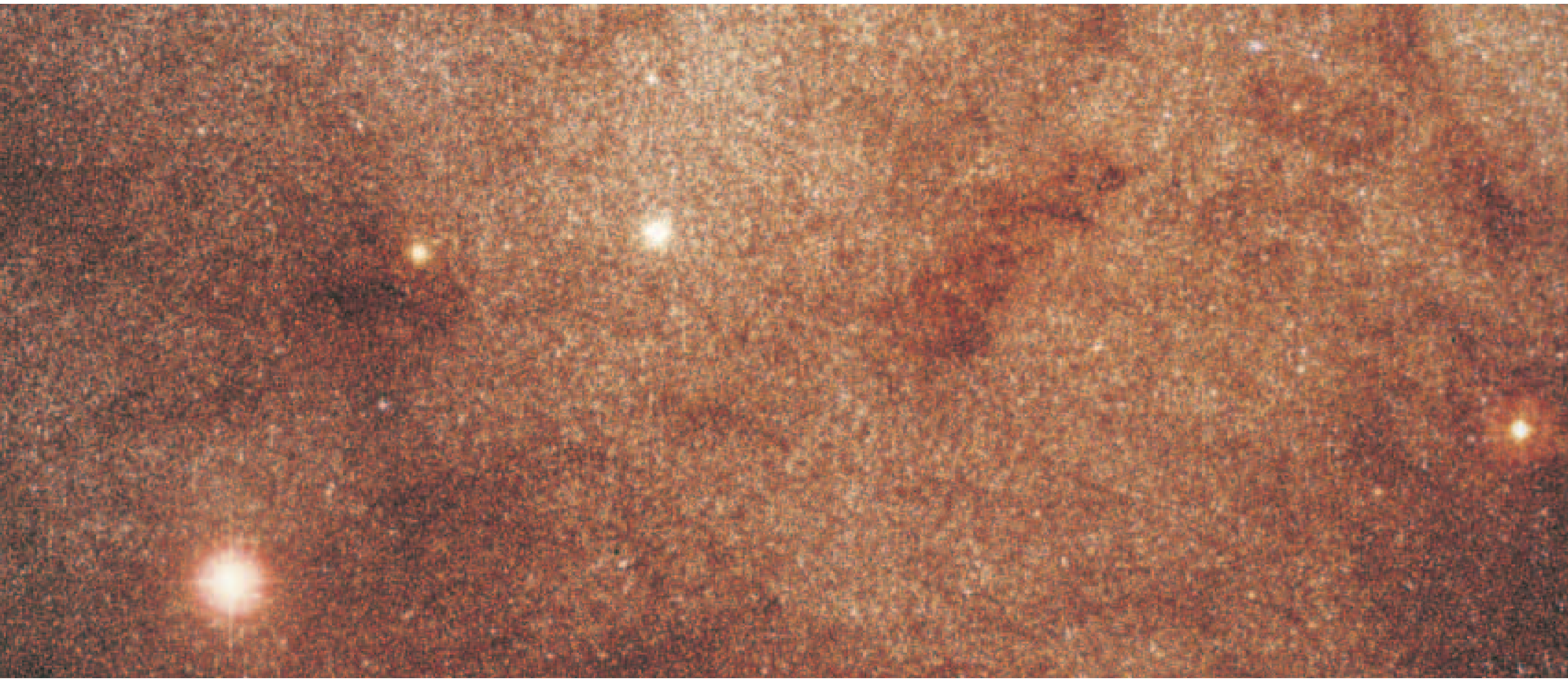
THE LIVES OF STARS:

From Birth to Death and Beyond (PART I)



BAADE'S WINDOW, NGC 6528, AND NGC 6522 IN SAGITTARIUS. COPYRIGHT 1993 DAVID MALIN AND THE ANGLO-AUSTRALIAN TELESCOPE BOARD

Many of the sky's most dramatic showpieces are but chapters in the lives of stars.

By Icko Iben Jr.
and Alexander V. Tutukov

A look at the star-filled night sky produces one of the deepest impressions of eternity and infinity accessible to humankind. People have probably always attempted to understand the nature of stars and the universe, thereby looking for their place in the world. The modern scientific picture of the universe has deep historical roots reaching back to the ancient Greeks. Not only did they contribute many of its fundamental elements, they also populated the sky with mythological heroes whose memory is preserved to this day in the names of the constellations.

