

Where Do Chemical Elements Come From?

By Carolyn Ruth

In 1054, Chinese astronomers recorded what they called a “guest star” in the constellation of Taurus, the Bull. This star had never been seen before, and it became brighter than any star in the sky. In the American Southwest, a culture rich in astronomical tradition called the Anasazi also witnessed this brilliant new star. Easily visible in broad daylight, the observers could read by it at night. Today, we know the Chinese and Anasazi were witnessing a huge star explosion, called a supernova.

NASA, ESA, HEIC, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

What these observers did not know is that during the explosion, the star not only emitted huge amounts of light—more light than a billion suns—but also released chemicals in space. Inside the star were most of the first 26 elements in the periodic table, from simple elements, such as helium and carbon, to more complex ones, such as manganese and iron; and the giant explosion sprayed them in space. During the explosion, other elements were created as well, and after the explosion, the chemicals in space combined with each other to form ions and molecules.

These elements travel in space and ultimately end up in planets like Earth, being part of everything we see around us and ourselves. The carbon in our cells, the oxygen in the air, the silicon in rocks, and just about every element, were all forged inside ancient stars before being strewn across the universe when the stars exploded.

During the past century, scientists have been studying how chemical elements form in stars and in outer space. Like genealogists—experts who study the origins of people and families—these scientists can track down where most chemical elements came from and how they descended from each other. And, similar to forming a family tree, studying

the links between the chemical elements has brought—and keeps bringing—many surprises and interesting discoveries.

Stellar ovens

A young star is composed primarily of hydrogen, the simplest chemical element. This hydrogen ultimately leads to all known elements. First, the two constituents of each hydrogen atom—its proton and electron—are separated. The high pressure inside the star can literally squeeze together two protons, and sometimes, a proton will capture an electron to become a neutron.

When two protons and two neutrons band together, they form the nucleus of helium, which is the second element in the periodic table. Then, when two nuclei of helium fuse with each other, they form the nucleus of another element, beryllium. In turn, the fusion of beryllium with helium produces a carbon nucleus; the fusion of carbon and helium nuclei leads to an oxygen nucleus, and so on. This way, through successive fusion reactions, the nuclei of most elements lighter than iron can be formed (Fig. 1). Scientists call this process nucleosynthesis (for “synthesis of nuclei”).

In stars, these fusion reactions cannot form elements heavier than iron. Up until the formation of iron nuclei, these reactions release energy, keeping the star alive. But nuclear reactions that form elements heavier than iron do not release energy; instead, they consume energy. If such reactions happened, they would basically use the star’s energy, which would cause it to collapse.

Not all stars form iron, though. Some stars explode before creating that many ele-

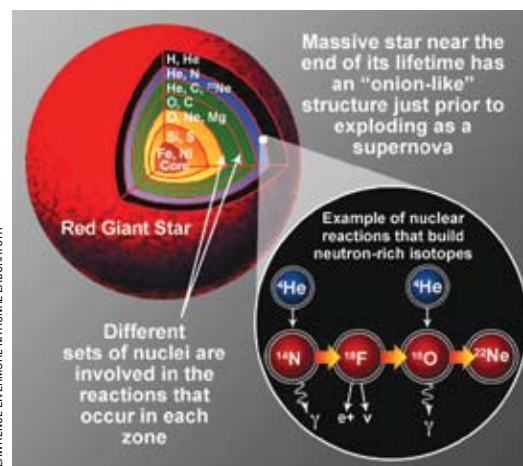


Figure 1. The chemical composition of a star before it explodes into a supernova.

ments. In stars less massive than the sun, the reaction converting hydrogen into helium is the only one that takes place. In stars more massive than the sun but less massive than about eight solar masses, further reactions that convert helium to carbon and oxygen take place in successive stages before such stars explode. Only in very massive stars (that are more massive than eight solar masses), the chain reaction continues to produce elements up to iron.

