The Origin of the Elements

edited by

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Introduction

The ordinary matter in our universe (known as baryonic matter) is made up of 94* naturally occurring elements, the familiar beasts of the periodic table. It is one of the stunning achievements of twentieth century science that the question of where these elements came from has now been answered.

The story of the origin of the elements is intimately intertwined with the evolution of our universe. It is also a central part of the evolution of life on Earth. The elements that make up our bodies reflect the cosmic abundance of the elements, and their presents on the Earth is, itself, part of the evolutionary history of stars. As Neil de Grasse Tyson, an astrophysicist and the director of New York City's Hayden Planetarium, has put it: "We are not simply *in* the universe; we are born from it." (Tyson 1998).

Web Reference for Periodic Table
http://pearl1.lanl.gov/periodic/default.htm

*Web Reference for 94 Naturally Occurring Elements
http://www.curtin.edu.au/curtin/centre/waisrc/OKLO/index.shtml

Allan Sandage on Stellar Evolution

"Historians of science a hundred years hence will remember twentieth-century astronomy for two main accomplishments. One is the development of a cosmology of the early universe, from creation through consequent expansion. The other is the understanding of stellar evolution. Although not as well known among nonscientists as the Big Bang is, the notion of the evolution of stars provided the foundation upon which astronomers built the grand synthesis of cosmological origins. The idea that stars change as they age and that these changes in turn alter their local environment and the chemical makeup of their parent galaxy--an idea that has developed only within the past fifty years--stands in the same relation to astronomy as the Darwinian revolution does to biology. It is a conceptual breakthrough that makes possible the modern understanding of the origin, evolution, and fate of the universe.

Because all elements heavier than helium have been nucleosynthesized in the deep interiors of stars, the heavier chemical elements that are the raw materials of life were all present at one time inside at least one star.

We are the product of the stars. This is one of the most profound insights to have arisen out of twentieth-century astronomy. Life is clearly a property of the evolving universe made possible by stellar evolution." (Sandage 2000)

Web Reference for Allan Sandage
http://www.ociw.edu/research/sandage.html

The Origin of the Light Elements

The origin of all the naturally occurring elements fall into two phases: Big Bang or Primordial Nucleosynthesis -- the origin of the “light” elements; and Stellar Nucleosynthesis -- the origin and production of the “heavy” elements.

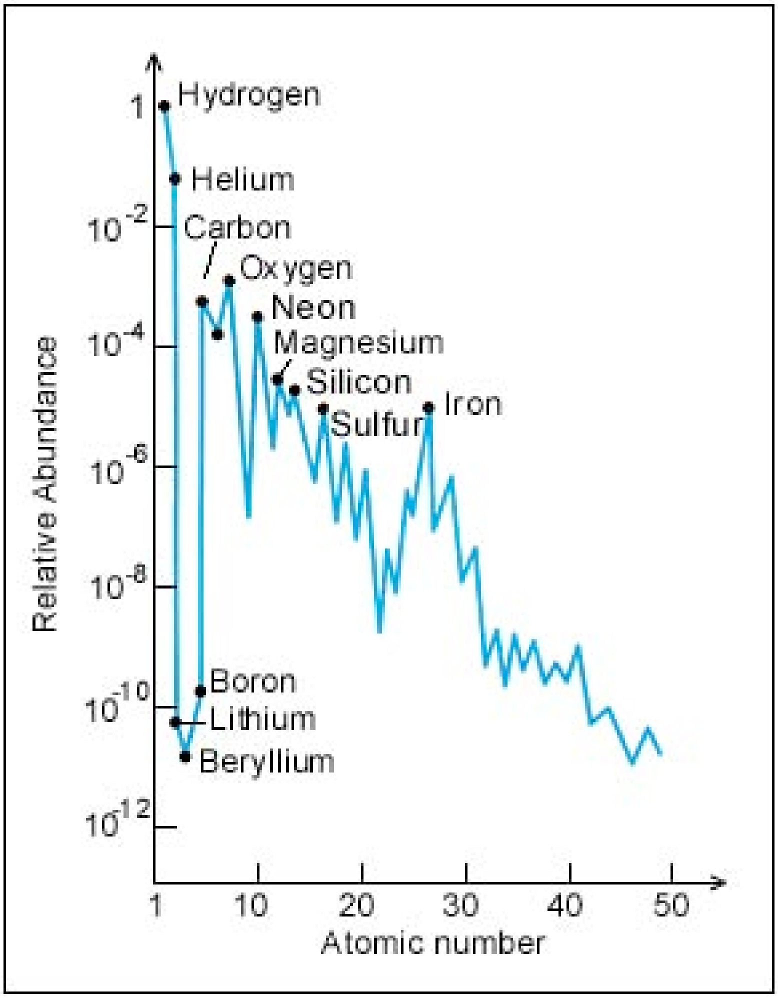
When astronomers refer to the “light elements”, they refer mainly to hydrogen and helium and their isotopes, and for very important reasons. Hydrogen is the simplest possible atom by definition, one proton and one electron. Anything less and it is no longer an atom; it is a subatomic particle with very different properties from the energetically stable atom. With this in mind it is easier to understand that the most abundant atoms in our universe should be the ones that formed first from subatomic particles.

Big Bang nucleosynthesis refers to the process of element production during the early phases of the universe, shortly after the Big Bang. It is thought to be responsible for the formation of hydrogen (H), its isotope deuterium 2H, helium (He) in its varieties 3He and 4He, and the isotope of lithium (Li) 7Li. Nuclei of hydrogen (protons) are believed to have formed as soon as the temperature had dropped enough to make the existence of free quarks impossible. For a while the number of protons and neutrons was almost the same, until the temperature dropped enough to make its slight mass difference favor the protons. Isolated neutrons are not stable, so the ones that survived are the ones that could bond with protons to form deuterium, helium, and lithium.