The role of stars in astronomy is evident from the name of the science itself. In Greek, *astro* means "star" and *nomos* means "law." And though modern astronomy includes the study of the interstellar medium, galaxies, and the universe as a whole, stars remain prime objects of study. This is understandable, given the fact that our Sun, though a rather ordinary star, is an entity without which we would not exist!

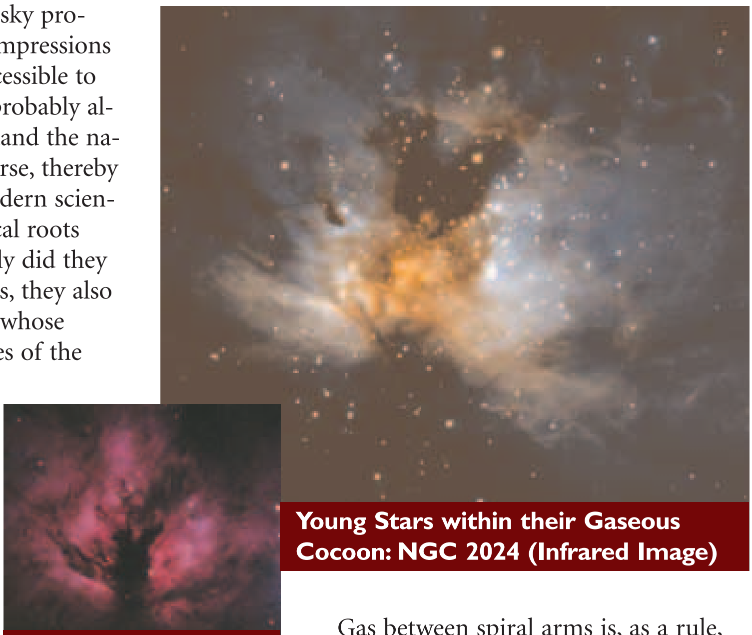
Yet many of the global physical attributes of stars were unknown until the last century drew to a close. By then, some stellar distances had been measured, and an understanding of electricity and magnetism enabled estimates of stellar luminosities. A full appreciation of stellar structure was not possible until the beginning of this century, when developments in atomic physics permitted realistic mathematical models of stars to be made.

Even then, however, one ingredient was missing from the nascent science of stellar evolution: the source of a star's energy. This lack was only remedied in 1938, when Hans Bethe, Carl von Weizsäcker, and Charles Critchfield identified several of the nuclear-fusion reactions that keep the stars shining. The transformation of hydrogen and helium into heavier chemical elements was recognized as the driving force of stellar evolution, and models incorporating newly measured nuclear-reaction rates allowed estimates of stellar lifetimes to be made for the first time.

Since this fundamental turning point, astronomers have devoted countless hours to the problems of star birth, star death, and all that takes place in between. The resulting paradigm of stellar evolution accounts for many of astronomy's most provocative subjects — white dwarfs; black holes; supernovae — and connects them to the countless stars we see on a clear, moonless night.

The Birthplaces of Stars

In today's picture of star formation, our galaxy's spiral arms play a critical role. They are the result of sound-like density waves that travel through the galaxy's disk, compressing matter along the way. The disk is in a continuous state of flux. Rarefied matter (gas and dust) is compressed into stars; later, some of it is returned by these same stars to the interstellar medium, albeit in different forms.



