The amazing lives of two stars

Pull back the curtain to see that stars — both big and small — are as dynamic and diverse as people. /// TEXT BY MARCIA BARTUSIAK /// ILLUSTRATIONS BY ROEN KELLY

The Sun is going to die.

Not soon, but eventually. While none of us is going to see it, astronomers continue to investigate our star's fate. In the same way they can predict the Sun's demise, scientists also study and model such fascinating events as the Sun's early formation and the dynamic molecular activity powering the hyper-productive, super-brilliant orb of energy. From its early formation from an interstellar cloud, to its twilight as a white dwarf, the Sun will experience numerous phases — the most stable of which, we're enjoying now. But what goes on inside that big, bright ball during its unstable phases? And how does our Sun's evolution compare to a star 15 times its size? Let's find out.

See "Red Sun dying" on page 40 to learn about the transition of the habitable zone in relation to the Sun's evolution.

[SOLAR-MASS STAR]

PHASE I: It begins with a nudge inside a small nebula. The push is forced by a shock wave passing through the galactic neighborhood. As a result, a roughly spherical clump of gas and dust, about a light-year in diameter, begins to collapse.

Like pizza dough whirling outward in the hands of a chef, the cloud spins faster as it condenses and flattens out. Under gravity's pull, the densest pocket of material collects in the center of the swirling disk of matter. A star, about the same mass and size of our Sun, has formed.

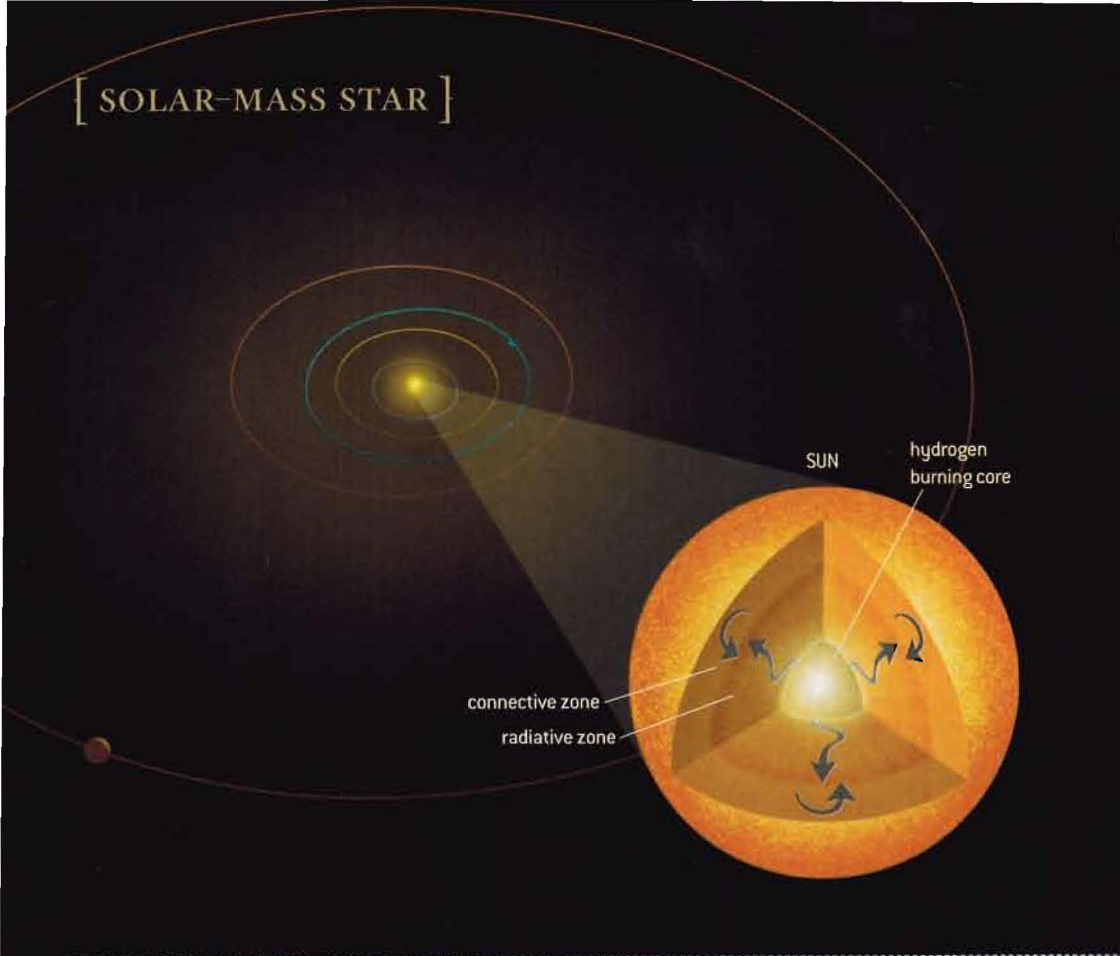
At the surface of this glowing sphere, the gases are spread thinly, their density just 1/10,000 that of air. Halfway toward the center, about a quarter-million miles in, the density of matter is comparable to water. But deep in the star's heart, where temperatures can exceed 10,000,000° Celsius, the density is 12 times that of lead. In this way, gravity has fashioned a wondrous power plant.