Why didn't all the neutrons bond with protons and make all the elements up to iron? While the temperature was dropping, the universe was also expanding, and the chances of collision were getting smaller. Also very important is the fact that there is no stable nucleus with 8 nucleons. So there was a bottleneck in the nucleosynthesis that stopped the process there. In stars, this bottleneck is passed by triple collisions of 4He nuclei (the triple-alpha process), but in the expanding early universe, by the time there was enough 4He the density of the universe had dropped too much to make triple collisions possible.

Using the Big Bang model, it is possible to make predictions about elemental abundances and to explain some observations which would otherwise be difficult to account for. One such observation is the existence of deuterium. Deuterium is easily destroyed by stars, and there is no known natural process other than the Big Bang which would produce significant amounts of deuterium.

Web Reference http://astron.berkeley.edu/~mwhite/darkmatter/bbndetails.html



The observed abundance of baryonic matter in our universe shows hydrogen makes up ~75% and helium ~25% of ordinary matter. All the other elements are a small fraction of the total (~1%) and represent the material that has been subjected to high enough temperatures and densities in stars to burn helium and make the heavier elements. Observation therefore closely matches the theoretical predictions of the standard Big Bang model. Note the chart uses a log scale in order to show the rarer, heavier elements on the vertical axis.

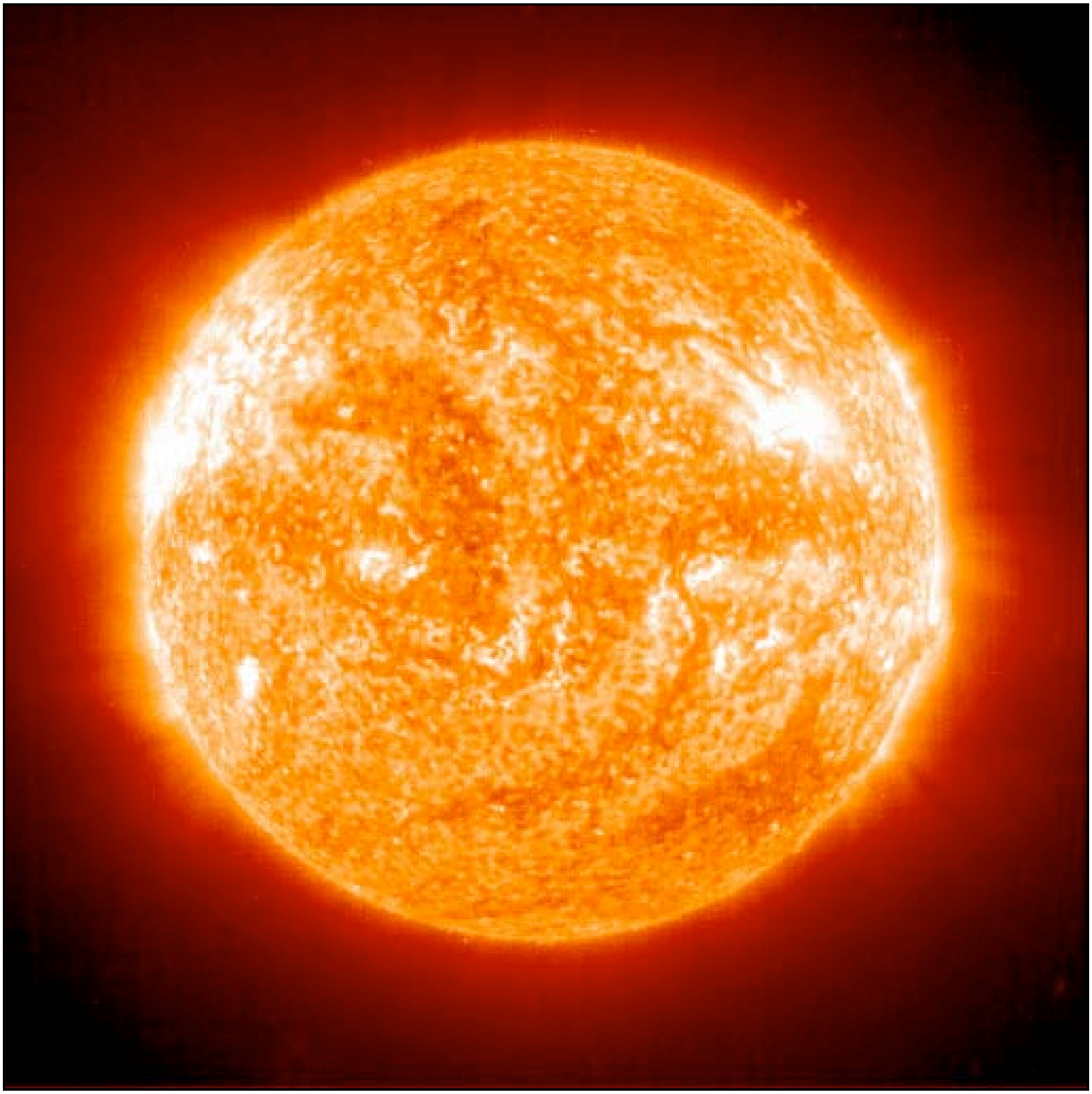
The Origin of the Heavy Elements

In recent decades, astronomers have gained a reasonably good understanding of how stars proceed through the various evolutionary paces from birth to death--how stars change their temperatures and densities while struggling to reestablish their burning cycles and how they create most of the heavy elements, without which rocky planets, life itself, and intelligent beings could not exist.

Relative abundances of the elements in the universe reveal the processes that synthesized heavier elements out of the hydrogen and helium from the Big Bang. Fusion in stars created more helium, skipped over lithium, 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 on the preceding page has a logarithmic scale, in which abundance increases by a factor of 10 for each unit of height. Elements heavier than cadmium (Cd) are too rare to be displayed.