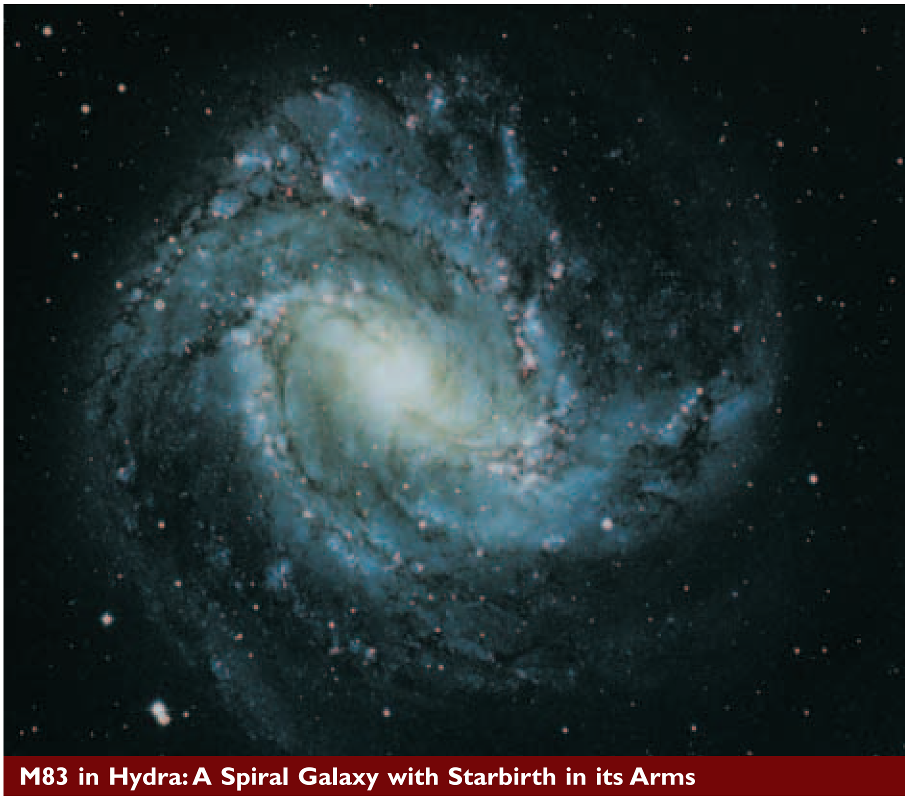
Visible-light Photo

Young Stars within their Gaseous Cocoon: NGC 2024 (Infrared Image)

IAN McLEAN / UCLA; INSET: W. A. TREMBLY JR.

Gas between spiral arms is, as a rule, rather hot and highly ionized, and its relatively high pressure prevents gravity from inducing collapse. In a galaxy arm, however, the gas density is large enough for collisions of ions and atoms with dust grains to "cool" gas clouds, initiating the formation of hydrogen molecules. Molecular gas then concentrates itself into giant clouds (60 to 300 light-years across) with 100,000 to 1,000,000 times the mass of our Sun.

Magnetic fields prevent molecular clouds from collapsing immediately, as do tidal forces from our galaxy's bulge. Nevertheless, the density of matter in such clouds increases slowly with time and, at some point, gravity



M83 in Hydra: A Spiral Galaxy with Starbirth in its Arms

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More than anything else, a star's initial allotment of mass sets the course of its subsequent evolution.

wins out and the clouds fragment into smaller, denser bodies, each bearing 1,000 to 10,000 Suns in mass. In turn, the collapse of these smaller clouds leads to the formation of compact groups of young stars.

The star-formation efficiency in these groups — the fraction of the gas and dust actually converted into stars — is about 25 percent, and this has fateful consequences for most new open clusters. The massive stars in such a cluster heat the remaining gas to a temperature of about 10,000° Kelvin, driving the gas out of the cluster. As a result, the young cluster's total mass is reduced to the extent that the stars can escape its gravitational grip and run away from their place of birth. Thus paradoxically, though most stars are formed in open clusters, almost 95 percent of these clusters die at the moment of their birth.

The few open stellar clusters we see, such as the Pleiades and the Hyades, are very rare long-term survivors, but even they are currently in the process of evaporating. Presumably the lives of these clusters have been prolonged because the process of star formation in them was more efficient than usual.

