Astronomy magazine

# STARS
# THE GALAXY'S BUILDING BLOCKS

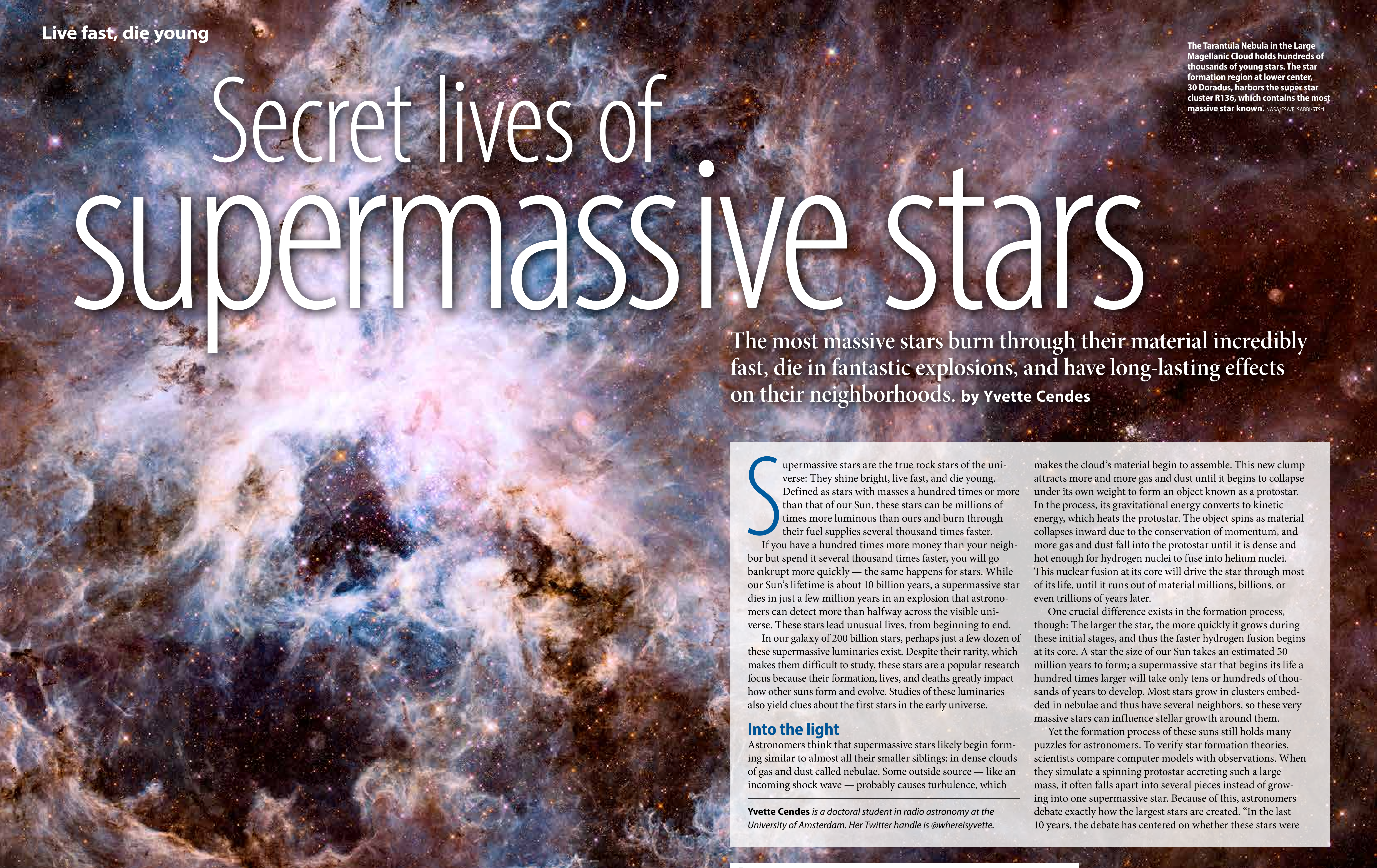
NASA, ESA

CONTENTS



A supplement to *Astronomy* magazine

# Secret lives of supermassive stars



The Tarantula Nebula in the Large Magellanic Cloud holds hundreds of thousands of young stars. The star formation region at lower center, 30 Doradus, harbors the super star cluster R136, which contains the most massive star known. NASA/ESA/E. SABBI/STScI

The most massive stars burn through their material incredibly fast, die in fantastic explosions, and have long-lasting effects on their neighborhoods. **by Yvette Cendes**

Supermassive stars are the true rock stars of the universe: They shine bright, live fast, and die young. Defined as stars with masses a hundred times or more than that of our Sun, these stars can be millions of times more luminous than ours and burn through their fuel supplies several thousand times faster.