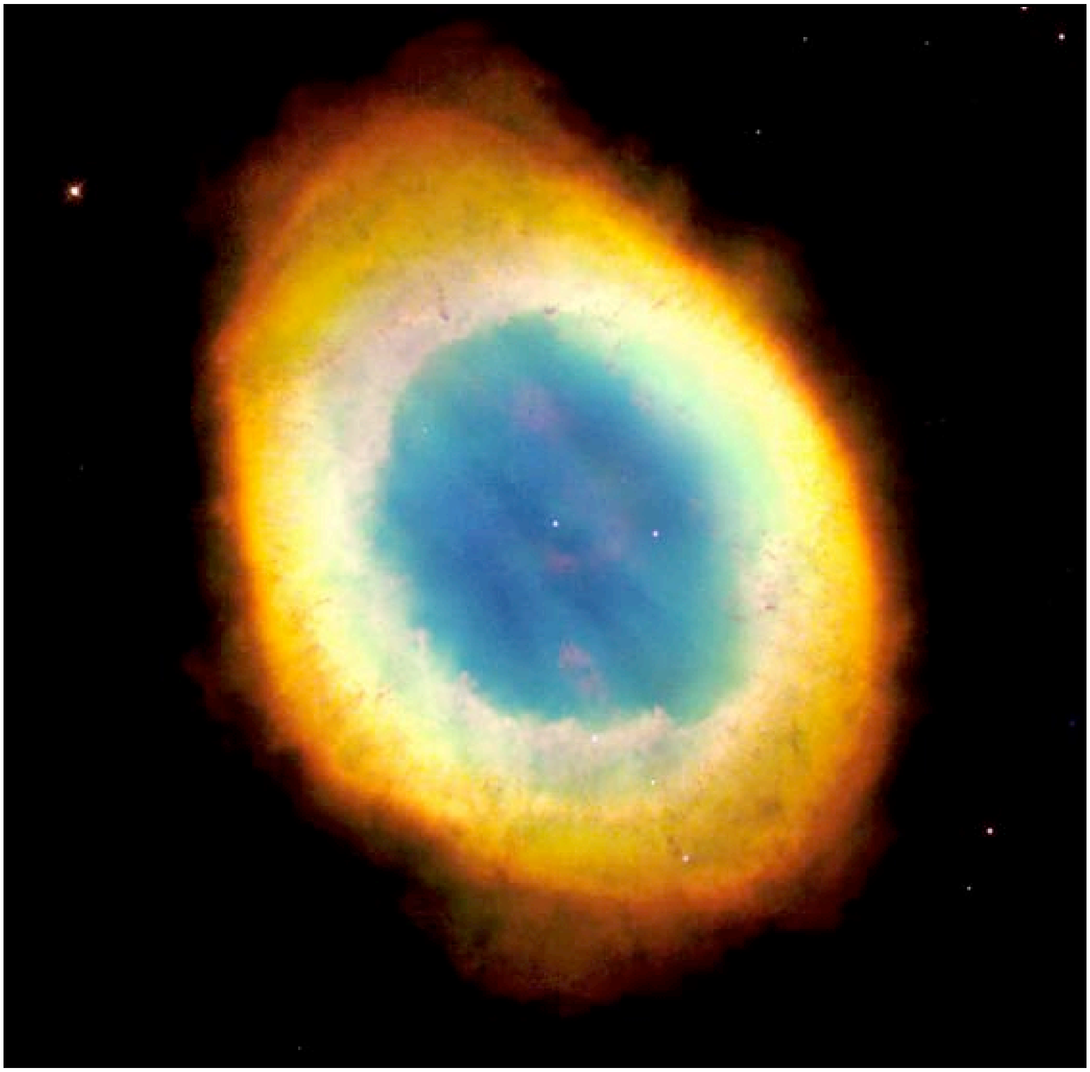
Web Reference

http://www.tufts.edu/as/wright_center/cosmic_evolution/docs/text/text_stel_6.html



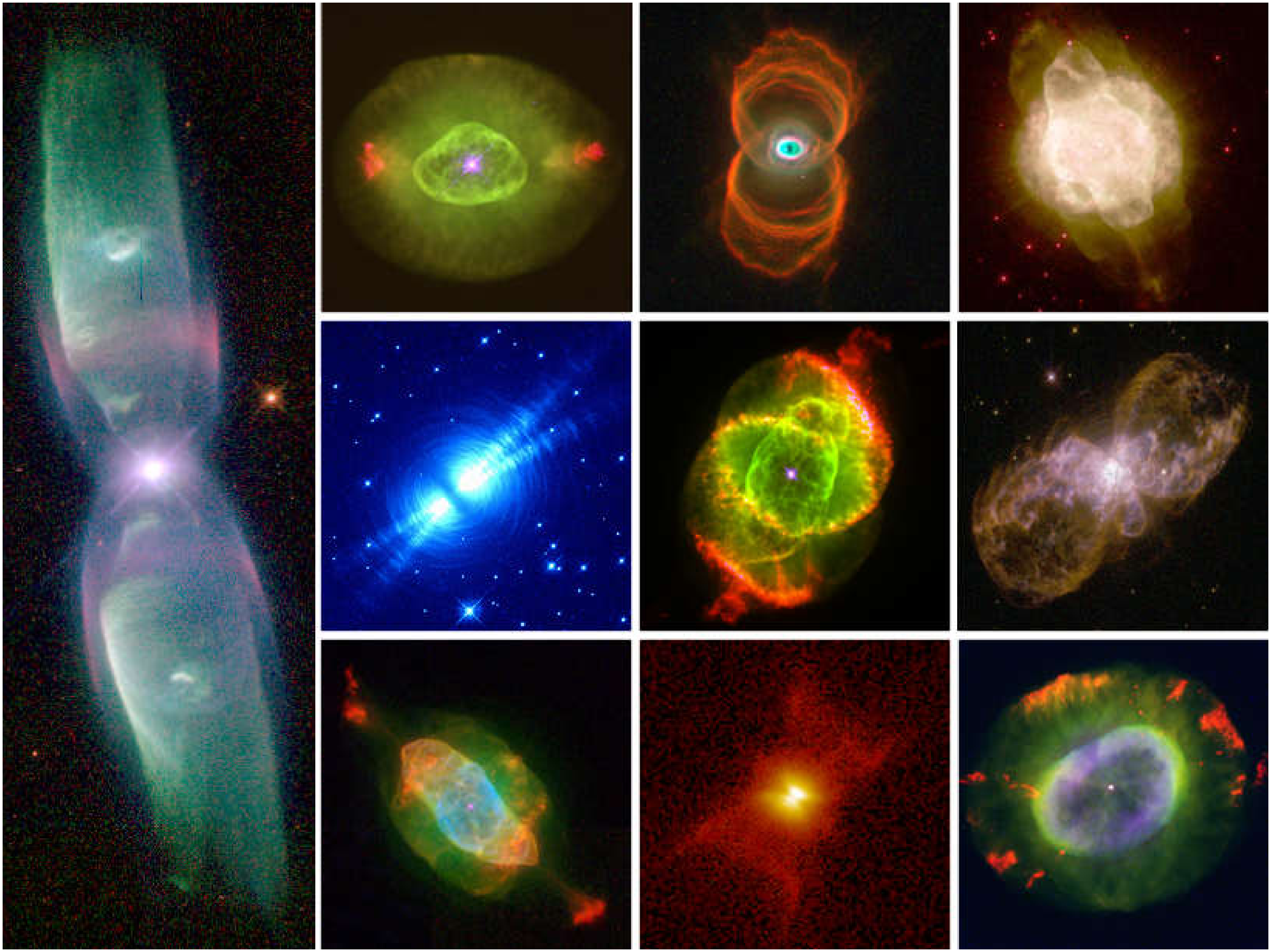
Stars, such as our Sun (above), are the only place in our universe where the elements heavier than hydrogen and helium are produced. Stars with a mass similar to our Sun can produce heavier elements up to oxygen.

