The Origin of the Elements

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Note: In PDF format most of the images in this web paper can be enlarged for greater detail.

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. And 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://periodic.lanl.gov/index.shtml

http://en.wikipedia.org/wiki/Chemical_element - Recently_discovered_elements

*Web References for 94 Naturally Occurring Elements

http://en.wikipedia.org/wiki/Natural_nuclear_fission_reactor

http://antwrp.gsfc.nasa.gov/apod/ap050220.html

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, 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 by stars, all the heavier chemical elements that are the raw materials of life were one time part of a stellar life cycle. 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)

Allan Sandage was co discover of quasars and the astronomer heir of Edwin Hubble's project to determine the rate of expansion of the universe.

Web Reference
http://en.wikipedia.org/wiki/Allan_Sandage

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.

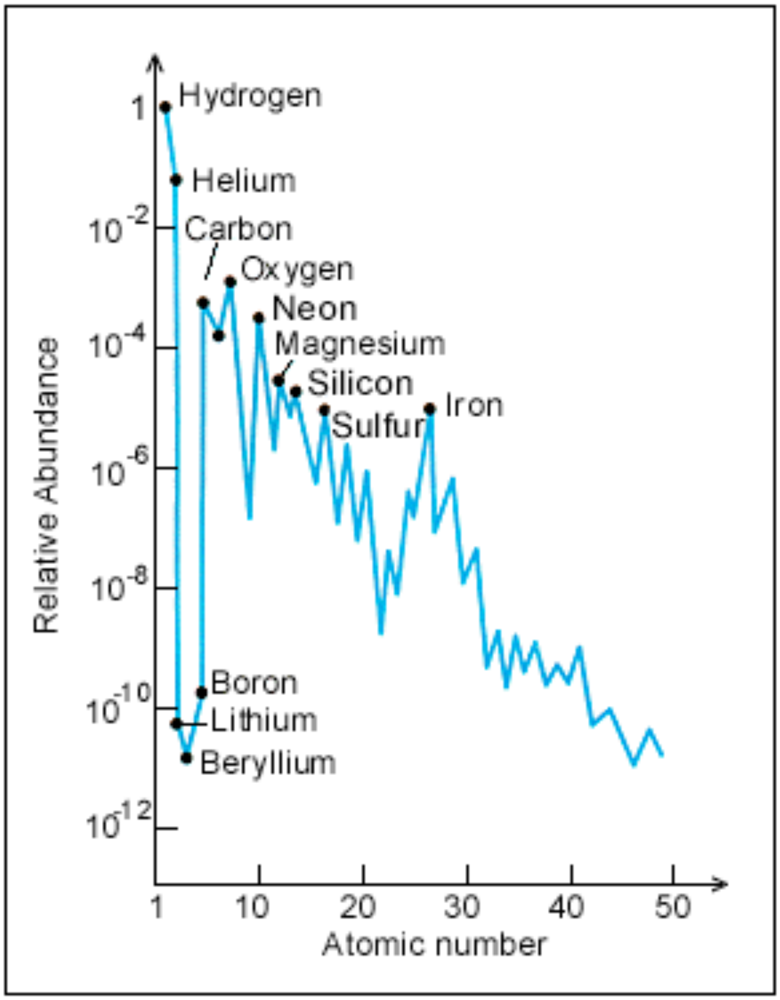
When astronomers refer to the "light elements", they refer mainly to hydrogen and helium and their isotopes, and for very important reasons. Hydrogen is the simplest possible atom by definition, one proton and one electron. Anything less and it is no longer an atom; it is a subatomic particle with very 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 stages 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 References

http://en.wikipedia.org/wiki/Supernova (see "Source of heavy elements" section)

For a detailed history of the development of our understanding of the formation of the heavy elements see Arno Penzias' 1978 Nobel Prize Lecture available at:

http://nobelprize.org/nobel_prizes/physics/laureates/1978/penzias-lecture.html

Sir Fred Hoyle (1916-2001)

"The concept of nucleosynthesis in stars was first established by Hoyle in 1946. This provided a way to explain the existence of elements heavier than helium in the universe, basically by showing that critical elements such as carbon could be generated in stars and then incorporated in other stars and planets when that star "dies". The new stars formed, now, start off with these heavier elements and even heavier elements are formed from them. Hoyle theorized that other rarer elements could be explained by supernovas, the giant explosions which occasionally occur throughout the universe, whose temperatures and pressures would be required to create such elements."—William Alfred Fowler

Web Reference
http://en.wikipedia.org/wiki/Fred_Hoyle

Hoyle's Role in B2FH

IN JULY 2007, THE NUCLEAR ASTROPHYSICS 1957–2007 conference commemorated the 50th anniversary of the publication of "Synthesis of the elements in stars," by Burbidge, Burbidge, Fowler, and Hoyle (referred to by the shorthand B2FH). In response, D. D. Clayton ("Hoyle's equation," Perspectives, 21 December 2007, p. 1876) wrote that a key paper by Hoyle in the development of the theory of stellar nucleosynthesis has been under cited and, by implication, that not enough credit has been given to Fred Hoyle. I agree.

As one of the only two survivors of B2FH, I would like to provide some additional comments. First, the theory of stellar nucleosynthesis is attributable to Fred Hoyle alone, as shown by his papers in 1946 and 1954 and the collaborative work of B2FH. In writing up B2FH, all of us incorporated the earlier work of Hoyle.

In my view, Hoyle's work has been under cited in part because it was published in an astrophysical journal, and a new one at that (the very first volume, in fact), whereas B2FH was published in a well established physics journal, *Review of Modern Physics*. When B2FH was first written, preprints were widely distributed to the nuclear physics community. Willy Fowler was very well known as a leader in that community, and the California Institute of Technology already had a news bureau that knew how to spread the word.

As I pointed out at the meeting in July, Margaret Burbidge and I wrote the first draft of B2FH. We deliberately incorporated extensive observations and experimental data supporting the theory, and Hoyle and Fowler worked extensively on the early draft to see that all of the work was covered. There was no leader in the group. We all made substantial contributions, and Hoyle was entirely happy with the result.

Hoyle should have been awarded a Nobel Prize for this and other work. On the basis of my private correspondence, I believe that a major reason for his exclusion was that W. A. Fowler was believed to be the leader of the group. As I stated in Pasadena, this was not the case.

