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SOLAR SYSTEM PIONEER
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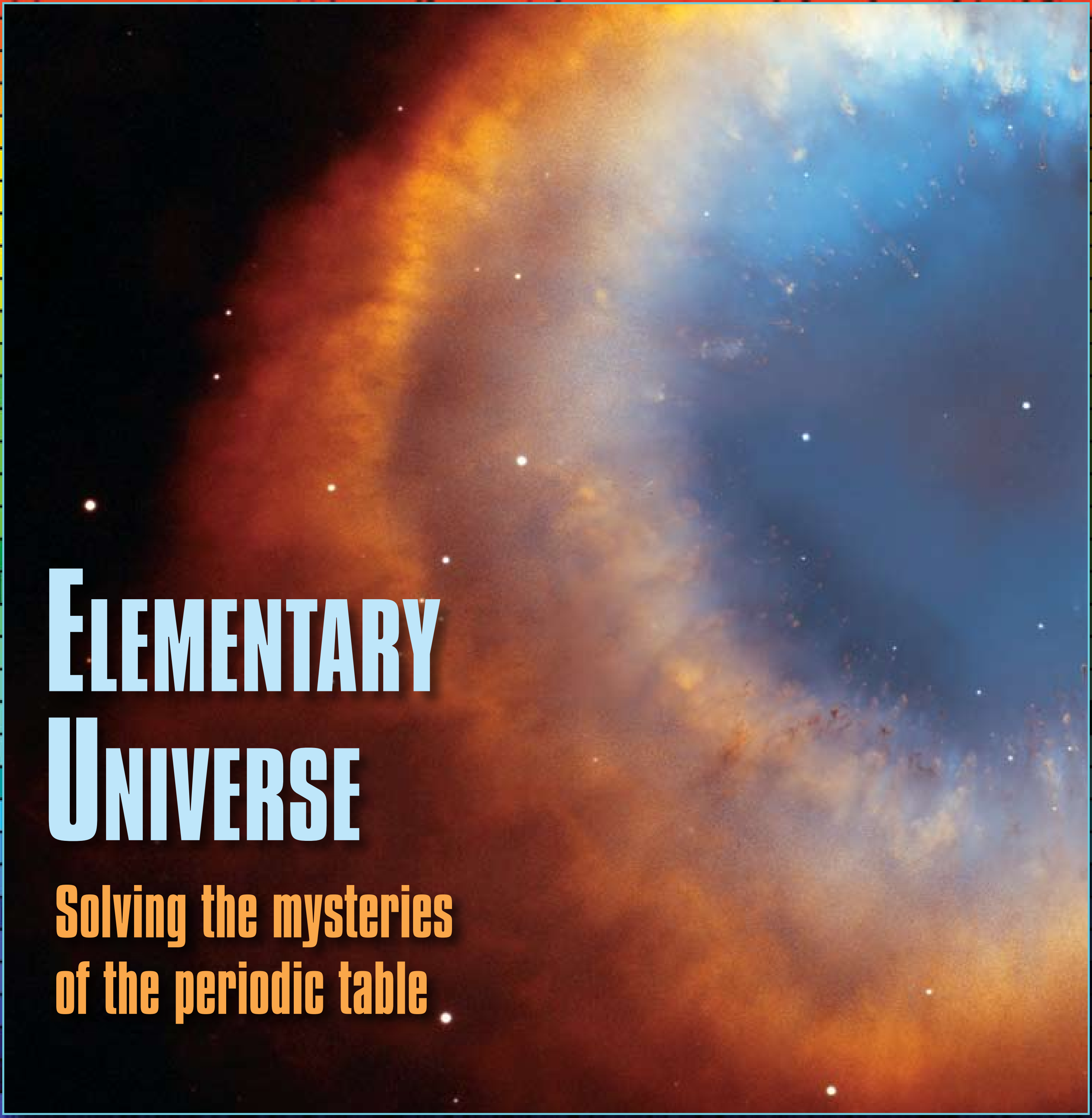
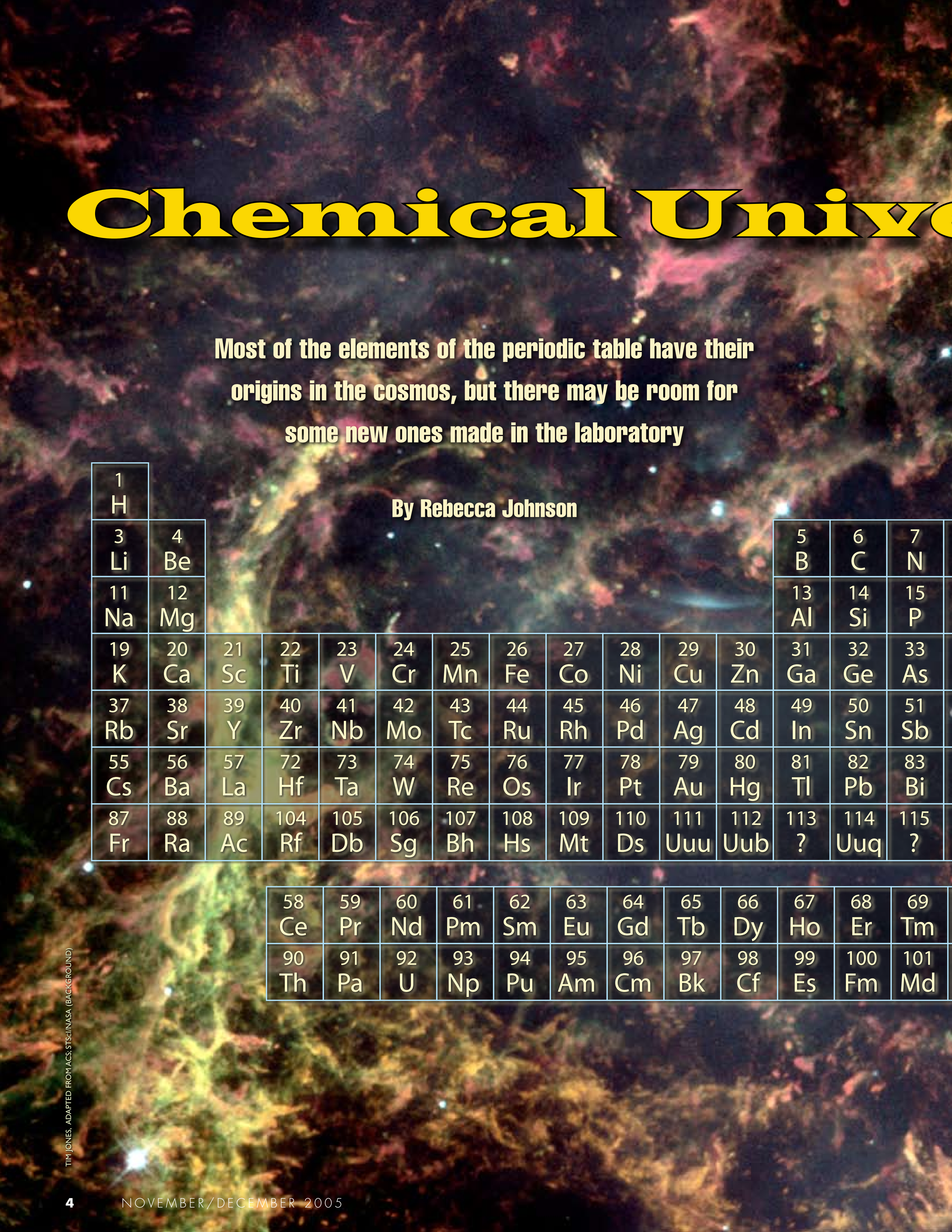