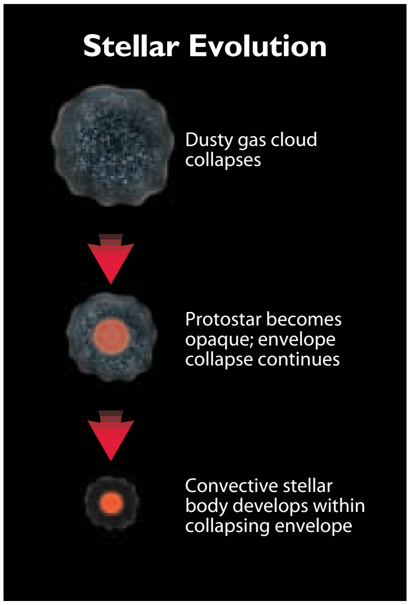
A Star Is Born

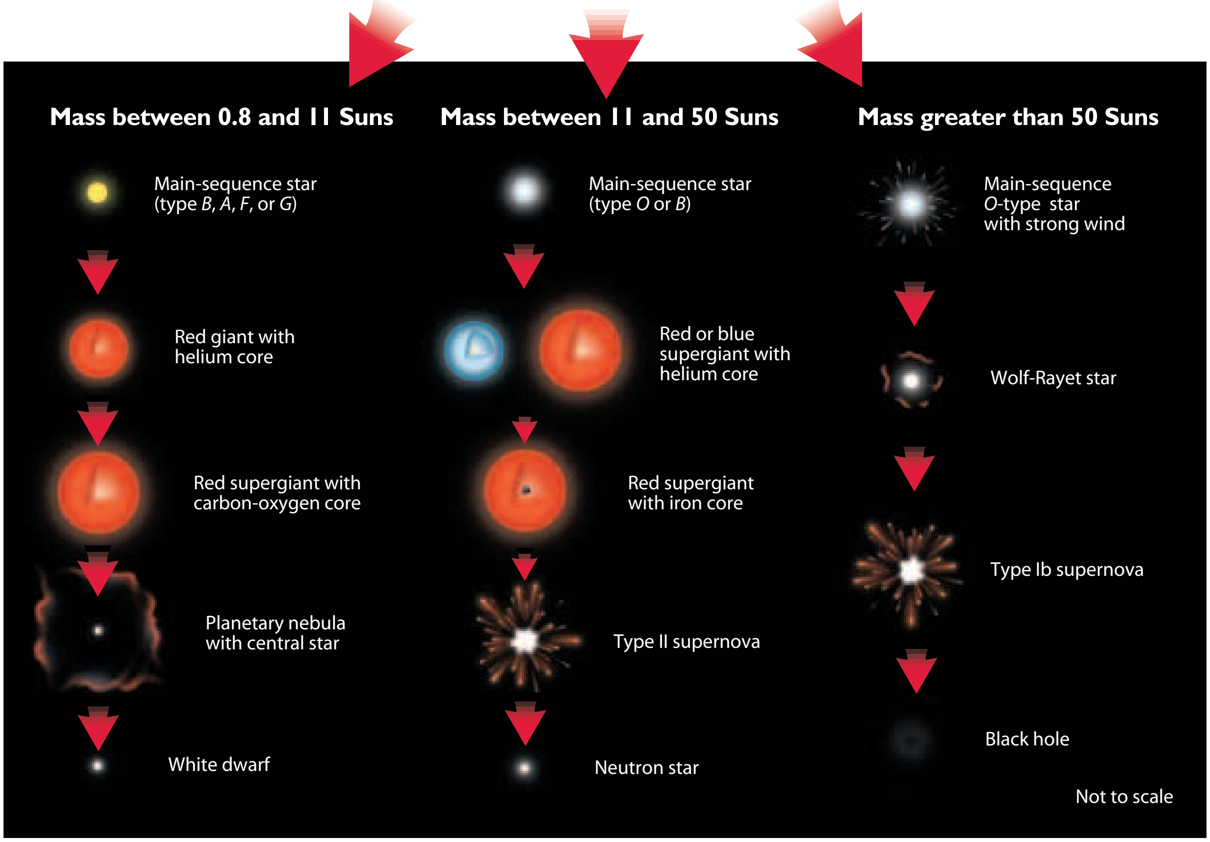
In the story line above, we glossed over the means by which stars actually form from collapsing, fragmentary gas clouds. So let's examine this crucial birth event in more detail.

As the material destined to form a solitary star collapses, it develops a dense, central core of gas and dust. This core temporarily stops collapsing when it becomes opaque to its own infrared radiation. This opaque core weighs in with a mass 1⁄10 our Sun's, and it spans about 1,000 times our Sun's diameter. The gas-dust core contracts slowly for about 3,000 years, accreting matter from overlying layers all the while.