Racing within the stellar core, protons gain enough energy to overcome their electromagnetic repulsion and collide with one another, allowing them to stick together with a strong nuclear bond. Through an elegant series of chain reactions, four protons (in effect, four hydrogen atoms stripped of their electrons) are welded to create the heavier element helium, whose nucleus contains two protons and two neutrons. With each second, some 600 million tons of hydrogen are converted into helium. But along the way, a tiny fraction of that matter — less than 1 percent — is transformed into energy, according to Albert Einstein's famous equation $E=mc^2$. It is this radiation that makes its way through the star eventually to escape, bathing its surroundings in heat and light.

[15-SOLAR-MASS STAR]

PHASE I: A vast compression wave moves through a galaxy. Spiral shaped, the wave slowly ripples through the galactic disk, and a cosmic traffic jam ensues. As gas encounters this invincible wall of compression, it gets squeezed, forming huge clouds, dark and formidable. Some contain as much matter as 2 million suns. Temperatures inside these clouds are cold enough for hydrogen molecules to form. After several million years, big, new stars turn on within these molecular clouds, illuminating the galaxy's spiraling form. These luminous stars — supergiants in size — live fast, burn bright, and die young. They perish even before they can move out of the traffic tie-up.

[SOLAR-MASS STAR]



PHASE II: For eons, this process continues as the small star performs the universe's most amazing balancing act. While gravity pulls the stellar material inward, trying to squeeze it tighter and tighter, the pressure of the hot gases and particles bouncing around inside the star — energized by its ongoing nuclear reactions — acts as a counterbalance. Thus, the star's material neither disperses nor shrinks into oblivion. The star shines a brilliant yellowish-white.

But a star's fuel, while vast, is hardly inexhaustible. By 10 billion years after its birth, most of the hydrogen within this tiny star's core is converted to helium. The central furnace flames out, leaving the core inactive. Nuclear burning continues, but only in a shell of hydrogen surrounding the dormant helium core.