Web Reference
http://sohowww.nascom.nasa.gov/

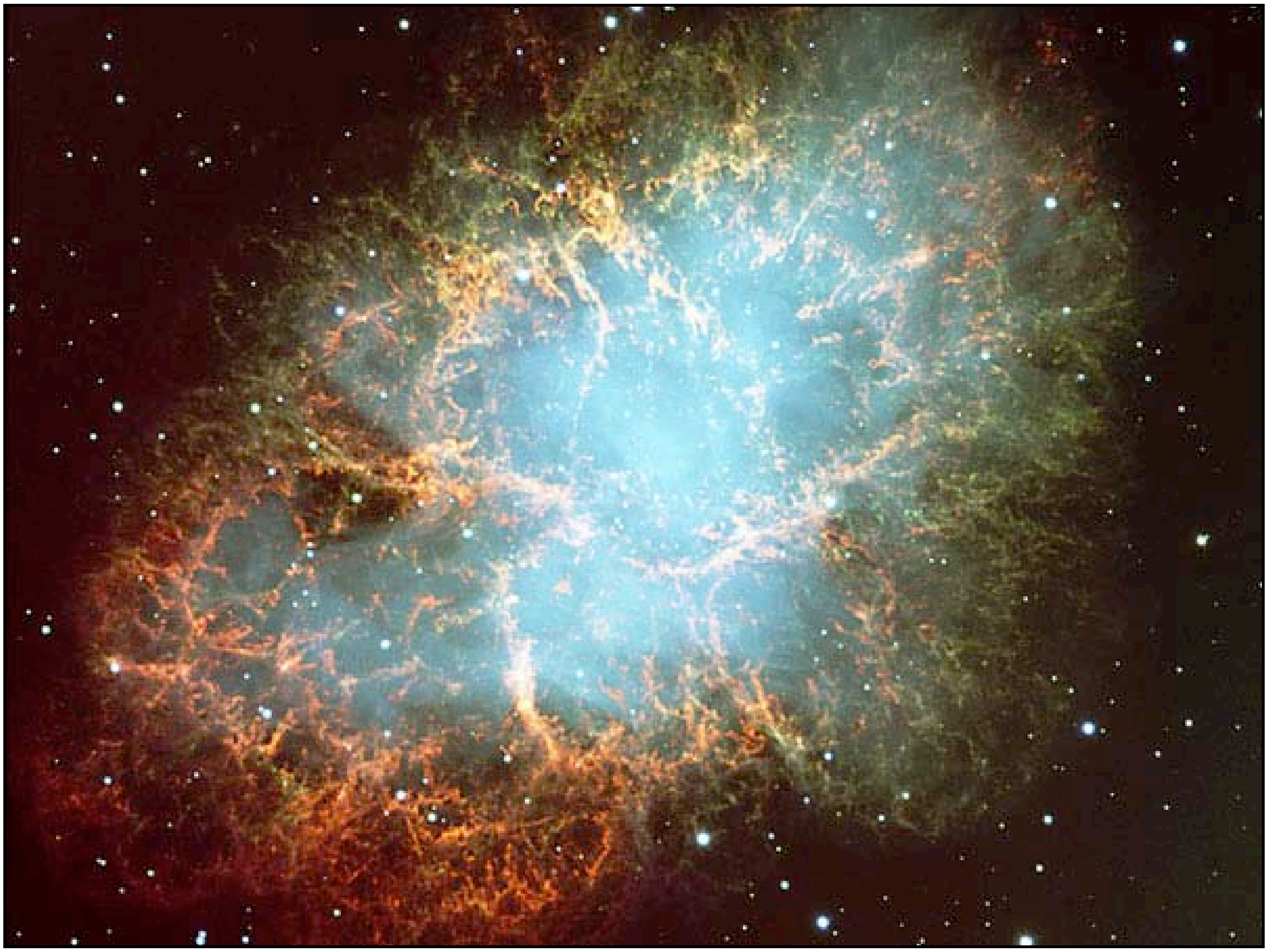


Stars the size of our Sun are fated to cast off their outer shell of gas into space creating a nebula similar to the Ring Nebula pictured above. This nebula is approximately one light-year in diameter and is located some 2,000 light-years from Earth. The colors correspond to three different chemical elements: helium (blue), oxygen (green), and nitrogen (red).