A star is a balancing act between two huge forces. On the one hand, there is the crushing force of the star's own gravity trying to squeeze the stellar material into the smallest and tightest ball possible. On the other hand, there is tremendous heat and pressure from the nuclear reactions at the star's center trying to push all of that material outward.

The iron nucleus is the most stable nucleus in nature, and it resists fusing into any heavier nuclei. When the central core of a very massive star becomes pure iron nuclei, the core can no longer support the crushing force of gravity resulting from all of the matter above the core, and the core collapses under its own weight.



Combined X-ray and optical images of the Crab Nebula.

The collapse of the core happens so fast that it makes enormous shock waves that blow the outer part of the star into space—a supernova. It is during the few seconds of the collapse that the very special conditions of pressure and temperature exist in the supernova that allow for the formation of elements heavier than iron. The newly created elements are ejected into the interstellar dust and gas surrounding the star.

“The amount of elements released through a supernova is truly phenomenal,” says Stan Woosley, professor of astronomy

and astrophysics at the University of California at Santa Cruz. “For example, SN1987A, a supernova seen in 1987, ejected 25,000 Earth masses of iron alone.”

How stars make elements heavier than iron

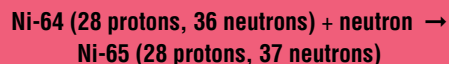
Elements that are heavier than iron can be assembled within stars through the capture of neutrons—a mechanism called the “s” process. The process starts when an iron nucleus captures neutrons, thus creating new nuclei. These nuclei can be either stable, that is, they do not change, or radioactive, meaning that they transform, or decay, into another element after a certain amount of time, which can be as short as a fraction of a second and as long as a few million years.

Also, the newly formed nuclei can be different versions of a given element. These different versions of an element are called isotopes. They all contain the same number of protons in their nucleus but have different numbers of neutrons. Some isotopes are radioactive, while others are stable and never change.

For example, nickel can appear in the form of 23 different isotopes. They all have 28 protons, but each isotope contains between 20 and 50 neutrons. Of these 23 isotopes, only five are stable, while the others are radioactive.

If a nucleus produced through the “s” process is stable, it may capture another neutron. If it is radioactive, it transforms into another nucleus. This other nucleus can, in turn, absorb another neutron, leading to a heavier nucleus.

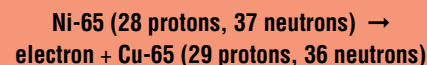
For example, nickel-64, which contains 28 protons and 36 neutrons, can absorb a neutron, leading to nickel-65, which contains 28 protons and 37 neutrons:



Nickel-65 is radioactive. It exists for only 2 and a-half hours, and then transforms into copper-65—the next element in the periodic table, which contains 29 protons and 36 neutrons. This is a process called beta decay, in which a neutron transforms into a proton and an electron:



The Crab Nebula is a six-light-year-wide expanding remnant of a star's supernova explosion.



Copper-65 is stable, so nothing happens after that.

This neutron capture mechanism, called the “s” process, is extremely slow. Hundreds or thousands of years might elapse between neutron strikes. But another process, called the “r” process, which stands for “rapid,” allows for the rapid capture of neutrons. Unlike the “s” process, which occurs inside a star before it explodes, the “r” process happens only during the explosion of a star.

Exploding and cooking elements at the same time

When a star explodes into a supernova, it produces a huge amount of light and releases an extremely high number of neutrons (on the order of 10 thousand billion billion neutrons per square inch per second). These neutrons are then rapidly captured by the various nuclei that are also released by the exploding star, producing new nuclei through the “r” process.