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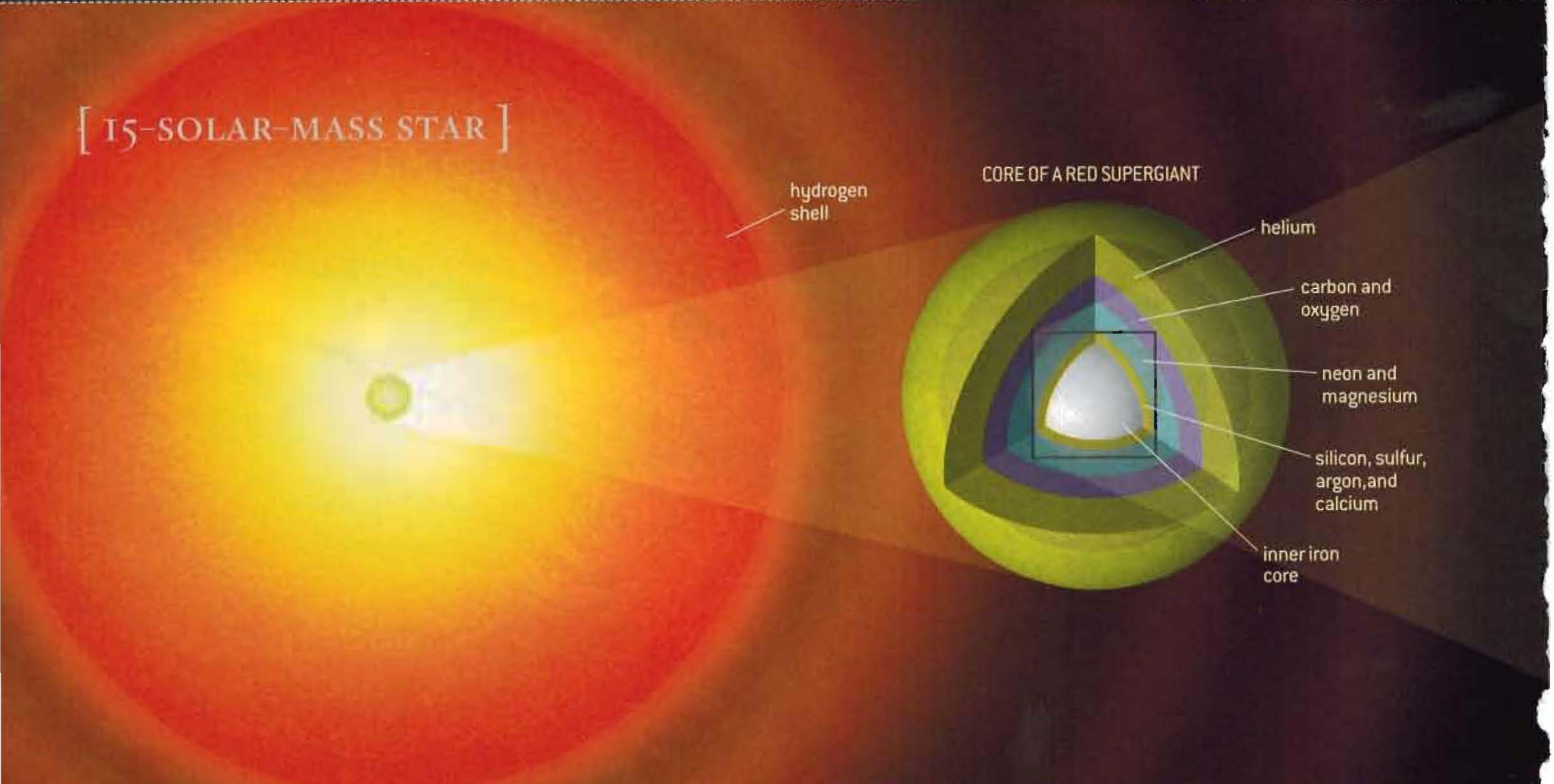
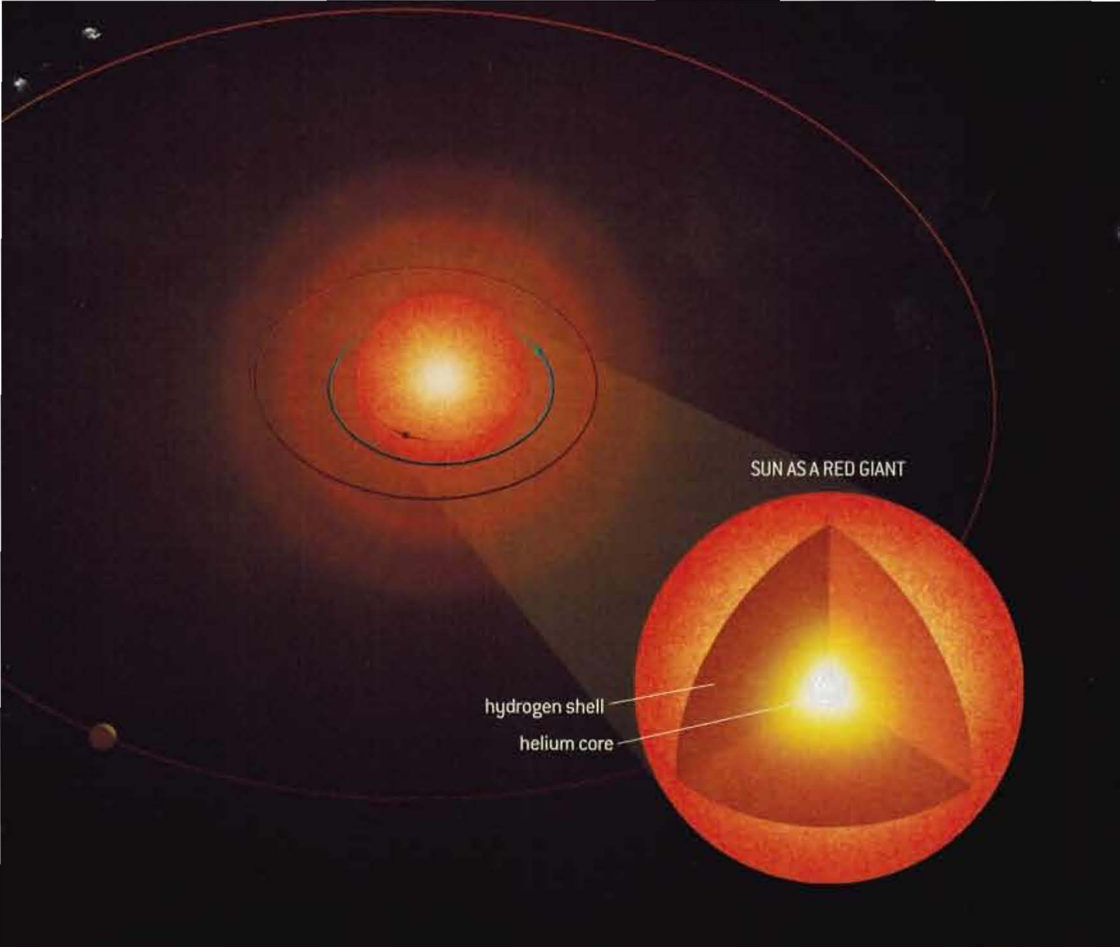
[15-SOLAR-MASS STAR]