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap010729.html



A montage of images of planetary nebulae made with the Hubble Space Telescope. These illustrate the various ways in which dying stars eject their outer layers as highly structured nebulae. Credits: Bruce Balick, Howard Bond, R. Sahai, their collaborators, and NASA.



The heaviest elements are produced in supernova explosions of massive stars that are at least eight times the size of our Sun. The Crab Nebula, pictured above, was produced by a supernova explosion witnessed by Chinese astronomers in 1054 A.D.. Now approximately 10 light years in diameter, it is still expanding at about 1,100 miles/sec.

Web Reference
http://www.eso.org/outreach/press-rel/pr-1999/pr-17-99.html

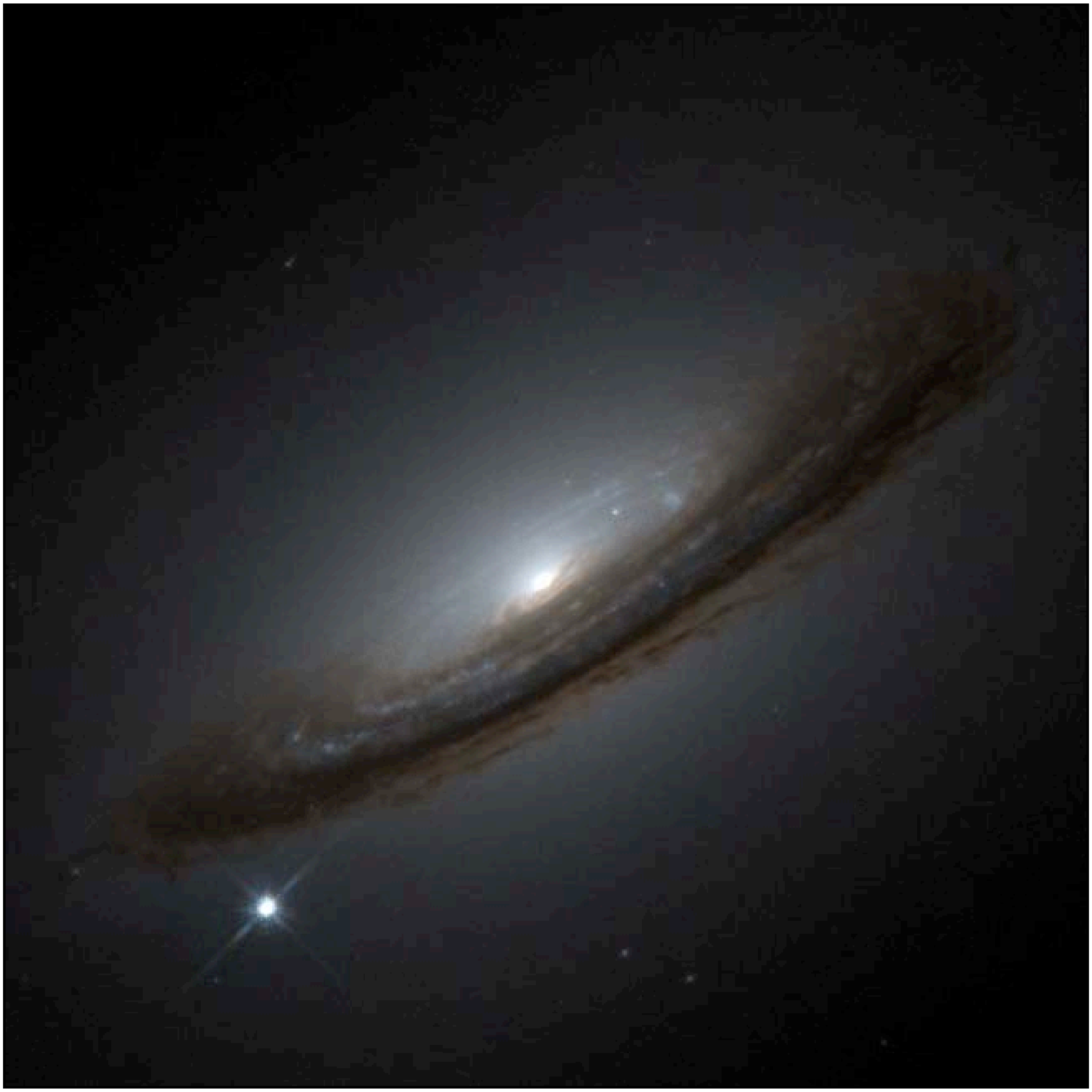
Supernovae are divided into two basic physical types:

Supernova Type Ia

These result in some binary star systems between a red giant and a white dwarf. In such a system, mass flows from the red giant to the white dwarf. Eventually, so much mass piles up on the white dwarf that it can no longer support itself and it collapses in a supernova explosion.

Supernova Type II

These supernovae occur at the end of a massive star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. If the star's iron core is massive enough then it will collapse and become a supernova.



Supernova 1994D, visible as the bright spot on the lower left, occurred long ago in the outskirts of disk galaxy NGC 4526. Supernova 1994D is not of interest for how different it was, but rather for how similar it is to other supernovae. The light it emitted during the weeks after its explosion identified it as a Type Ia supernova, which are of great interest to astronomers.

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap981230.html

The Evolution of Double Stars and Supernovae of Type Ia

Almost half the stars in the sky are double or multiple. If the two stars are close together then they can have dramatic effects on each other. The more massive of the two stars will evolve faster and when it becomes a red giant it may be so big that gravity draws its outer atmosphere across to the companion star. The transfer of material can lead to all kinds of interesting and exciting effects, depending on the properties of the two stars.