ELEMENTARY UNIVERSE

Solving the mysteries of the periodic table

THE UNIVERSITY OF TEXAS AT AUSTIN McDONALD OBSERVATORY



Chemical Unive

Most of the elements of the periodic table have their origins in the cosmos, but there may be room for some new ones made in the laboratory

By Rebecca Johnson

1 H														
3 Li	4 Be											5 B	6 C	7 N
11 Na	12 Mg											13 Al	14 Si	15 P
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub	113 ?	114 Uuq	115 ?
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md

TIM JONES, ADAPTED FROM ACS; STSCI/NASA (BACKGROUND)

"The alchemists basically had it right," says Texas astronomer Chris Sneden, referring to the Middle-Ages conjurers who labored in vain to turn base metals into gold. To make the elements, "you needed fire, and you needed to excite the material, to make it hot and dense enough to change from one element to another. The trouble was, they couldn't get it hot enough and dense enough."

Such hot and dense conditions do exist in nature, though. All of the 115 or so known chemical elements were created in the Big Bang that began the universe, in the cores of stars, or in the supernova explosions that herald the ends of massive stars' lives. Some of the heaviest elements, however, were created most recently of all — in Earth-bound laboratories.

"Most beginning chemistry students accept the periodic table as God-given," Sneden says. "The periodic table just didn't magically appear. It wasn't one of the things Moses brought down from the mountain."

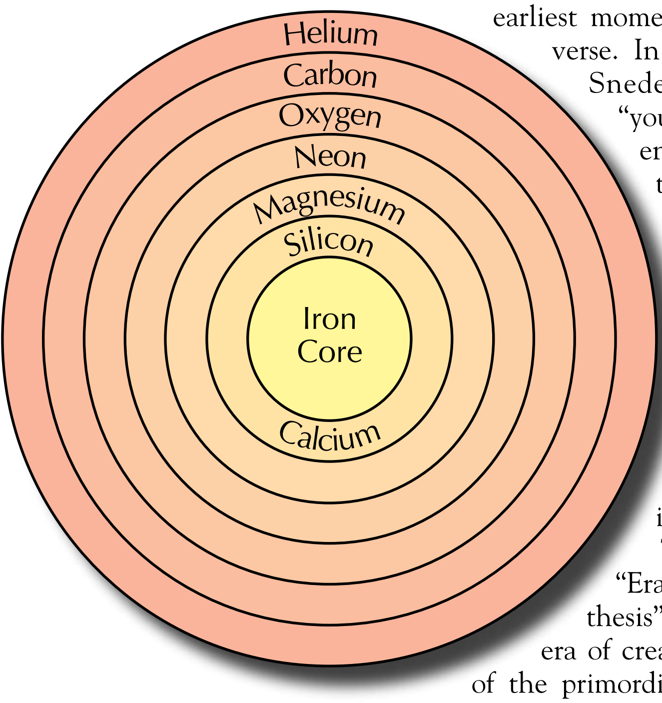
Previous page: The periodic table overlies the Crab Nebula, the remains of a star 10 times as massive as the Sun that exploded in 1054. The explosion blew chemical elements created inside the star into space, including hydrogen (orange), nitrogen (red), sulfur (pink), and oxygen (green).

Russian chemist Dimitri Mendeleev organized the then-known elements into the first modern periodic table in 1869. Mendeleev arranged the elements by their atomic number, which refers to how many protons are in the nucleus of one atom. Hydrogen, with one proton, is first, and ununoctium, with 118, currently is the last. The higher the number of protons, and thus the atomic number, the heavier the element.

Since Mendeleev's time, scientists have been looking for more elements, filling in blank spots in the table, and even claiming to find some elements that were later disproved. But the most efficient element-builder of all is Mother Nature.

The three lightest elements — hydrogen (atomic number one), helium (atomic number two), and lithium (atomic number three) — were created in the earliest moments of the universe. In the Big Bang, Sneden explains, "you begin with the entire matter of the universe, incredibly dense and incredibly hot," he says. "*Something* happens, and this material starts to expand. And it cools very rapidly."

The so-called "Era of Nucleosynthesis" — that is, the era of creating atoms out of the primordial cosmic soup — began one-thousandth of a second after the Big Bang and lasted about three minutes. By the end of this period, the universe had expanded so much that the density had dropped too low for nucleosynthesis to continue.



TIM JONES

A slice through the center of a massive star at the end of its life reveals its onion-like structure. The core is the hottest, with successive outward layers a bit cooler.