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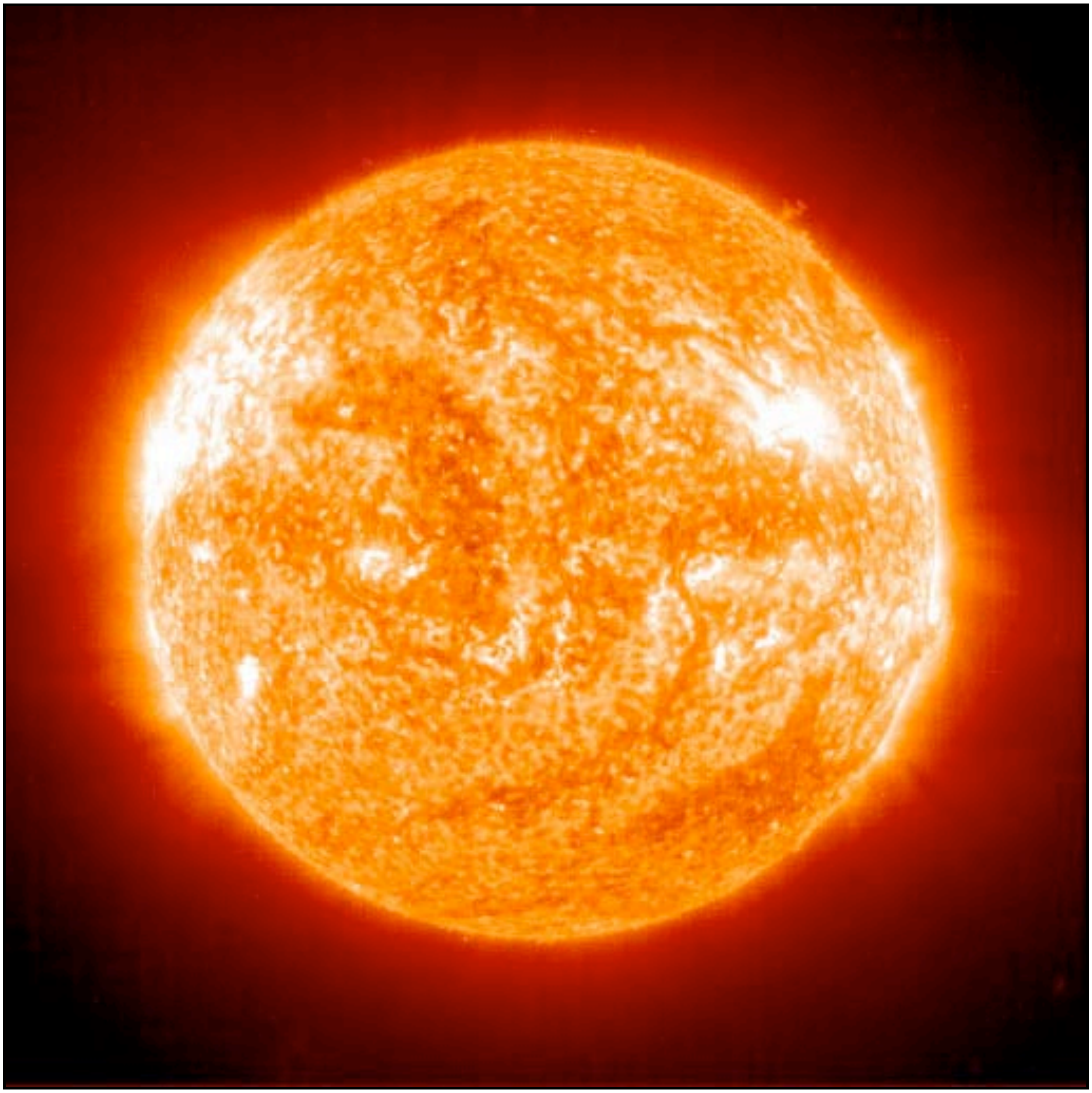
(Letter to *Science*, Vol. 319, 14 March 2008, 1484)



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/

Planetary Nebulae

~ 95% of all stars that we see in our own galaxy, the Milky Way, will ultimately become "planetary nebulae". This includes the Sun. Planetary nebulae are formed when a red giant star ejects its outer layers as clouds of luminescent gas, revealing the dense, hot, and tiny white dwarf star at its core. The other 5% of stars—that is, those born with masses more than eight times larger than our Sun—end their lives as supernovae.

The name "planetary nebula" is a misnomer. The name arose over a century ago when early astronomers looking through small and poor-quality telescopes saw these objects as compact, round, green-colored objects that reminded them of the view of Uranus. However, "planetary nebulae" are not made of planets, and no planets are visible within them. Rather, they are the gaseous and dusty material expelled by a geriatric star just before death. A far better name for these objects would be "ejection nebulae". Think of ejection nebulae as a cloud of smoke which escapes from a burning log as it collapses and crumbles into embers.

Web References

http://en.wikipedia.org/wiki/Planetary_nebula

http://oposite.stsci.edu/pubinfo/PR/97/pn/photo-gallery.html

The Life of a Star like the Sun

by Bruce Balick

The Sun generates all of its heat in its core. This heat both warms the Earth and prevents gravity from forcing the Sun to undergo a catastrophic gravitational collapse. The fuel which supplies the heat is hydrogen. Hydrogen nuclei are converted to helium as heat is released.

Five billion years from now the Sun's hydrogen fuel will be depleted. Gravity will then force the spent core, now almost pure helium, to shrink, compress, and become even hotter than at present. The high temperatures will eventually ignite the helium ashes. The result is carbon nuclei and even more heat. The "second wind" of heat release will be furious, increasing the light emitted from the future Sun's surface by a thousand fold. Meanwhile, the same heat will cause the outer layers of the present Sun to expand and form a huge "red giant".