As the core collapses, its interior heats until the dust evaporates. Having temporarily become transparent, the core collapses once more until hydrogen becomes ionized, making the core opaque yet again.

The collapse phase that follows lasts only 10 to 30 years. This means that at any given time only a few dozen stars in the entire galaxy are in this phase! The radius of the young, completely convective stellar core is about 3 to 5 times our Sun's. With a surface temperature of 3,000°K, the boiling core radiates at visual and infrared wavelengths. But this radiation is deeply hidden by the dust in the still-collapsing envelope,





and the star continues to be seen only in the infrared portion of the spectrum.

The accretion of envelope matter onto the core proceeds for 100,000 to 1,000,000 years, until the envelope matter is either exhausted or expelled by the star's radiation or by its "solar-wind" particles. Intermediate-mass stars (those with 1 to 11 times our Sun's mass) contract over a period of 100,000 to 10,000,000 years until they reach the so-called *main sequence.* In that prolonged state of stellar adulthood, gravity balances gas pressure and the energy lost from the stellar surface matches that liberated by nuclear reactions in the core. Stars more massive than 11 Suns are essentially born on the main sequence, skipping adolescence entirely.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Young Stellar Adults: The Pleiades

From Dwarf to Giant

The main source of energy that keeps stars shining is the transformation of hydrogen into helium. How long this process can last depends on a star's mass, which determines the temperature and pressure in its core. Ironically, smaller stars live longer than their high-mass siblings — even though they have less fuel to "burn" (that is, to fuse into heavier elements). That's because their cores are cooler, and nuclear reaction rates are very sensitive to temperature.

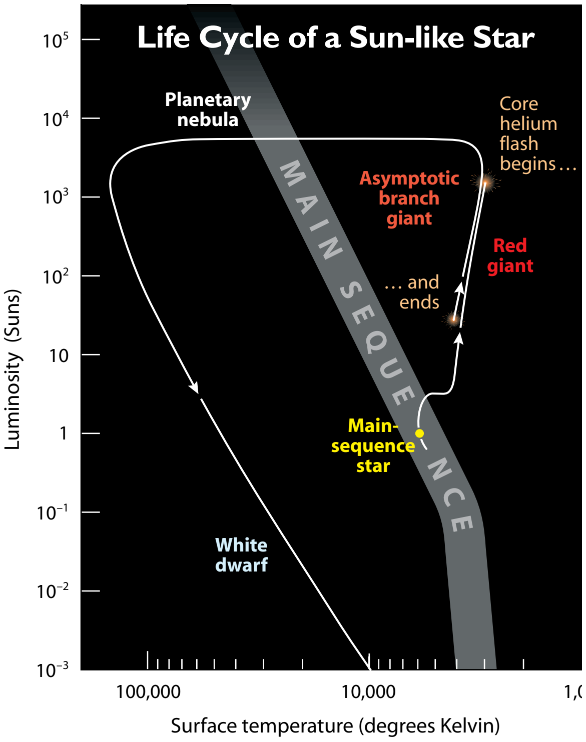
As it turns out, at most 5 percent of all the stars yet born have been privileged to evolve beyond the main sequence. On the other end of the scale, the main-sequence lifetime of the most massive stars (those with more than 11 solar masses) is 10,000,000 years or less. As a result, thousands of generations of those heavyweights have come and gone since the Big Bang. Note that when we say these stars have "come and gone," usually that means only that they have been transformed into a "dead" remnant that no longer feeds on nuclear energy. But before acceding to astronomical anonymity, most stars go through dramatic changes that produce some of the sky's most stunning showpieces.

A low- or intermediate-mass star spends between 80 and 90 percent of its life in the main-sequence phase. This comes to an end when a large fraction of the star's hydrogen has been converted into helium. Temporarily too cool to tap the next source of nuclear energy, the star's core — now composed of helium — contracts. In the meantime, hydrogen burns at an even greater rate than before in a shell surrounding the core. This causes the stellar envelope to expand until it spans some 100 to 1,000 present-day solar diameters, transforming the star into a *red giant.*

Eventually, core temperatures rise until helium nuclei begin to fuse into those of carbon and oxygen. In stars that start out with less than about 2.3 solar masses, core helium burning begins abruptly, engendering a brief thermonuclear runaway, or *core helium flash*. When this happens, hydrogen burning actually slows in the surrounding shell, because it expands and cools; this makes the star's luminosity drop. By contrast, helium burning begins more gradually in stars with masses between 2.3 and 11 Suns.