PHASE II: Like our Sun, a 15-solar-mass star first fuses hydrogen into helium for fuel, but it goes through its supply of hydrogen at an astounding clip, shining with the white-hot intensity of 50,000 suns. While our Sun takes some 10 billion years before its central nuclear furnace runs out of hydrogen and transforms into a red giant, this massive star accomplishes that task a thousand times faster. It expands to monstrous proportions, well beyond the size of a red giant.

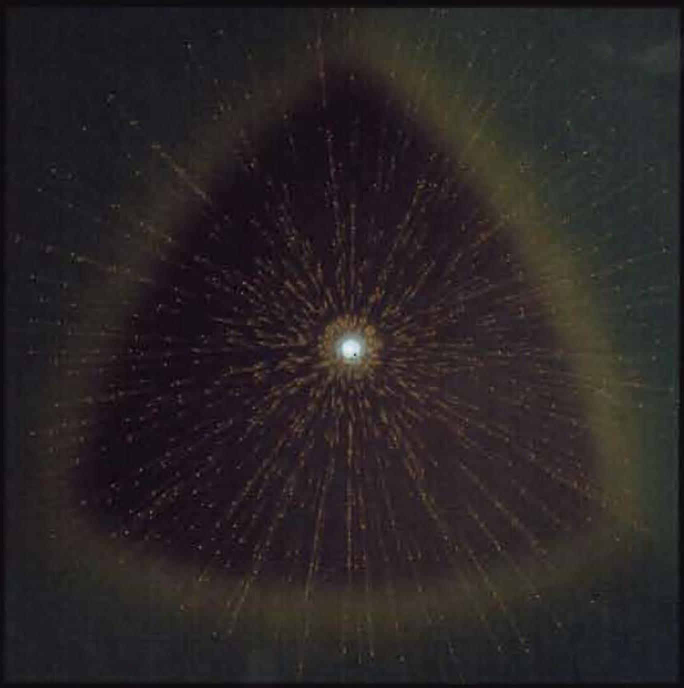
PHASE III: The red supergiant develops a series of layers, like an onionskin, deep in its center. A hydrogen shell at first surrounds the dormant helium core and continues to fuse. As helium is added to the core, it ignites and begins to fuse into carbon and oxygen. Consequently, the carbon core is surrounded by a helium-burning shell, with a hydrogen-burning shell farther out. Squeezed inward and heated to a billion degrees, the carbon and oxygen nuclei fuse into



PHASE III: The star experiences one of the most dramatic mutations in the cosmos. It is the astronomical equivalent of a caterpillar's metamorphosis into a butterfly. Because the nuclear fire in the center of the star has been extinguished, the quiescent helium core, which is about the size of a giant planet, starts to contract. But in shrinking, the helium core and its shell of hydrogen generate energy that conversely pushes the outer envelope of the star outward. The star, formerly 1 million miles wide, eventually spans nearly 100 million miles, engulfing any planets within the stellar advance. The star's hue turns from yellow to a cooler shade, as temperatures decrease in the greatly expanded surface layers. The tiny star has become a red giant.

During this red-giant phase, new fusion reactions come into play. With the hydrogen-burning shell heaping helium on the dormant core, the center gets compressed — and heated. Once the core temperature reaches 100 million degrees Celsius, the helium ignites in a flash and starts to fuse into carbon and oxygen.