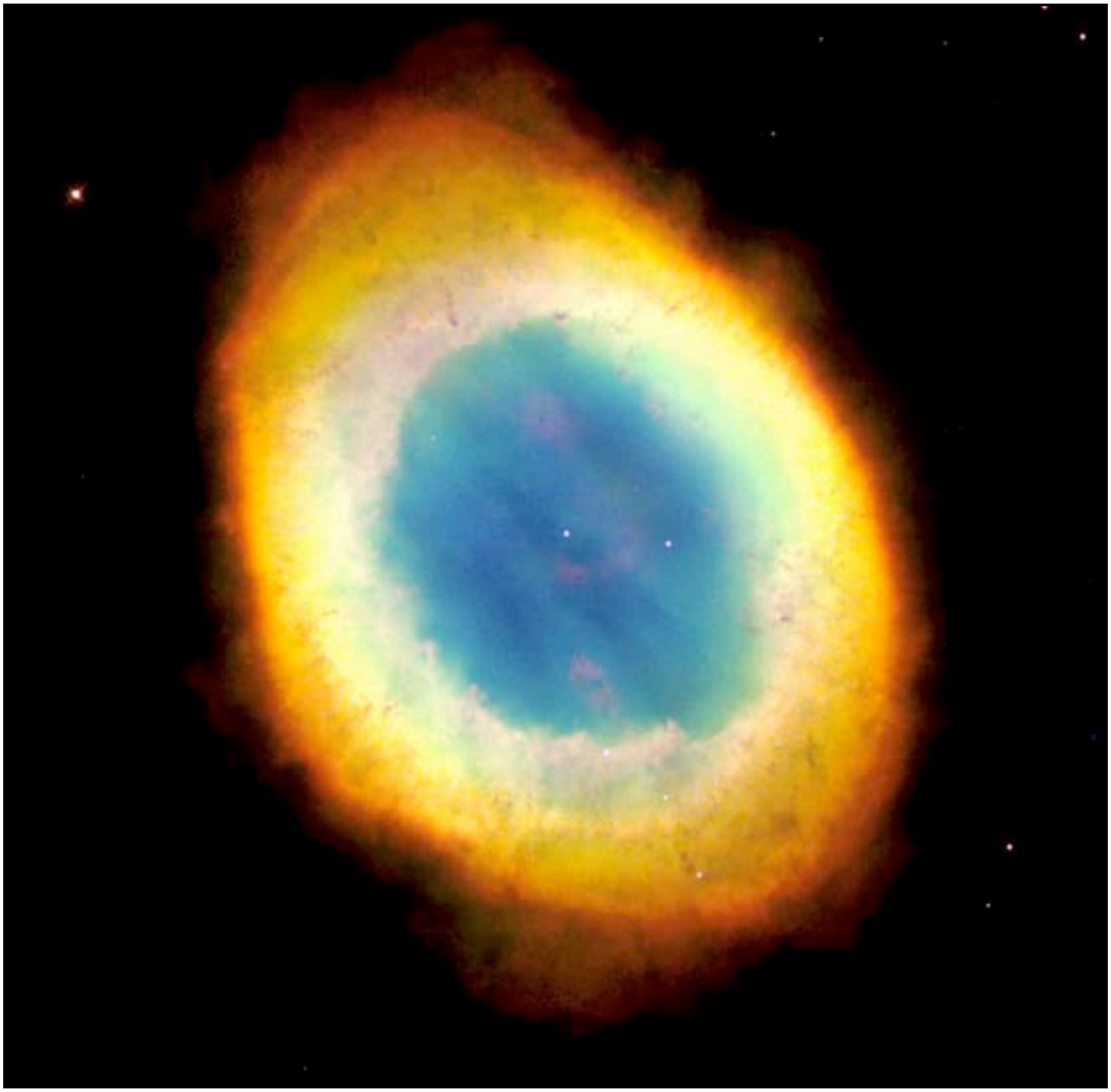
As stellar time goes, the helium won't last long—certainly less than a mere few hundred million years. With its helium transformed into unburnable carbon, the solar core shrinks suddenly (a few thousand years) until just over half the mass of the present Sun is packed into a hot (million degree), dense (a ton per teaspoon) ball the size of the Earth. This amazing stellar remnant is called a white dwarf. The remnant's fuel reserves are now finally gone. Its shrunken stellar core is now entering retirement. Even so, one large final fling lies ahead for this star.

The story shifts from the dying core to the star's distended outer layers. The core, their underlying foundation, now has all but imploded. The outer layers of the Sun fall inward toward the core. But the base material ignites on the way in, causing the outer surfaces to bounce and vibrate. Eventually the outer 40% of the Sun's mass will be spasmically "coughed" into space, floating outward through the solar system and beyond in a concentric set of spherical bubbles. Seen from far away, these may eventually blend together into a gigantic stellar "halo". As the outer layers are flung outward increasingly deeper and deeper layers of the Sun become exposed as its outermost surface, like peeling an onion.

When the process ends, the former core of the Sun emerges through its expanding veil of ejected material as a white dwarf. The highly energetic forms of light emitted by the hot white dwarf interact with the electrons attached to the atoms in the gas cloud, resulting in a colorful nebula. (For more on Planetary Nebulae see Balick & Frank, 2004.)

Web Reference

http://www.astro.washington.edu/balick/WFPC2/



The Hubble Space Telescope captured this view of the Ring Nebula (M57), the most famous of all planetary nebulae. In the image, the telescope has looked down a tunnel of gas cast off by a dying star thousands of years ago. The image, also, shows elongated dark clumps of material embedded in the gas at the edge of the nebula, and the dying central star floating in a blue haze of hot gas. The nebula is about one light-year in diameter, and is located some 2,000 light-years from Earth. The colors are approximately true colors, and represent three different chemical elements: helium (blue), oxygen (green), and nitrogen (red).

Web Reference
http://apod.nasa.gov/apod/ap091115.html

Planetary nebulae have long been appreciated as a final phase in the life of a sun-like star. Only much more recently however, have some planetary nebula been found to have halos like this one, likely formed of material shrugged off during earlier active episodes in the star's evolution. While the planetary nebula phase is thought to last for around 10,000 years, astronomers estimate the age of the outer filamentary portions of this halo to be 50,000 to 90,000 years.

(Composite image by Tony and Daphne Hallas)

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap040709.html

The classic appearance of the Ring Nebula is due to perspective—our view from planet Earth looks down the center of a roughly barrel-shaped cloud of gas. But graceful looping structures are seen to extend even beyond the Ring Nebula's familiar central regions in this false-color infrared image from the Spitzer Space Telescope.

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap050311.html

A classic planetary nebula, the Cat's Eye Nebula (NGC 6543), seen above, shows the final, brief yet spectacular phase in the life of a sun-like star. This nebula's dying central star produced the simple, outer pattern of dusty concentric shells by shrugging off outer layers in a series of regular convulsions.