As helium burns in the core of a low- or intermediate-mass star, hydrogen continues to burn in a surrounding shell, and this provides most of the star's luminosity. The core helium-burning phase lasts from 10 to 25 percent of the main-sequence lifetime that preceded it.

In the end, when helium in turn is exhausted within an appreciable portion of its center, a star that started out with anywhere from 0.8 to 11 solar masses forms a



After spending billions of years as a stable nuclear-fusion reactor, a low-mass star like our Sun follows a complicated path in the Hertzsprung-Russell diagram — a crucial diagnostic tool that uses the temperatures and brightnesses of stars to track stellar evolution. Courtesy the authors.

Stellar Death Shroud: The Helix Nebula in Aquarius

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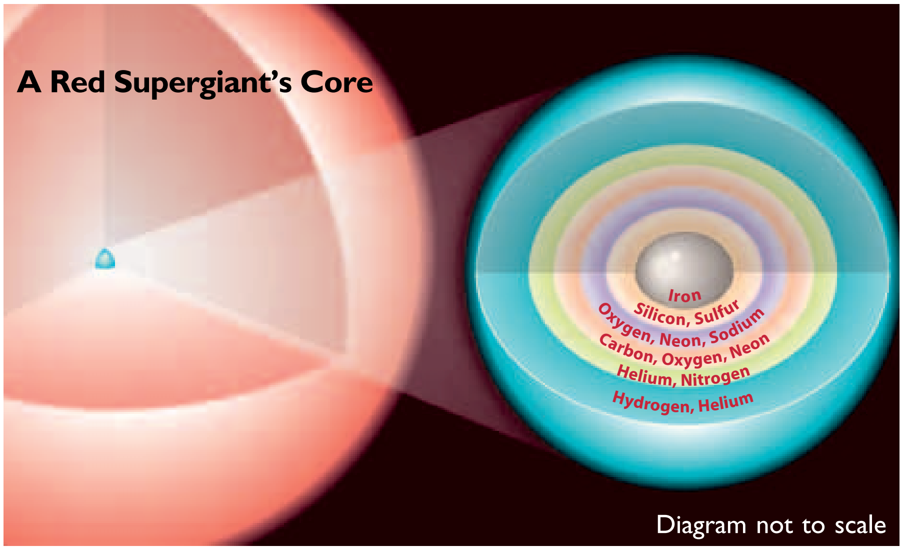
> *As their lives come to an end, stars seed the galaxy with the elements upon which life depends.*

nearly degenerate core of carbon and oxygen nuclei. Above, hydrogen and helium burning continue to power the swollen star. The star spans several hundred solar radii (exceeding the radius of Earth's orbit) and glows with a relatively cool surface temperature of 3,000° K. Such a star is called an *asymptotic giant branch (AGB) star,* thanks to the shape of its evolutionary track on the Hertzsprung-Russell diagram (see page 39).

Roughly 97 percent of the single stars (or those in wide binaries) that evolve off the main sequence within a 15-billion-year time frame become AGB stars. The nuclear reactions that occur in AGB stars are responsible for at least half of the carbon in the universe, and for approximately 200 neutron-rich isotopes of elements like tin, cadmium, and lead.

Observations show that AGB stars pulsate with typical periods of 200 to 600 days, and that they lose matter from their surfaces in the form of powerful winds. These winds carry out freshly made carbon and neutron-rich elements as well as dust grains that have been formed in the star's relatively cool outer atmosphere. By producing the dust grains that so efficiently cool molecular gas clouds, AGB stars pave the way for the formation of future generations of stars and planets!