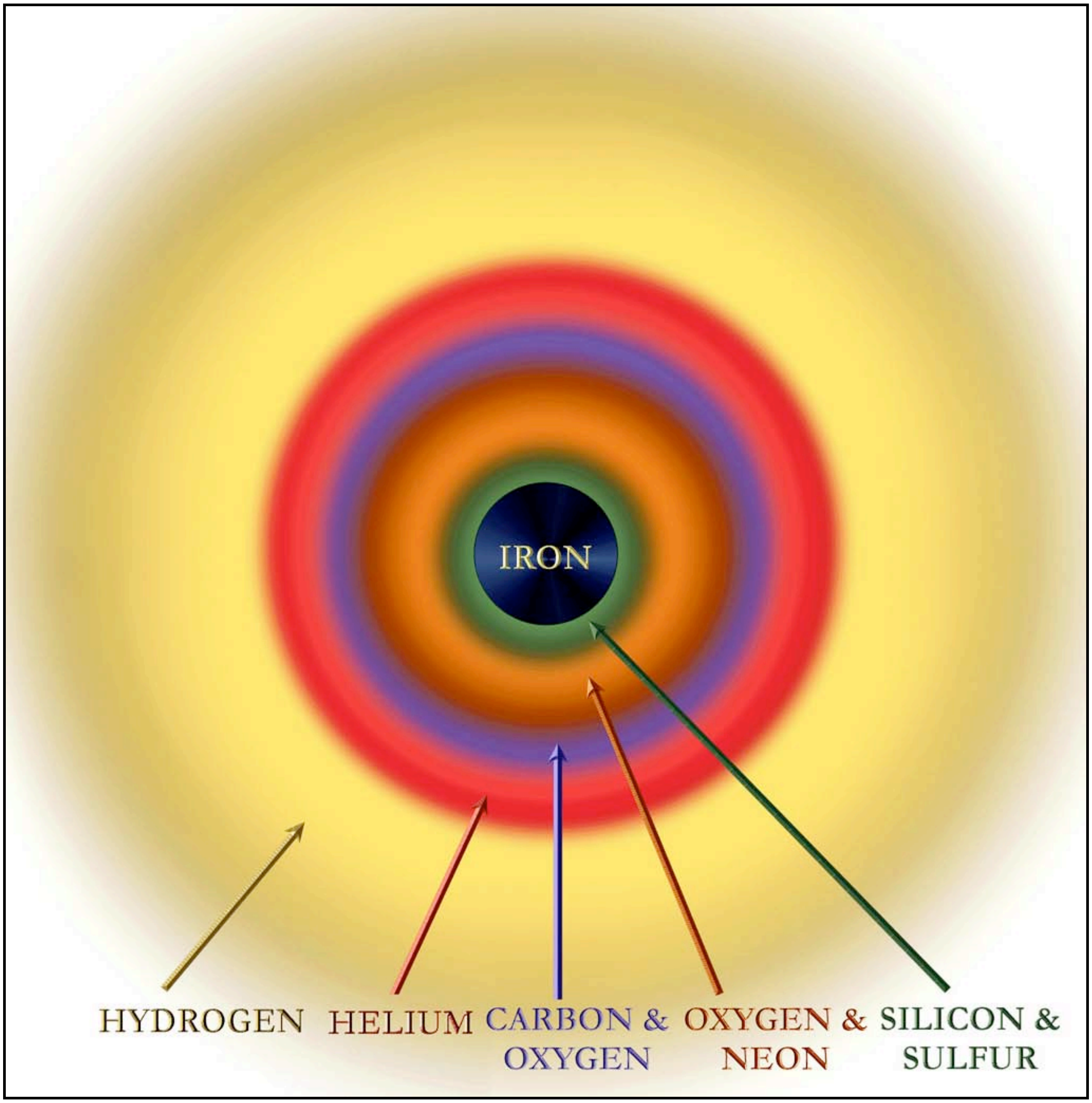
Stars that have lost their atmospheres to their companions are identical to the white dwarves in the center of planetary nebulae. The less massive companion star, assisted by the extra mass it has gained, eventually becomes a red giant and starts to transfer material back onto its white dwarf companion. This can have the effect of increasing its mass beyond a critical limit of 1.4 times the mass of the Sun, known as the Chandrasekhar limit. When this happens the carbon-oxygen core can suddenly explode, converting half the mass by nuclear fusion into elements like chromium, manganese, iron, cobalt and nickel. This is called a Type Ia supernova. Because they are very bright and we think they always explode releasing about the same amount of energy, they are used as standard brightness light sources. The recent discovery that the expansion of the universe is accelerating, was made by observing these supernovae in galaxies 5,000 million light years away. Type Ia supernovae are also a major source of iron and other heavy elements.