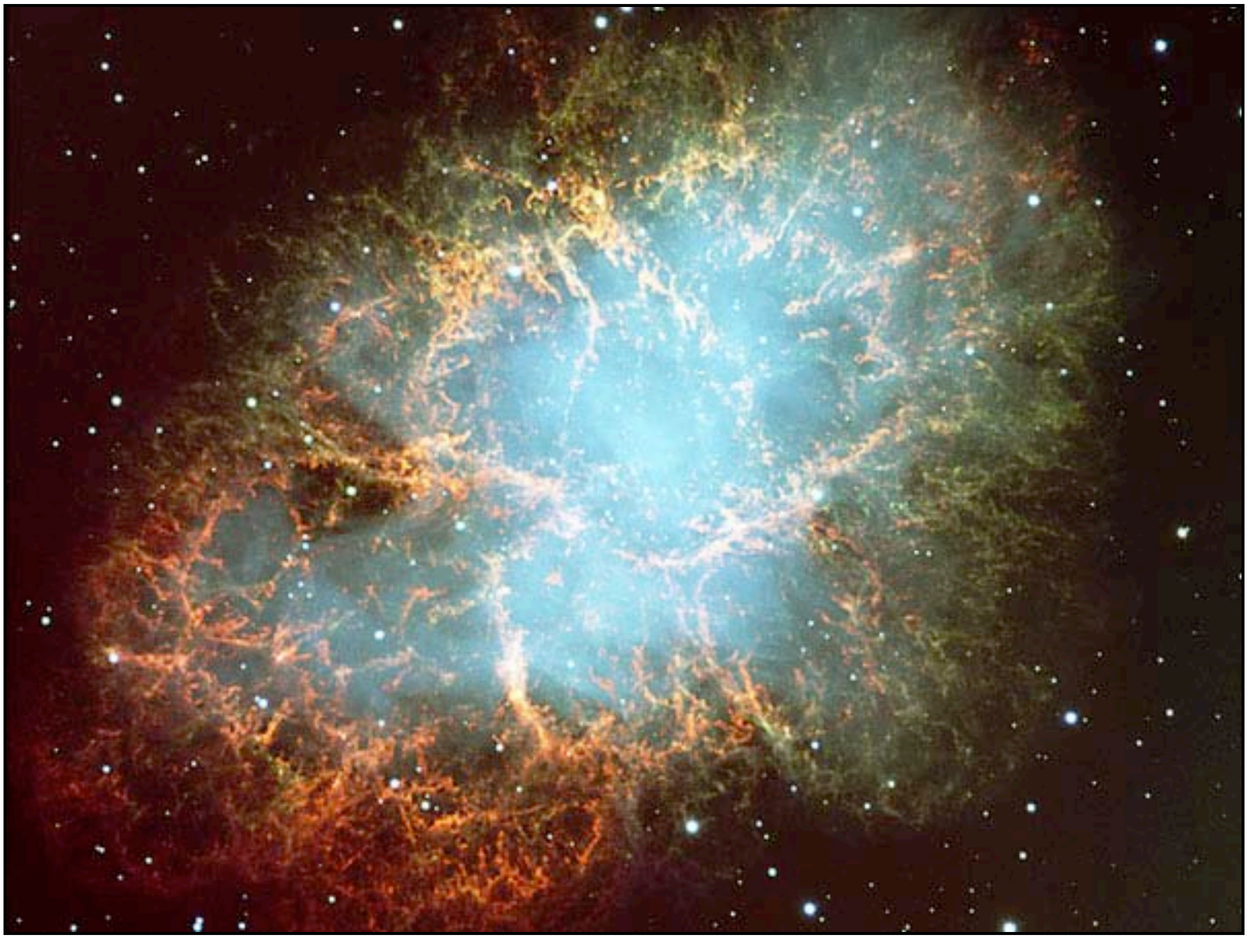
Web reference
http://www.youtube.com/watch?v=sPJ8ncAdp_A&feature=related

But the formation of the beautiful, more complex inner structures, shown in this close-up view, is not well understood. Seen so clearly in this Hubble Space Telescope image, the nebula is over half a light-year across and lies three thousand light-years from Earth. By observing the Cat's Eye Nebula, astronomers may well be seeing the fate of our sun, destined to enter its own planetary nebula phase of evolution 5 billion years from now.

Web References

http://antwrp.gsfc.nasa.gov/apod/ap040910.html

http://www.youtube.com/watch?v=CJMz0Ke4AGU&NR=1



The Crab Nebula

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 per second.

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

Types of Supernovae

(Gilmore, 2004)