The Ghosts of Sun-like Stars

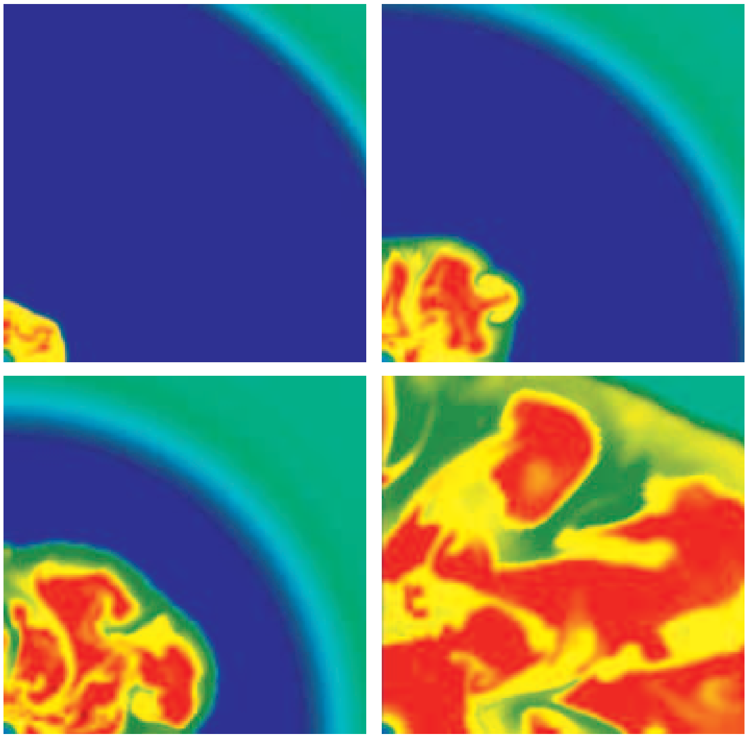
After several hundred thousand years on the asymptotic giant branch, a low-mass star expels its hydrogen-rich envelope. The remnant star contracts rapidly, raising its surface temperature as high as 100,000° K. At such high temperatures, the dying star's surface emits copious ultraviolet light and low-energy X-rays. This radiation agitates atoms and molecules in the ejected gas, causing them to fluoresce. The result: a *planetary nebula* that remains visible for typically 10,000 years.

The name "planetary nebula" came about because some of these stellar shrouds resemble the planet Uranus when viewed at the eyepiece of a telescope. There are roughly 10,000 planetary nebulae in our galaxy.

Ultimately, the stellar cinder at a planetary nebula's heart ceases to burn hydrogen and evolves into a cooling *white dwarf.* In a white dwarf, the gravitational forces compressing matter are balanced by the quantum-mechanical pressure of degenerate electrons. As it turns out, a white dwarf counterintuitively gets smaller as you increase its mass! Typically white dwarfs are comparable in size to the Earth. Although 10 billion white dwarfs are believed to inhabit our galaxy, with today's telescopes we can see only those within about 600 light-years of the Sun. Sirius's faint companion is such a star, as is Procyon's.

Going Out with a Bang

The most massive stars follow a very different life cycle from that of their lightweight counterparts. After a relatively brief main-sequence phase, a single star that started out with 11 to 50 solar masses also forms a car-


J. C. HAYES / A. BURROWS

A Supernova Begins (computer simulation)

bon-oxygen core. But this core is not degenerate, and hence it can contract until another set of reactions kicks in, producing neon nuclei as well as more oxygen.

In turn, the resulting oxygen-neon core contracts and heats until neon-burning reactions are ignited. The cycle of contraction, heating, and ignition continues until a core of iron-peak elements is formed. (Iron-peak elements are those that have roughly 26 protons and 30 neutrons in one of their isotopic nuclear configurations.) Creating yet heavier elements requires expending energy rather than producing it. As a result, a massive star's iron core ceases to be a source of nuclear energy.

As lighter elements continue to burn in shells above it, the iron core grows in mass until its mass exceeds the Chandrasekhar limit — the maximum possible mass of a white dwarf, some 1.4 Suns. The core then begins to collapse. The stellar core's iron-peak nuclei decompose into those of helium, which then fragment into neutrons at the price of the star's gravitational potential energy. The core collapses, producing a *neutron star* — a degenerate ball of neutrons somewhat akin to a white dwarf, but far, far denser. (A neutron star typically packs 1.5 to 2 solar masses into a ball the size of a small city.)