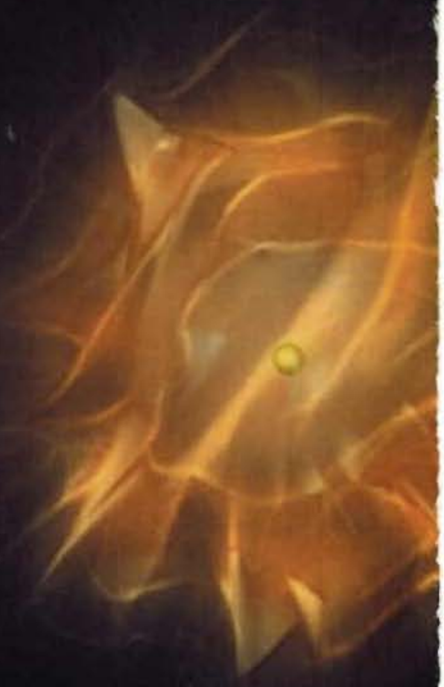
neon and magnesium. These, in turn, serve as the raw materials in the construction of even heavier elements, such as silicon, sulfur, argon, and calcium. Each chemical group burns in successive concentric shells. This fusion proceeds up the periodic table until iron is formed. Upon reaching iron, the star is at the end of the line. Instead of generating power, two iron nuclei require energy to fuse. It's a critical moment in this star's life. It faces its Waterloo.



PHASE IV: The iron begins to disintegrate because of the 10-billion-degree temperature in the star's core. Such destruction robs the stellar core of the energy that kept it intact. Without fusion-generated heat, the iron core can no longer withstand the force of its own gravity. In less than a second, the star's hidden core, which encompasses a volume about the size of Mars, collapses to the size of a metropolis. In the blink of an eye, a neutron star forms.

[SOLAR-MASS STAR]

PHASE IV: The star shrinks back as it adjusts to its new fuel mixture. But during the next 100 million years, as helium begins to burn steadily, the star again expands. Once the rubylike orb reaches its full extension, it becomes one of the brightest stars in the galaxy for tens of thousands of years. Its brilliance nearly equals Aldebaran (the ruddy gleam in the eye of Taurus the Bull) and Arcturus (Boötes's brightest star, whose name signifies "guardian of the bear" for its nearness to Ursa Major and Minor). It may even pulsate at some point as a variable star.



[15-SOLAR-MASS STAR]

PHASE V: A white dwarf star resists further compaction due to electron pressures, but here, the gravitational force of the star's extra mass overwhelms that resistance. Now neutron pressures, as well as nuclear forces, keep the star from gravitationally shrinking more. In essence, the neutron star is one huge atomic nucleus that happens to contain about a billion trillion trillion trillion trillion particles. Its creation releases a firestorm of neutrinos that speeds out of the star in all directions at near the speed of light, a prelude to a more visible event to come.

PHASE V: Toward the end of helium burning, the intense radiation spawned by the nuclear reactions moves to the star's surface and generates stellar winds, blowing at dozens of miles per second. The gales whisk away much of the red giant's transparent envelope. It is a cosmic striptease that recycles element-rich material back into the interstellar medium for the next generation of stars and planets. Shells of material waft off the star and balloon into space, leaving a white dwarf star behind.

PHASE VI: The star's energetic radiation causes this ever-expanding bubble of gas — the red giant's discarded raiment — to glow softly as a planetary nebula. This fluorescent sign stays on for thousands of years, until the gas disperses. The giant's hot core of carbon and oxygen lives on as a white dwarf star.

With its thermonuclear engine turned off, the white dwarf contracts to the size of Earth. A new state of matter emerges when gravity wins its lengthy struggle with radiation pressure. All the electrons and nuclei in the star are packed like droves of tiny billiard balls into the smallest volume possible. Only the electrons' pressure prevents further compaction. The white dwarf still emits radiation — merely the energy left from its more fiery past.

Over time, this white-hot ember turns yellow, then orange, and then red. After billions of years, it becomes a dark, crystalline cinder consigned for eternity to the graveyard of space.

PHASE VI: A lone beacon remains. As the star's core collapsed to form the neutron star, it had to spin faster and faster, like a figure skater bringing her arms toward her body during a spin. It's simply conservation of angular momentum. In this situation, the star's magnetic field is compressed and intensified. A neutron star's magnetic field is more than a trillion times stronger than Earth's. Such a highly magnetized body becomes a gigantic electrical generator producing trillions of volts that enable charged particles to race away from the star's surface. Magnetic field lines channel the particles into two narrow beams that shoot out in opposite directions and emit a stream of electromagnetic energy, in frequencies from radio to X ray. These beams sweep around space, like a lighthouse beam skims a coastline. Radio telescopes, for example, observe each rotation as a pulse of energy, a periodic blip.

This "pulsar" marks the spot where the once massive star, too heavy to die quietly, tore itself apart as a supernova. The pulsar then spins a thousand times a second. After millions of years, it slows down and then is heard from no more.

To view animations of star formation, visit www.astronomy.com/toc