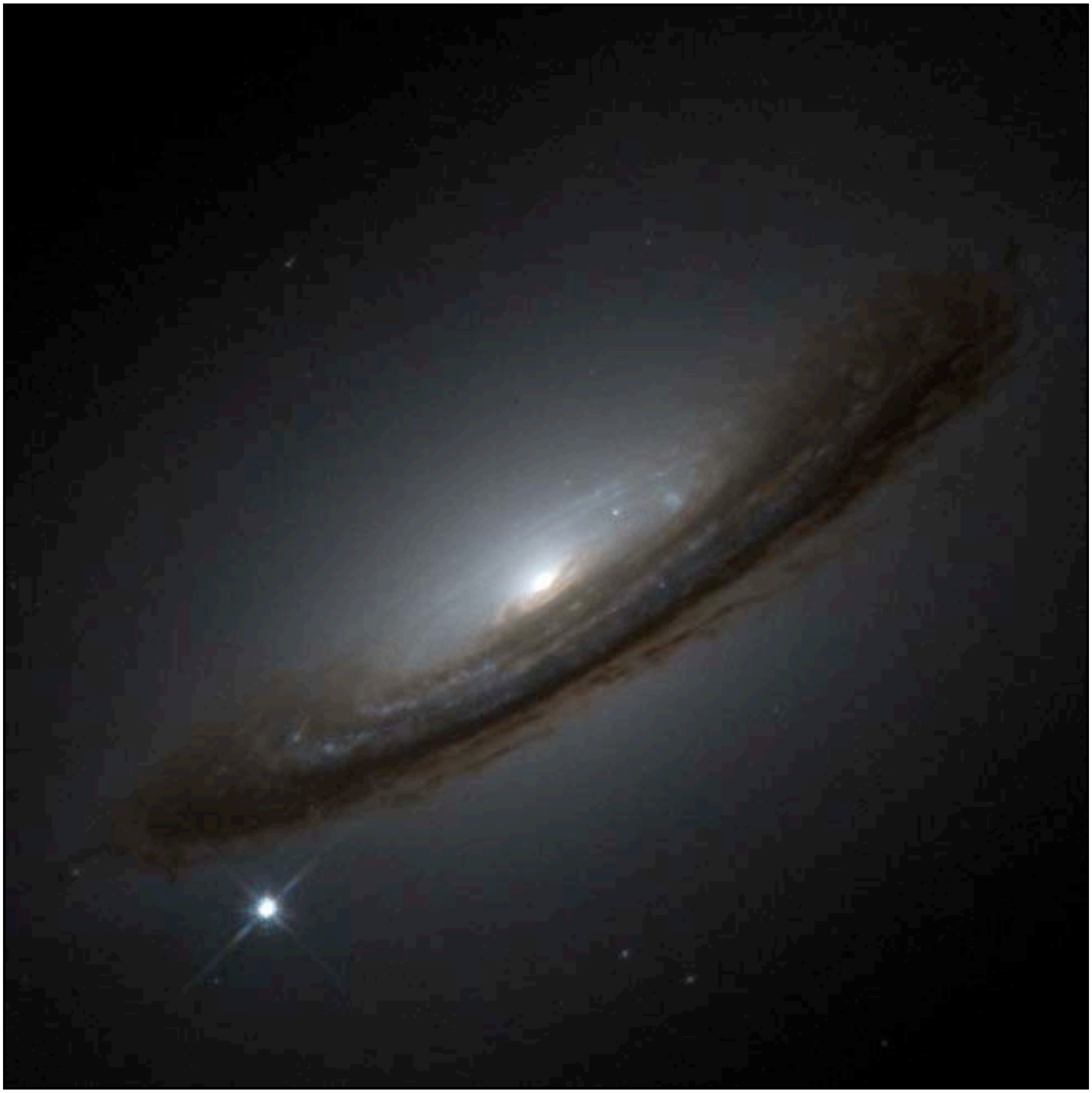
Type Ia Supernovae

Supernovae come in several types, classified according to their origin. Type Ia supernovae, for instance, are caused by the explosion of a white dwarf, a remnant of a star with mass up to a few times that of our Sun. Over time, it accretes too much mass to remain stable and completely self-destructs. The mass accretion process most likely involves a merger of two discrete white dwarfs, which fuse briefly into a single unstable object, leaving behind a cooling, expanding debris remnant after the explosion. This process creates and disperses most of the chemical elements with atomic masses near and above that of iron. The use of type Ia supernovae as probes in studying cosmology is now well established.

Type II Supernovae

Stars more massive than about nine times the mass of the Sun become internally unstable, as they end their lives exploding as type II supernovae. By dying, they create and disperse their stardust, including the elements with masses near that of oxygen, elements of which life on Earth is largely made.

Supernova explosions of massive stars have a variety of appearances, depending on their detailed history and whether the parent star is part of a binary system. Type Ib/c supernovae are associated with parent stars of more than about 30 solar masses and are probably closely related to, or may even be, the ultra luminous gamma-ray bursters, whereas stars with masses below this limit but above nine solar masses become various subtypes of type II supernovae.



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 Type Ia Supernovae

Almost half the stars in the sky are double or multiple. If the two stars are close together, 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.

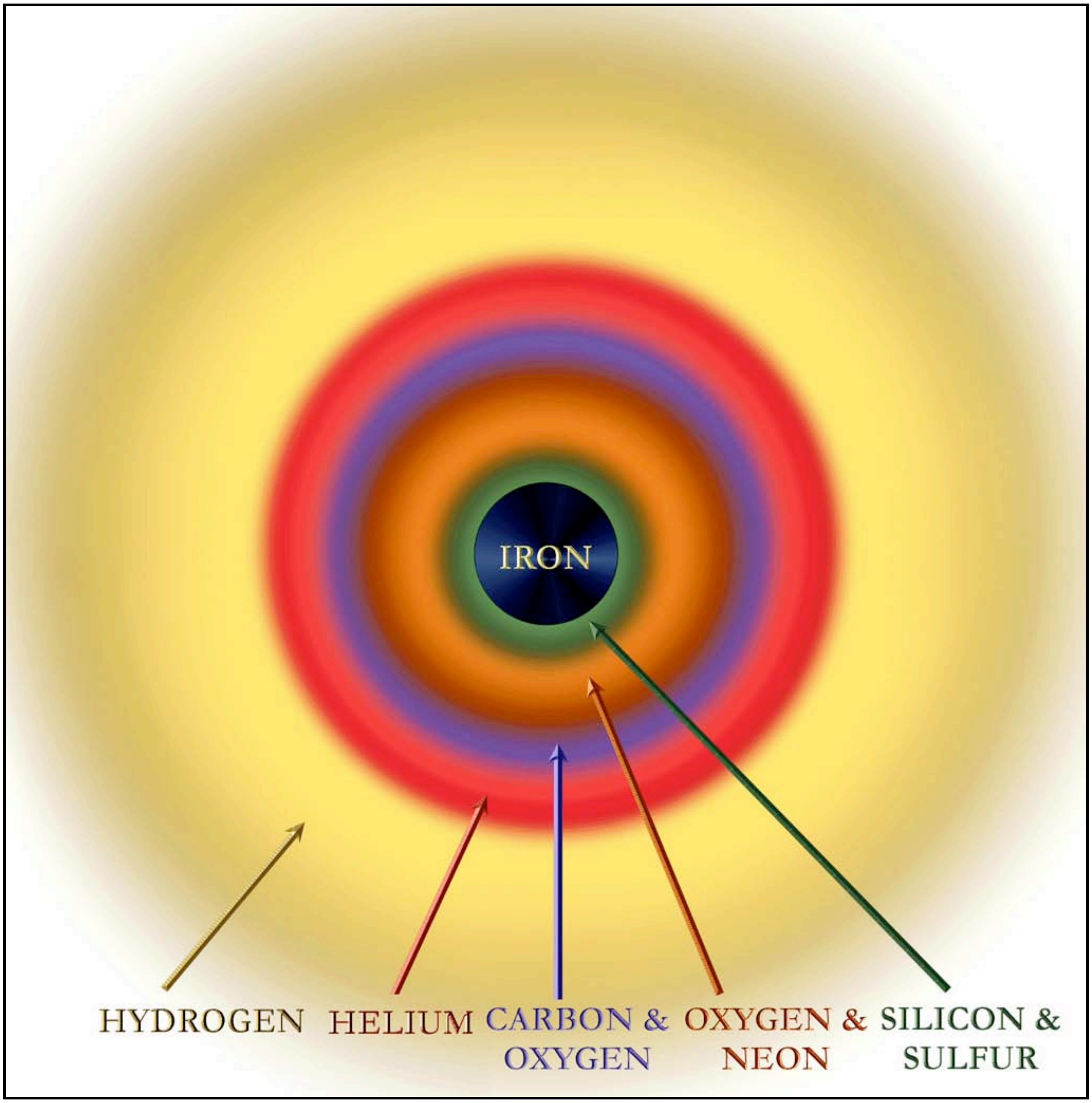
Stars that have lost their atmospheres to their companions are identical to the white dwarves in the center of planetary nebulae. The less massive companion star, assisted by the extra mass it has gained, eventually becomes a red giant and starts to transfer material back onto its white dwarf companion. 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 type Ia supernovae in galaxies 5,000 million light years away.