If you have a hundred times more money than your neighbor but spend it several thousand times faster, you will go bankrupt more quickly — the same happens for stars. While our Sun's lifetime is about 10 billion years, a supermassive star dies in just a few million years in an explosion that astronomers can detect more than halfway across the visible universe. These stars lead unusual lives, from beginning to end.

In our galaxy of 200 billion stars, perhaps just a few dozen of these supermassive luminaries exist. Despite their rarity, which makes them difficult to study, these stars are a popular research focus because their formation, lives, and deaths greatly impact how other suns form and evolve. Studies of these luminaries also yield clues about the first stars in the early universe.

## Into the light

Astronomers think that supermassive stars likely begin forming similar to almost all their smaller siblings: in dense clouds of gas and dust called nebulae. Some outside source — like an incoming shock wave — probably causes turbulence, which makes the cloud's material begin to assemble. This new clump attracts more and more gas and dust until it begins to collapse under its own weight to form an object known as a protostar. In the process, its gravitational energy converts to kinetic energy, which heats the protostar. The object spins as material collapses inward due to the conservation of momentum, and more gas and dust fall into the protostar until it is dense and hot enough for hydrogen nuclei to fuse into helium nuclei. This nuclear fusion at its core will drive the star through most of its life, until it runs out of material millions, billions, or even trillions of years later.

One crucial difference exists in the formation process, though: The larger the star, the more quickly it grows during these initial stages, and thus the faster hydrogen fusion begins at its core. A star the size of our Sun takes an estimated 50 million years to form; a supermassive star that begins its life a hundred times larger will take only tens or hundreds of thousands of years to develop. Most stars grow in clusters embedded in nebulae and thus have several neighbors, so these very massive stars can influence stellar growth around them.

Yet the formation process of these suns still holds many puzzles for astronomers. To verify star formation theories, scientists compare computer models with observations. When they simulate a spinning protostar accreting such a large mass, it often falls apart into several pieces instead of growing into one supermassive star. Because of this, astronomers debate exactly how the largest stars are created. "In the last 10 years, the debate has centered on whether these stars were

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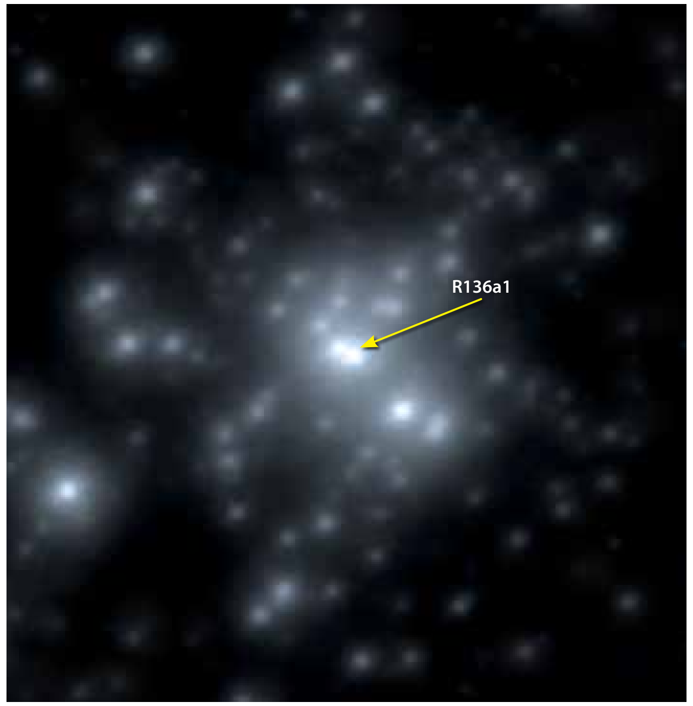