Hydrogen and helium are the two most abundant elements in the universe. Hydrogen makes up about 75 percent of normal matter (that is, detectable matter, not dark matter) and helium about 25 percent. The remaining one percent or so comprise what astronomers call heavy elements, or "metals" — lithium and everything heavier.

The amount of lithium created in the Big Bang has important implications for understanding the universe's future — whether it will continue to expand, or ultimately close on itself. That's because the amount of lithium made depends on the precise density of the universe during the Era of Nucleosynthesis. Astronomers investigate this by measuring the amount of lithium in very old stars. "It may be a holdover from the Big Bang," Sneden says. Other studies — notably those involving the distances to certain classes of exploding stars, have shown that the universe will expand forever, and that its expansion is speeding up. Studying lithium in old stars is an independent check on the conclusions from these and other studies.

If the first three elements were made in the first three minutes, the rest didn't come along until about a billion years later, with the formation of the first stars and galaxies. That's because the other elements were forged in the universe's chemical factories: the stars. Except for those created in the laboratory, every element heavier than lithium was created by a star. That includes every atom of oxygen that we breathe, every atom of calcium in our bones and iron in our blood, every atom of gold in our jewelry. So without the finely tuned processes of nuclear fusion, neither our planet nor its inhabitants would exist.

Like the overall universe, stars are made mostly of hydrogen. A star forms when a vast cloud of gas and dust collapses. As it pulls in on itself, and its density increases, it gets hotter. When the temperature in the center of this collapsing star reaches about 10 million degrees Celsius (18 million F), the nuclei of hydrogen atoms ram together with enough force to combine to form helium, and a new star is born.

A star will continue the multi-step fusion process that yields helium for millions or billions of years. Inevitably, though, the supply of hydrogen runs low. The star's core shrinks and gets hotter. As the core temperature rises to slightly below one billion degrees Celsius (1.8 billion F), helium begins to "burn" (a physicist's jargon for the process of nuclear fusion) to form carbon (atomic number six). When the temperature climbs slightly higher, the star produces neon; at two billion degrees Celsius (3.6 billion F), oxygen.

The energy released in these nuclear reactions is what powers the stars. “That’s what the star’s structure cares about,” Sneden says. “The star’s structure could care less that it’s changing hydrogen into helium, helium to carbon … all it’s doing is squeezing the nuclei so tightly that they’ll fuse and release energy, which stabilizes the star against the inward crunch of gravity.” The fusion of hydrogen to helium converts about 0.7 percent of the mass of the original hydrogen atoms to energy. The Sun “fuses” about 600 million tons of hydrogen every second. This yields 596 million tons of helium atoms, while four million tons of mass are converted to energy.

The core is the hottest part of the star, but after fusion starts, the rest of the star heats up naturally as the energy released from the core struggles outward. The star forms a layered structure, like an onion; the core is the hottest layer, and successively outward layers are cooler.

What happens next depends on the star’s mass. Stars like the Sun, and those up to several times its mass, can only fuse elements up to oxygen. They simply don’t get hot and dense enough to make heavier elements.

When such a star has a core full of carbon and oxygen, it dies. Fusion stops, and the star’s outer layers blow off into space, forming a beautiful cloud of gas and dust known as a planetary nebula. The star’s leftover core, at the heart of the nebula, becomes a white dwarf — a ball of matter only about as big as Earth, but containing most of the star’s mass. It no longer produces energy through nuclear reactions, but shines through the heat built up during its long life. This will be the Sun’s fate.

More massive stars, of course, exert greater pressure on their cores, so their cores are correspondingly hotter than those of lighter stars, allowing them to create elements heavier than oxygen. But when the core begins to burn silicon into iron (atomic number 26), fusion stops in these massive stars, too. In fact, Sneden says, “all hell breaks loose.” The fusion reactions that make elements heavier than iron are *endothermic* — that is, they use up more energy than the reaction gives off. So “when you get an iron core,” Sneden says, “it sucks energy in and there’s a massive collapse.” This collapse generally produces a titanic explosion called a supernova.