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

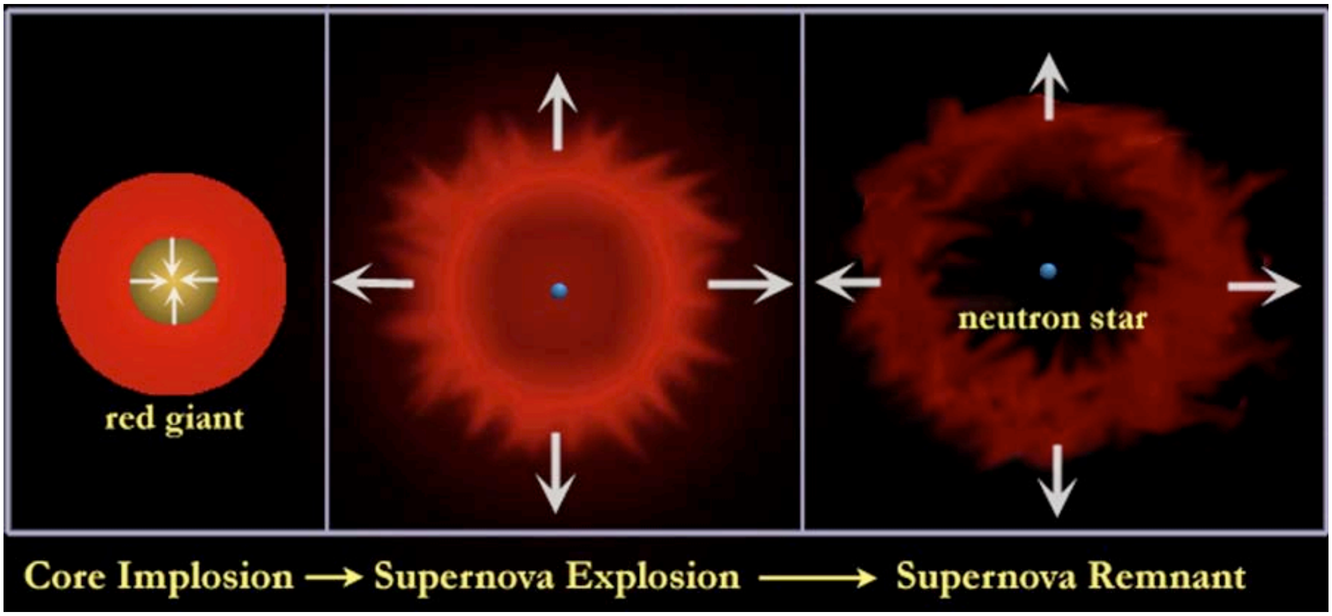
Massive Stars and Type II Supernova

The most significant locations for the natural alchemy of fusion are stars more massive than our 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.



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 over its entire lifetime.

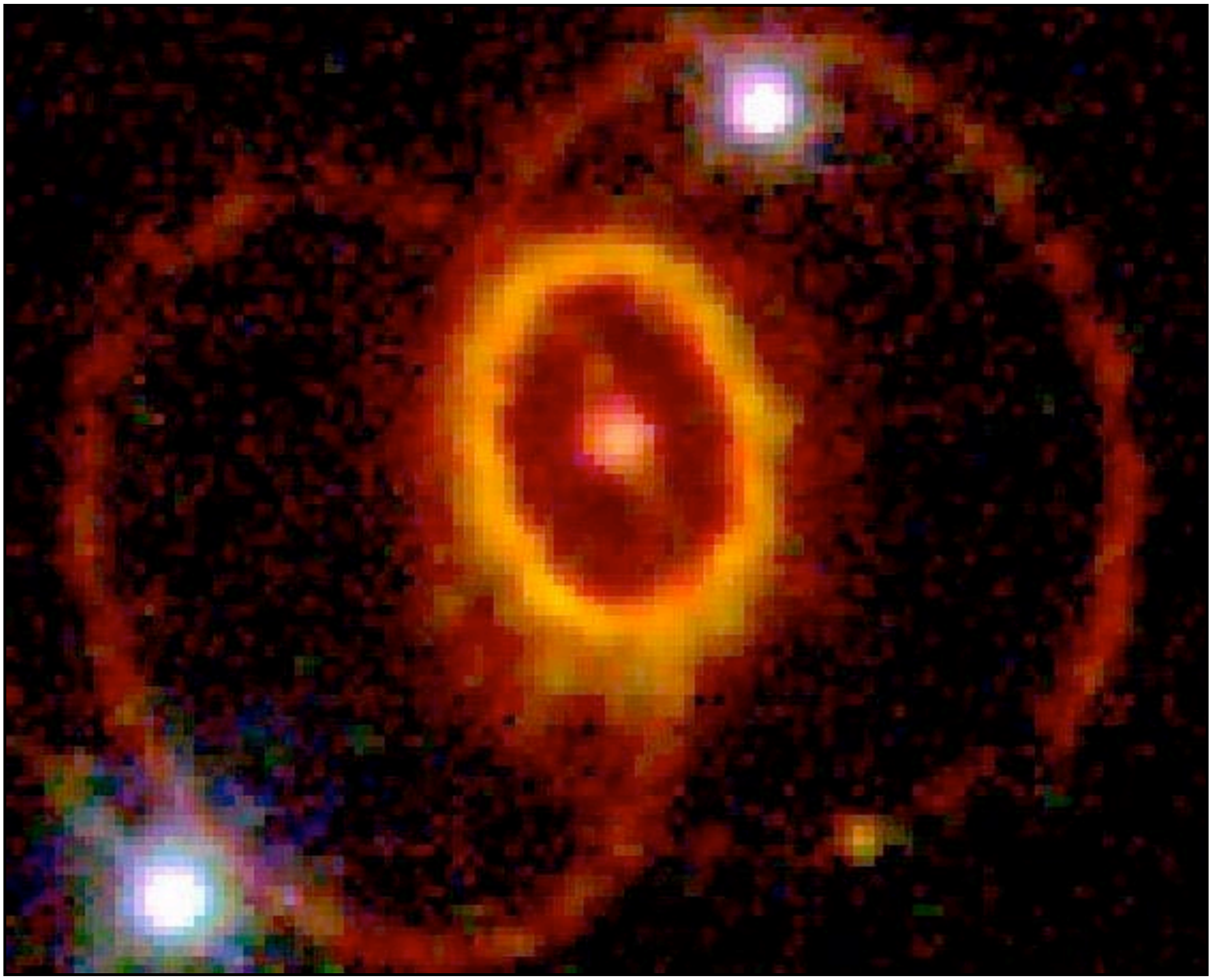
Such type II supernova explosions play a special role in the chemical enrichment of the universe. First, unlike stars of low mass that lock up their products in white dwarfs, exploding stars eject their outer layers, which are unburned. They belch out the helium that was formed from hydrogen burning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