Core collapse lasts only 1⁄10 of a second, and almost all of the gravitational potential energy released (some 10^{53} ergs) is converted into neutrinos, which leak out from the core over a period of about 10 seconds following collapse. Most of these neutrinos continue unimpeded through the rest of the star at the speed of light or nearly so. A small fraction of these ultralight particles scatter against the atomic nuclei that the dying star took so long to produce. This imparts so much energy and momentum to the matter above the core that the star's outer layers are expelled at high velocities. Far away, astronomers witness a *Type II supernova* — like the explosion that occurred in the Large Magellanic Cloud in 1987.

A typical Type II supernova shines for several weeks with 10 to 100 billion times our Sun's luminosity — comparable to that of an entire spiral galaxy. Most of what we know about supernovae comes from outbursts in other galaxies. Observations suggest that a Type II supernova should occur roughly every 50 years in our Milky Way.

Type II supernovae return to the interstellar medium (ISM) the chemical elements produced by their precursor stars. In doing so, they enrich the ISM with the heavy elements that are so important to our everyday existence. It has been discovered recently that the heavy-element abundance in intergalactic gases is comparable to that within galaxies themselves. Since there are no stellar sources of heavy elements in the intergalactic medium, about half of the heavy elements produced by supernovae must leave their parent galaxies. This probably takes place by way of "fountains" that form when dense clusters of supernovae punch holes in the disks of their parent galaxies.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A Supernova's Aftermath: The Vela Remnant

Black holes are formed when the brief lives of the most massive stars come to an end.

Evidence that Type II supernovae make neutron stars was discovered about 30 years ago when pulsating sources of radio waves were found. Once it became clear that they were not beacons from extraterrestrial civilizations, the radio sources were named *pulsars.* Most astronomers agree that the clocklike pulses are emitted from spinning neutron stars. The Crab Nebula and its pulsar offer a well-known example of a neutron star within the ejecta of a documented supernova explosion. More than 500 pulsars have been identified, and theory suggests that there may be up to one billion neutron stars in our galaxy.


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The Crab Nebula in Taurus: Remains of a Shattered Star

At the Top of the Scale

The stars starting out with the very highest masses — 50 to 100 Suns — shine with the brightness of 100,000 to 1,000,000 Suns during their brief lives as nuclear-fusion reactors. These exceptional stars lose mass at such high rates that only a helium core remains by the time they leave the main sequence. These relatively rare objects are known as *Wolf-Rayet stars.*

The interiors of Wolf-Rayet stars follow qualitatively the same evolutionary path as do the interiors of their lower-mass (11 to 50 solar-mass) cousins. However, their iron cores are so massive that their collapse cannot be halted by neutron degeneracy. Instead, collapse continues until the star's gravity prevents light waves from escaping. This is one of the ways nature creates *black holes.* The explosive collapse of a Wolf-Rayet star appears as a *Type Ib supernova* — one that lacks any spectral evidence for hydrogen.

The black hole created by a Type Ib supernova will be visible only for a limited time, as leftover stellar debris dribbles down its ultrasteep gravitational "well." Thereafter, even the most massive of single stars becomes one more "dead" remnant whose existence can be discerned only when it momentarily bends the light of background stars as it wanders through the galaxy.

JASON WARE

A Wolf-Rayet Star Sheds its Atmosphere: NGC 6888 in Cygnus

A Cycle of Creation

The stars we have considered here — solitary ones and those in wide binaries — evolve into white dwarfs, neutron stars, or black holes that eventually fade away without a trace. However, even in their death throes, stars play a continuing role in the life cycle of our galaxy. They seed interstellar space with the chemical elements out of which we and our home planet are made, and they produce the dust grains that play such a vital role in forming further generations of stars and planets. Our lives and those of the stars are inextricably intertwined.

An upcoming second installment will examine how stars' lives are altered when they orbit one another at close range.

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Further Reading

Kaler, James B. *Stars and Their Spectra: An Introduction to the Spectral Sequence.* Cambridge, U.K.: Cambridge University Press, 1989. Several chapters of this book first appeared as articles in *Sky & Telescope.*