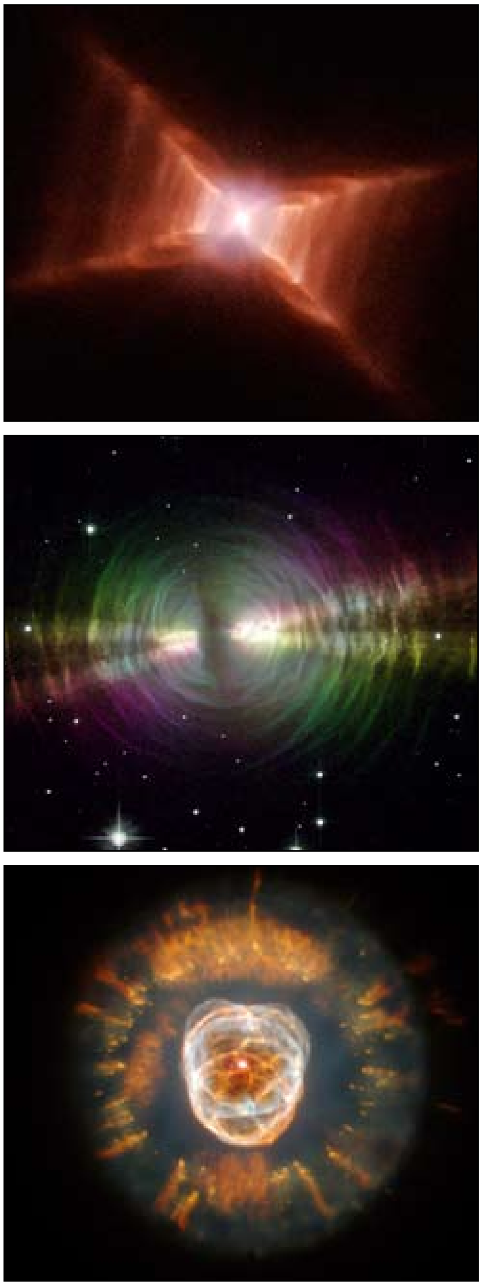
This is not the end of the periodic table; the universe contains dozens of elements with atomic numbers much higher than iron. All of these elements are produced by a process called *neutron capture*. Instead of adding protons, an element grows more massive by adding neutrons, the electrically neutral particles that make up an atom’s nucleus.

There are two types of neutron capture: slow and rapid. The slow process can create some elements, the rapid process creates others, and some elements can be formed by either process.

The slow process (commonly called the s-process) occurs inside old stars called red giants — one of the final stages in the life of a low-mass star like the Sun before it becomes a white dwarf. One example in the night sky is Aldebaran, which forms the bright orange “eye” of Taurus, the bull.

Red giants have exhausted the supply of hydrogen fuel in their cores and have started to burn helium. This creates free neutrons, which hit the nuclei of other elements inside the star. The neutrons have no electrical charge, so they aren’t repelled. They slowly enter the nucleus of the atom, one after another, until it becomes unstable. It then spits out an electron, so it forms a stable atom — and the next element on the periodic table.

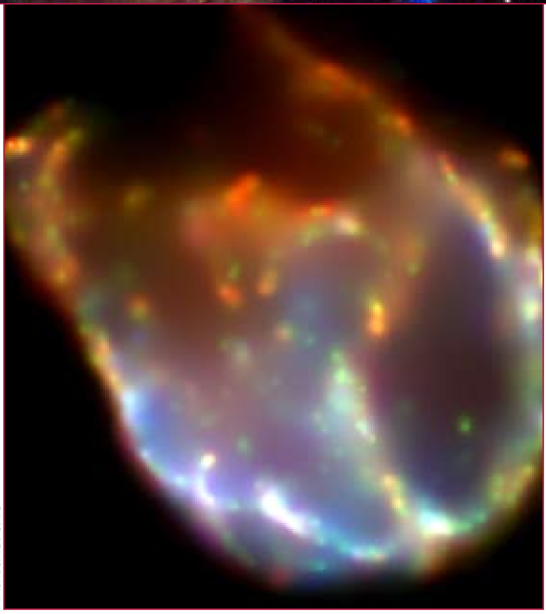
The rapid process (r-process) takes place in the cores of the most massive stars — those that are at least eight times as massive as the Sun. The list of supermassive stars visible in the night sky includes Betelgeuse and Rigel in Orion, Antares in Scorpius, and Spica in Virgo.



