.

A spinning remnant of a supernova explosion, beaming out powerful radio blasts, is nobody's vision of another solar system. Yet only a curmudgeon could fail to call its orbiting objects planets. It seems quite unlikely that these planets survived the supernova explosion that created the neutron star. The original star probably had a close binary companion, which is no longer present. The planets are perhaps formed from shreds of the companion. This is not your ordinary family history. Nevertheless, the study of pulsars may well shed light on the formation of more familiar planets such as the earth.

The composition of the earth is the natural by-product of energy generation in stars and successive waves of stellar birth and death in our galaxy. We do not know if other stars have earthlike planets where complex atoms, formed in stellar cauldrons, have organized themselves into intelligent systems. But understanding the history of matter and searching for its most interesting forms, such as galaxies, stars, planets and life, seem a suitable use for our intelligence.

FURTHER READING