In this process, even though many neutrons are available, only a limited number can be added to a given nucleus; otherwise, a nucleus becomes radioactive and breaks up. Neutrons in a nucleus are thought to occupy shells—similar to successive shells on a hard candy. When a nucleus gets “saturated” with neutrons, that is, when its shells are filled up, it undergoes a beta decay process to become the nucleus of the next element on the periodic table. This new nucleus, in turn, absorbs as many neutrons

Finding Chemicals Inside Stars

To determine which chemical elements are formed inside stars, scientists use a technique known as visible spectroscopy. It is based on a device, called a spectroscope, which spreads visible light into its component colors by passing it through a prism or grating.

These colors are called an emission spectrum, and their position and intensity differ according to the chemical element that emits the light. For example, the hydrogen's emission spectrum consists of four lines: purple, blue, green, and red, located at positions that correspond to their wavelengths. The emission spectrum of helium consists of six lines that are purple, cyan, green, yellow, orange, and red. In other words, atoms and molecules produce their own "fingerprint" or "signature" when the light they emit is spread in a spectroscope.

Astronomers also measure how much light is present at each spectral line. The overall strength or weakness of all the lines of an element depends on the number of atoms of that element. The percentage composition of the atoms in a stellar body can also be determined. For example, by looking at the light emitted by the sun, scientists have been able to determine the relative number of atoms from specific elements and infer their percentage by mass.

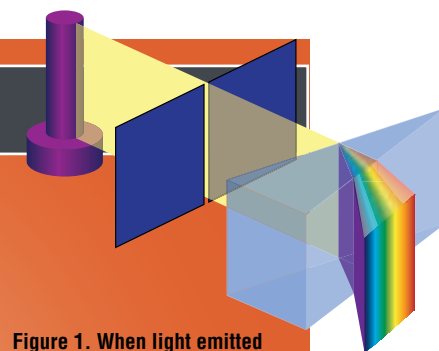
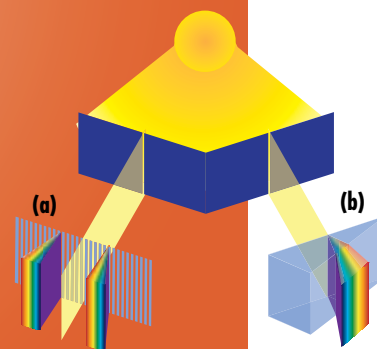


Figure 1. When light emitted by hydrogen is spread through a spectroscope, it reveals a characteristic emission spectrum specific only to hydrogen.

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Figure 2. Sketch of a spectroscope and how it forms a spectrum. The light emitted by a source from space goes through a narrow slit to form a beam of light, which is then spread into its components by a grating (a) or a prism (b), resulting in the light's spectrum.



as it can hold, and then decays when it is "saturated" with neutrons, and the cycle starts again. When an element formed through the "r" process becomes really heavy (total number of protons and neutrons close to 270), it spontaneously breaks apart through a process called nuclear fission.

"The neutrons add very rapidly at a temperature of a few billion degrees, going from iron to uranium in less than 1 second," Woosley says.

Elements created this way include transuranium elements—elements whose number of protons is higher than that of uranium—such as curium-250, californium-252, californium-254, and fermium-257.

Our stellar origins

When a supernova spews its newly made elements into space, the elements become part of an enormous cloud of gas and dust, called an interstellar cloud. The gas is made of 90% hydrogen, 9% helium, and 1% heavier



Supernova remnant ejected from the explosion of a massive star that occurred some 3,000 years ago.

atoms. The dust contains silicates (compounds made of silicon), carbon, iron, water ice, methane (CH₄), ammonia (NH₃), and some organic molecules, such as formaldehyde (H₂CO).

Such clouds are found so often between stars in our galaxy that astronomers think that all stars and planets have formed from them. Except for hydrogen, which appeared when

the universe formed through the Big Bang explosion, all of the elements on Earth have been cooked for billions of years in stars and then released in the universe through supernova explosions. The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, and the carbon in our apple pies were all made in the interiors of stars. The gold in jewels, tungsten in light bulbs, and silver in cookware were all produced during stellar explosions. We ourselves are made of "star stuff." ▲

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