Web Reference
http://www.pbs.org/wgbh/nova/universe/super1a.html

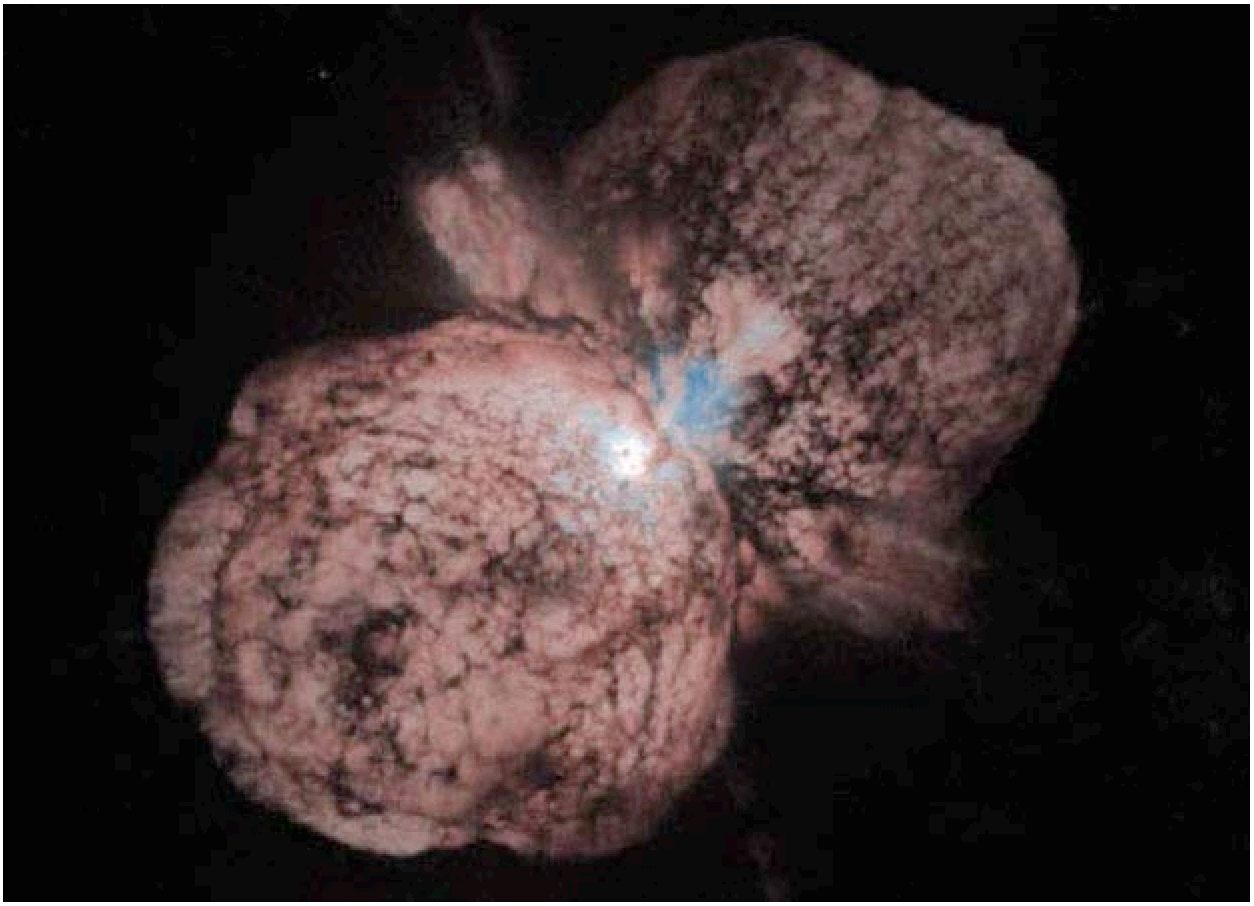
Massive Stars and Supernova Type II

The most significant locations for the natural alchemy of fusion are 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 sun like 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.

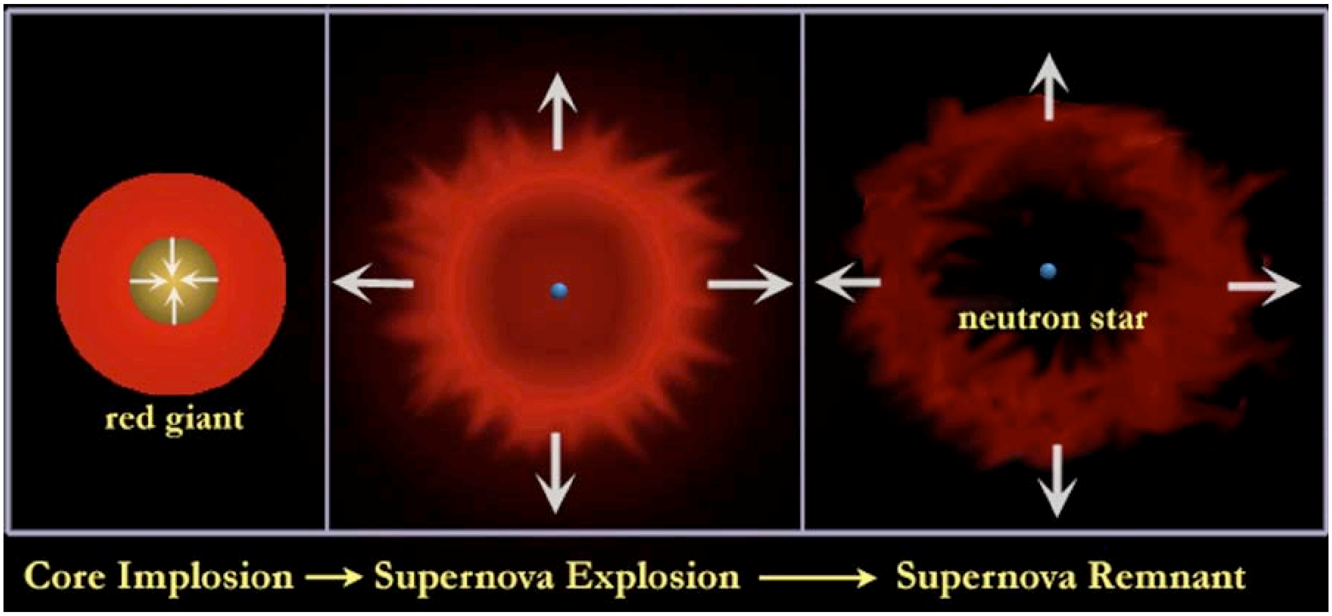


The iron nucleus occupies a special place in nuclear physics and, by extension, in the composition of the universe. Iron is the most tightly bound nucleus. Lighter nuclei, when fusing together, release energy. To make a nucleus heavier than iron, however, requires an expenditure of energy. This fact, 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 than can be replenished, it is perched on the edge of disaster.



Eta Carinae, a massive supergiant star thought to be 150 solar masses and 7,500 light years from Earth, had a violent outburst in 1841. This star is one of the most luminous star systems in our Galaxy, radiating millions of times more power than our Sun. Eta Carinae is also one of the strangest star systems known, brightening and fading greatly since the early 1800s. This Hubble Space Telescope image reveals two plumes, made of nitrogen and other elements synthesized in the interior of the star, moving out into the interstellar void at more than two million miles per hour. Some of the elements that make up the Earth came from similar discharges from ancestral stars. Speculation continues among astronomers that Eta Carinae will undergo a supernova explosion sometime in the next thousand years.

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap000813.html



For massive stars 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 our Sun in its entire lifetime.