New elements are also synthesized behind the outgoing shockwave of the supernova. 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 shockwave 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 with the Hubble telescope revealed astonishing rings around the supernova.

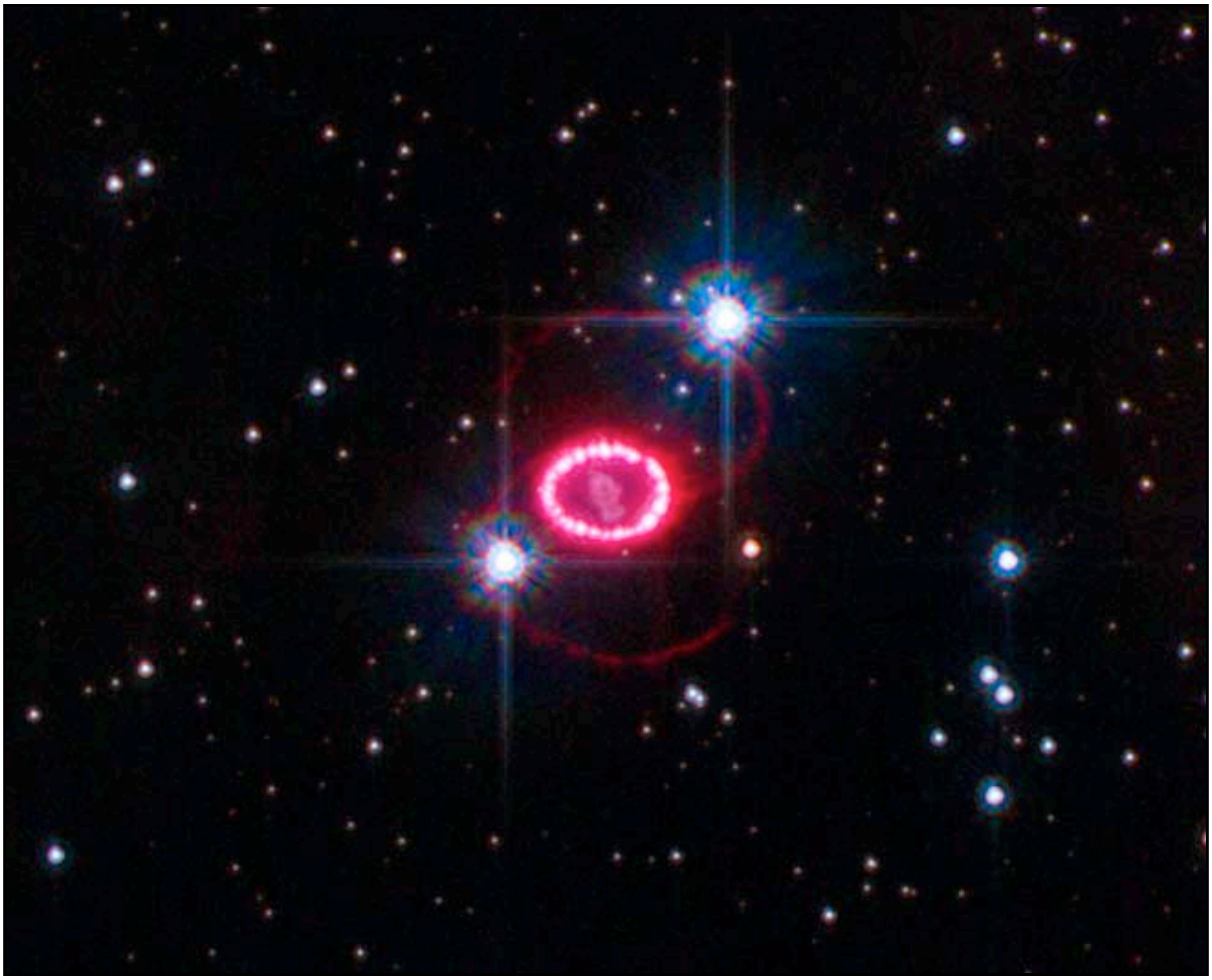
The inner ring is material that the star lost when it was a red giant, excited by the flash of ultraviolet light from the supernova. The outer rings are more mysterious but are presumably related to mass lost from the pre-supernova system. The products of stellar burning are concentrated in a central dot, barely resolved with the Hubble telescope, which is expanding outward at 3,000 kilometers per second.