STSCI/NASA (3)

Sun-like stars eventually blow off their outer gas layers to form planetary nebulae, while their cores remain intact as white dwarfs, cooling for millenia.

NASA/ESA/H.E. BOND (STScI)



NASA/SAO/CXC

Elements heavier than iron form through the neutron-capture process. Some form through the slow process in red-giant stars like V838 Monocerotis (top), while others form through the rapid process in supernovae like N132D (bottom, seen in X-rays) in the Milky Way satellite galaxy the Large Magellanic Cloud.

In the last days of its life, such a star produces a quick progression of ever-heavier elements. When its core is converted to iron, fusion stops. Without the radiation of the fusion reactions, nothing protects the star from the inward crunch of its own great gravity. It explodes as a supernova. The explosion creates an enormous blast of neutrons, which bombard the nuclei of all the atoms in the star's core. There are so many neutrons moving with such great energy that they rapidly attach themselves to all the available atoms. These neutron-rich nuclei form gold, silver, platinum, and other exotic heavy elements.

When stars explode as supernovae, the elements they created over their lifetimes — and in their death throes — spew into the galaxy, where they can be incorporated into new generations of stars, planets — and perhaps living organisms.

Each generation enriches the gas of the galaxy with heavier elements. The fact that astronomers find "living" stars with r-process elements in their atmospheres proves this, Sneden says.

Such a star had to be born from a gas cloud seeded with elements from previous supernovae. If the star had formed those r-process within elements itself — "Kaboom! It would be dead," Sneden says.

Because successive generations of stars contain more metals (all the elements heavier than helium), it follows that the most metal-poor stars in the galaxy are the oldest, and the most metal-rich are the youngest.

Walter Baade figured out in the 1940s that stars in the spiral arms of our Milky Way galaxy, such as the Sun, contain much higher amounts of heavy elements than the stars in the galaxy's halo — a vast spherical structure that surrounds the Milky Way's bright disk. He named the metal-rich stars of the spiral arms "Population I," and the metal-poor stars of the halo "Population II."

Sneden's studies focus on understanding the Milky Way's history through detailed analyses of stars' chemical make-up. But this is hard to do by studying the Sun and our solar system, Sneden says. "So many different generations of stars poured their elements into making the material of our solar system that it's hard to disentangle all of them. Big-mass stars, small-mass stars, rapid-blast products, slow neutron capture, proton-proton cycle … It's many different cycles from big- and small-mass stars."

He prefers to study the oldest stars in the galaxy. "I find these very metal-poor stars fascinating," Sneden says. "The stars that I look at, way out in the halo of the galaxy, they're really old. That means they were born right at the beginning of the galaxy. It's a simpler time."

When these stars formed, the Milky Way was a galactic infant. It had not lived long enough to evenly distribute the elements that were blasted into space during the explosions of the earliest massive stars. As a result, today astronomers see wild variations in the chemical compositions of the galaxy's oldest stars.

Part of Sneden's work is helping to figure out what events influenced the chemical makeup of the present-day galaxy. The fact that the oldest stars contain more europium (an r-process element made in supernovae) than barium (an s-process element), for example, means that the early formation of elements in our galaxy was influenced by supernova explosions more than anything else.

Sneden also is trying to figure out just how old the galaxy's oldest stars are, which is one way to tease out the age of the galaxy itself. "What I've been working on, which is still a matter of some dispute, is to try to age-date stars by thorium and uranium," he explains. "You have all of these elements built by the rapid-blast process, and many of them are stable. But thorium and uranium are not." So he studies the amounts of stable r-process elements in an ancient halo star and compares it to the amount of thorium, which decays with a half-life of about 14 billion years. In other words, in 14 billion years, about half of the thorium the star was born with should have decayed to form other elements.