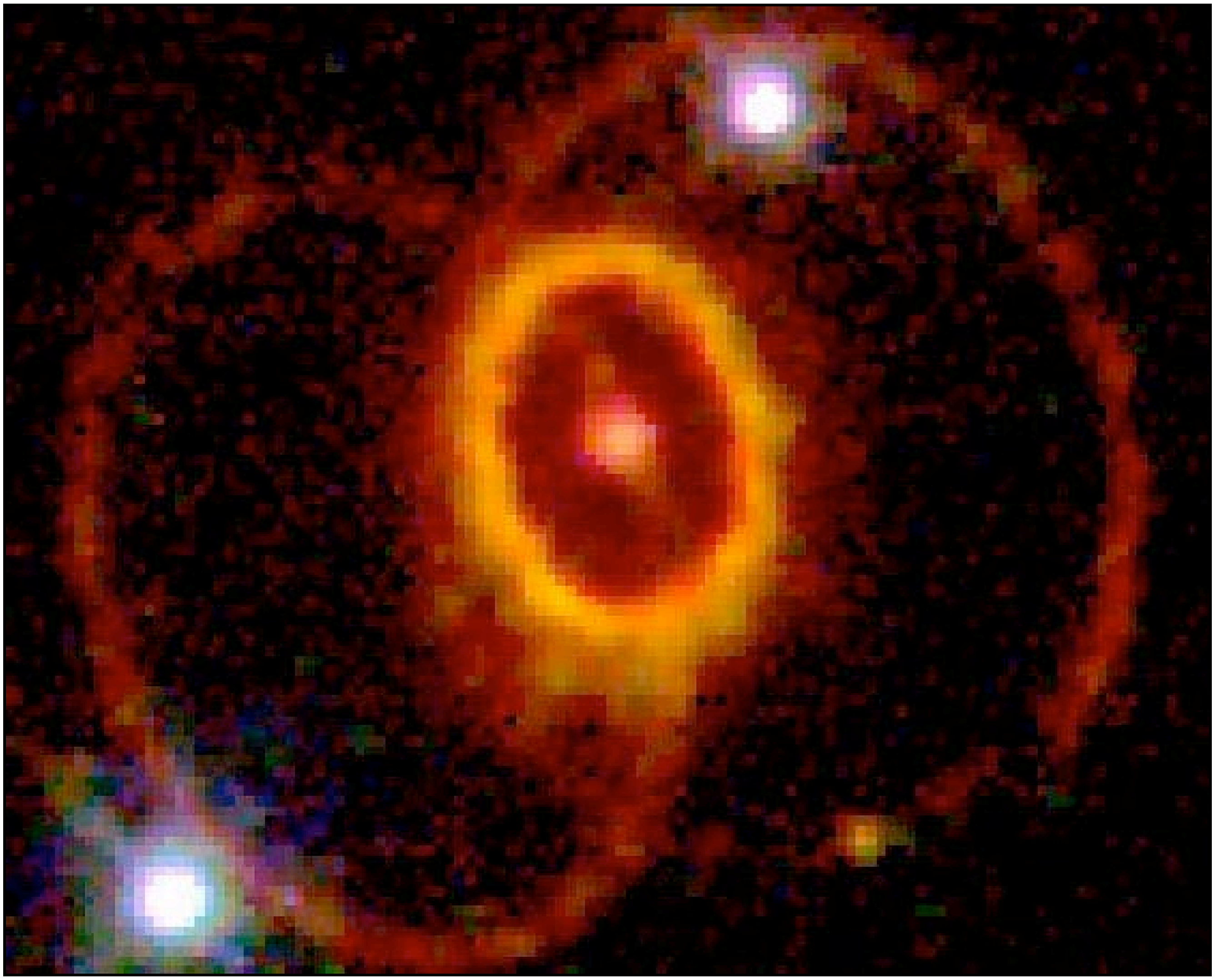
Such type II supernova explosions play a special role in the chemical enrichment of the universe. First, unlike stars of low mass that lock up their products in white dwarfs, exploding stars eject their outer layers, which are unburned. They belch out the helium that was formed from hydrogen burning 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, 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.

Web References

http://www.pbs.org/wgbh/nova/universe/super2.html

http://chandra.harvard.edu/xray_sources/supernovas.html



Supernova 1987A Seen in Infrared

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.

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.

Web Reference
http://proxy.arts.uci.edu/~nideffer/Hawking/early_proto/kirshner.html

The Crab Supernova Nebula

We have come full circle. The universe is the evolutionary story of generations; for every death there is a new beginning. In its death throes, supernovae enrich the interstellar medium so that new stars and planets can be born. Every atom of calcium in every bone in our bodies, every atom of iron in our blood, was shot out of a star billions of years ago, before the birth of our own Sun. We are literally and actually Children of the Stars.

Web References

http://antwrp.gsfc.nasa.gov/apod/ap020920.html

http://chandra.harvard.edu/xray_sources/crab/crab.html

References Cited

Sandage, A. (2000). Twinkle Twinkle. *Natural History*, 2/00, 64-6.

Tyson, N.(1998). Greatest Story Ever Told. *Natural History*. 3/98, 82-84.

Recommended Reading

Silk, Joseph (2001). *The Big Bang (3rd Edition)*, New York: W. H. Freeman .

Chown, Marcus (2001). *The Magic Furnace: The Search for the Origins of Atoms*. New York: Oxford University Press.

For more on the origins of the elements on the web go to:

Ned Wright's Cosmology Tutorial Big Bang Nucleosynthesis
http://www.astro.ucla.edu/~wright/BBNS.html

MAP Cosmology
http://map.gsfc.nasa.gov/m_uni/uni_101bbtest2.html

Particle Adventure
http://particleadventure.org/particleadventure/

This web paper was last updated 1/19/03.

For further information on related topics go to:

Cosmological Evolution
http://fire.biol.wwu.edu/trent/alles/Cosmic_Evolution_index.html

Alles Introductory Biology Lecture: *Cosmological Evolution*
http://fire.biol.wwu.edu/trent/alles/101Lectures_Index.html

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http://fire.biol.wwu.edu/trent/alles/index.html