Supernova 1987A 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 References

http://en.wikipedia.org/wiki/SN_1987A

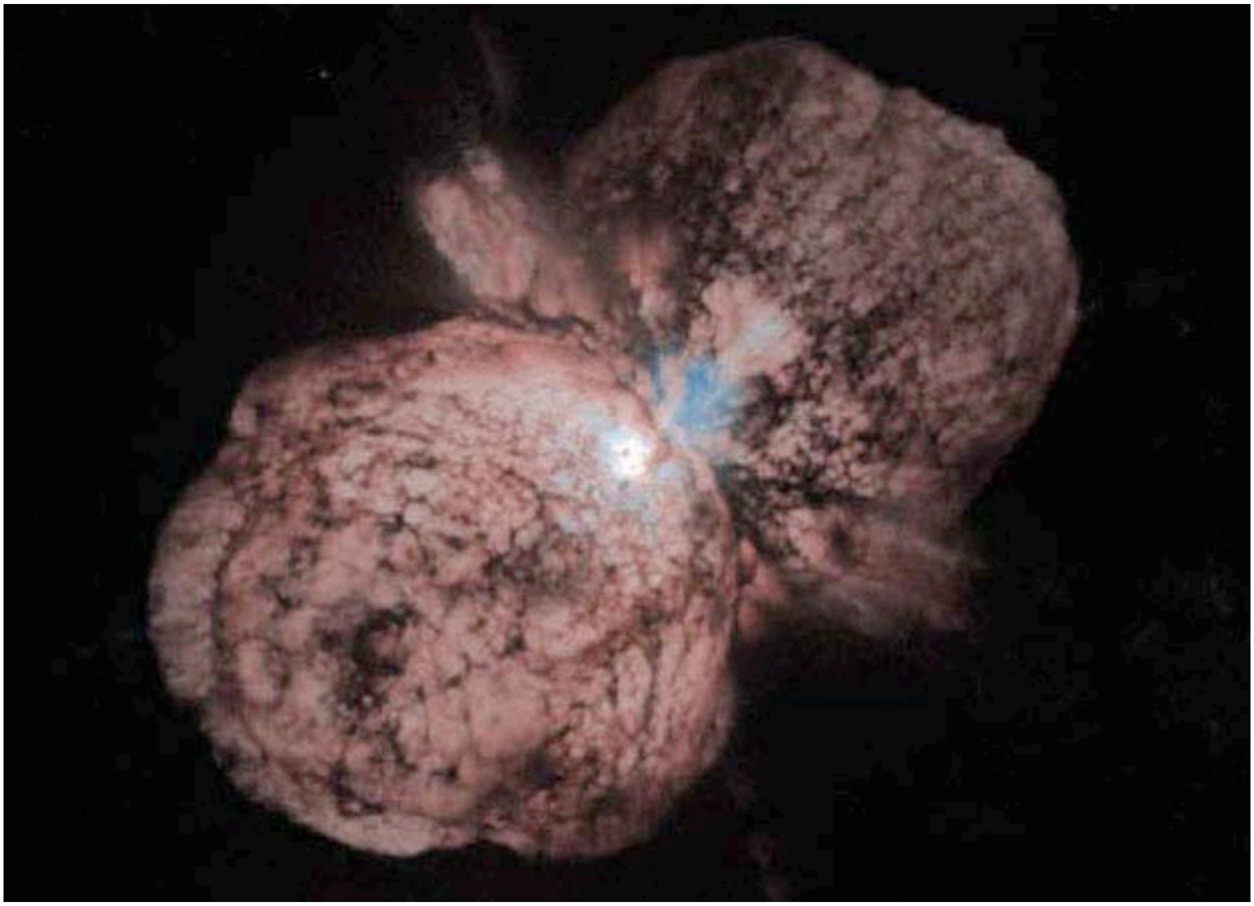
http://zebu.uoregon.edu/~soper/StarDeath/sn1987a.html



New Hubble Observations of Supernova 1987A Trace Shock Wave

This image shows the entire region around supernova 1987A. The most prominent feature in the image is a ring with dozens of bright spots. A shock wave of material unleashed by the stellar blast is slamming into regions along the ring's inner regions, heating them up, and causing them to glow. The ring, about a light-year across, was probably shed by the star about 20,000 years before it exploded.

Web Reference
http://hubblesite.org/newscenter/archive/releases/2010/30/image/a/



Eta Carinae, thought to be at least 150 solar masses, is a supergiant massive star some 7,500 light years from Earth. This star is one of the most luminous star systems in our Galaxy, radiating millions of times more power than our Sun. Speculation among astronomers is that Eta Carinae will undergo a supernova explosion sometime in the next thousand years. But because Eta Carinae is over the 30 solar mass limit of Type II supernovae, it may be destined to become a Type Ib/c supernovae associated with ultra luminous gamma-ray bursters.

Eta Carinae is also one of the strangest star systems known, brightening and fading greatly since the early 1800s. The Hubble Space Telescope image above 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. Stars destined to become Type II supernova, such as Sanduleak — 69° 202, may also produce similar discharges.

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

Eta Carinae and the Homunculus Nebula

This composite image from the Hubble Space Telescope shows Eta Carinae and the bipolar Homunculus Nebula which surrounds the star. The Homunculus was partly created in an eruption of Eta Carinae whose light reached Earth in 1843. Eta Carinae itself appears as the white patch near the center of the image, where the 2 lobes of the Homunculus touch.

Web References

http://antwrp.gsfc.nasa.gov/apod/ap080617.html

http://en.wikipedia.org/wiki/Eta_Carinae

The Crab Supernova Nebula
X-ray, Optical, and Radio Composite Image

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 (page 7)

References

Balick, B., & Frank, A. (2004). The Extraordinary Deaths of Ordinary Stars. *Scientific American*, 291(July), 50-59.

Gilmore, G. (2004). The Short Spectacular Life of a Superstar. *Science*, 304(June 25), 1915-1916.

Sandage, A. (2000). Twinkle Twinkle. *Natural History* (Feb.), 64-66.

Tyson, N. D. (1998). The Greatest Story Ever Told. *Natural History* (Mar.), 82-84.

Recommended Reading

Tyson, N. D. & Goldsmith, D. (2004). *Origins: Fourteen Billion Years of Cosmic Evolution*. New York: Norton.

Chown, M. (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/

For further information on related topics go to:

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

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

Alles Biology Home Page
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