Based on the amount of stable elements in a star, Sneden estimates how much thorium the star should have been born with. He then compares that to the amount it appears to have now, and he sees about half as much thorium as he predicted the star was born with. The exact amounts are "trying to tell us that there's been about 14 billion years since that thorium was made," Sneden says. The ages depend on just how much thorium the star had at birth, though — a quantity that is still a subject of intense debate, he notes.

Neutron capture accounts for the creation of the heaviest naturally made elements — those up to element 92, uranium. But the periodic table doesn't end there.

According to Sneden's collaborator John Cowan, a theorist at the University of Oklahoma, "there are roughly 14 to 20 artificial elements on top of the regular 92." The exact number is not certain because physicists argue back and forth over whether the evidence for some artificial elements is convincing or not, Cowan says.

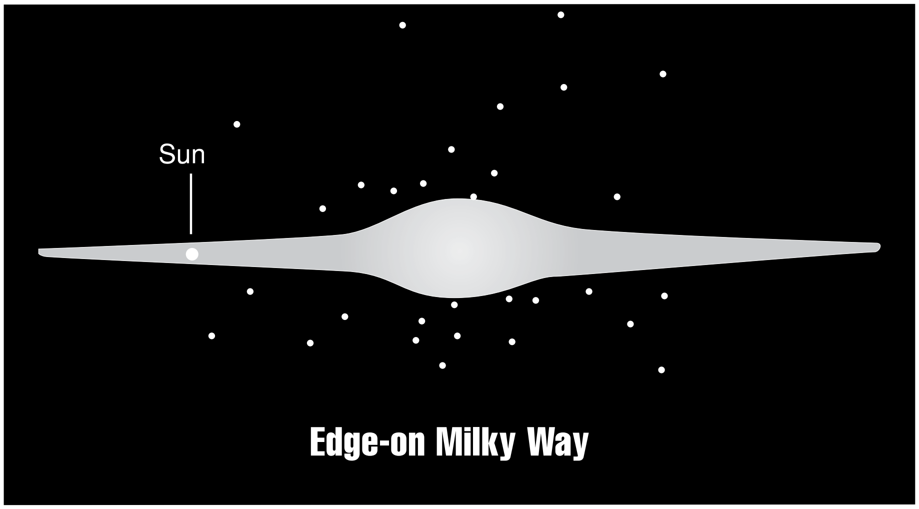
Artificial elements are created in laboratories by accelerating particles to great speeds and then making them collide with target nuclei to create new elements. Such elements "live for literally a billionth or a millionth of a second," Cowan says

"Over the decades," he says, "people have suggested that there might be a way for super-heavy elements to be created in certain supernova explosions. But no one has ever found such a thing."

Unlike the naturally occurring elements, artificial elements 93 through 110 were named by their creators. Since uranium was named for the planet Uranus, physicists continued the theme with the first two artificial elements: neptunium (atomic number 93), named for Neptune, and plutonium (94), for the then newly discovered Pluto. Elements 111 and above are awaiting final names.

Is the periodic table complete? Some physicists don't think so. They predict that bigger atom smashers will produce a slew of new elements. They have named this new real estate of the periodic table "the island of stability" because they predict that these elements may last up to thousands of years. "Even if these elements are never found," Sneden says, "the miracle is that we know how the elements were made. The periodic table is not a mystery."

Rebecca Johnson is the editor of StarDate.



TIM JONES

The Sun lies in our galaxy's disk, with other metal-rich Population I stars. The dots represent globular star clusters in the galactic halo, filled with ancient, metal-poor Population II stars.

RESOURCES

BOOKS

Stellar Alchemy: The Celestial Origin of Atoms, by Michel Cassé, 2003.

Nature's Building Blocks: An A-Z Guide to the Elements, by John Emsley, 2001.

The Periodic Kingdom, by P.W. Adkins, 1995.

INTERNET

Interactive Periodic Table
chemicalelements.com

Natures of the Stars
www.astro.uiuc.edu/~kaler/sow/star_intro.html