**R136a1, clocking in at 265 solar masses, lies at the center of this image. Astronomers have determined it was even larger when born 1.5 million years ago: more than 300 solar masses. A powerful stellar wind has contributed to its weight loss since birth.** ESO/P. CROWTHER/C. J. EVANS

## EARTH IN THE CROSSHAIRS?

Astronomers debate if supermassive binary Eta Carinae will release a gamma-ray burst (GRB, the most energetic type of blast in the cosmos) when it dies and whether such a GRB would impact life on Earth due to how close the system is to us — about 7,500 light-years. Such a burst, if it occurred, would not directly affect Earth's surface, but it would impact satellites and any astronauts in orbit. It also could severely deplete the ozone layer, which could lead to an extinction-level event. But don't get too worried: Eta Carinae's rotation axis is not aligned with Earth, so if the star generates a GRB, it is very unlikely to hit us. — *Y. C.*

created in one large disk accreting or competitive accretion with multiple clumps merging together to produce them," explains Paul Crowther of the University of Sheffield in the United Kingdom. The star clusters where supermassive stars form are especially dense and chaotic places, and the more massive members of a stellar cluster tend to appear toward its center. As a result, a supermassive star could be the outcome of several stars crashing into each other. Astronomers aren't yet sure which formation process nature follows or if both contribute to these mammoth stars.

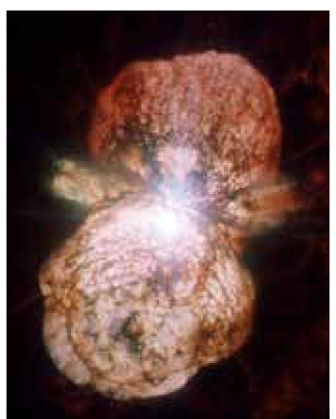
## Popular neighborhoods

While scientists may not know exactly how extremely massive suns form, they certainly know the stars exist. The most famous example, Eta Carinae, is a star visible to the unaided eye in the Southern Hemisphere. This binary system lies about 7,500 light-years from Earth and has a primary star with a whopping 100-some solar masses.

But stars can be even larger: In 2010, Crowther led a team that found R136a1, the most massive known star in the universe at 265 solar masses. This sun is part of the R136 cluster, which boasts several other massive stars. It lies in the 30 Doradus star cluster, which sits in the Tarantula Nebula (NGC 2070) in the Large Magellanic Cloud, a dwarf galaxy that's a satellite of the Milky Way. This nebula is the most active starburst region in our galaxy's local neighborhood; a famous stellar explosion in 1987 occurred near its edge. Astronomers now know that the progenitor of Supernova 1987A, as the event was cataloged, was about 20 solar masses before its energetic death. "We are very lucky 30 Doradus is right next door," explains Frank Tramper of the University of Amsterdam in the Netherlands, because it allows the team he works with to conduct what he calls "fishing expeditions" to find supermassive stars in the region using the Very Large Telescope in Chile.

But 30 Doradus holds thousands of stars, so in order to find and weigh the largest cluster members, astronomers must resort to several tricks. One of the most used methods requires them to first measure a star's brightness at different wavelengths to determine its intrinsic luminosity. They then utilize a relationship between a star's luminosity and its mass — an analysis that can carry high uncertainty because measuring an individual star's precise brightness can push the limits of current technology. Astronomers also rely on supermassive suns in binary star systems to calibrate these luminosity measurements by using the stars' orbits around each other and the laws of motion developed by German astronomer Johannes Kepler (which are also at work in our solar system). Luckily, and for reasons not entirely clear, scientists find most supermassive stars in multiple-star systems, so they can use this technique often.

Today, astronomers are discovering more and more of these objects to study. In early 2013, a team announced that the most massive known binary star, R144, has a combined mass between 200 and 300 times that of the Sun. The curious thing about R144 is that it lies in the outer regions of 30 Doradus. Current theories about supermassive star formation — driven not just by observations but by computer simulations of how these stars form — dictate that the system should have formed toward the more hydrogen-rich center of the nebula. In fact, astronomers have not yet successfully modeled a binary forming in isolation. Further complicating matters, no one has observed a supermassive binary in its creation stages. Either the current theories are wrong about supermassive binary formation, or R144 interacted with other stars often enough to be flung rapidly from the cluster's dense center.

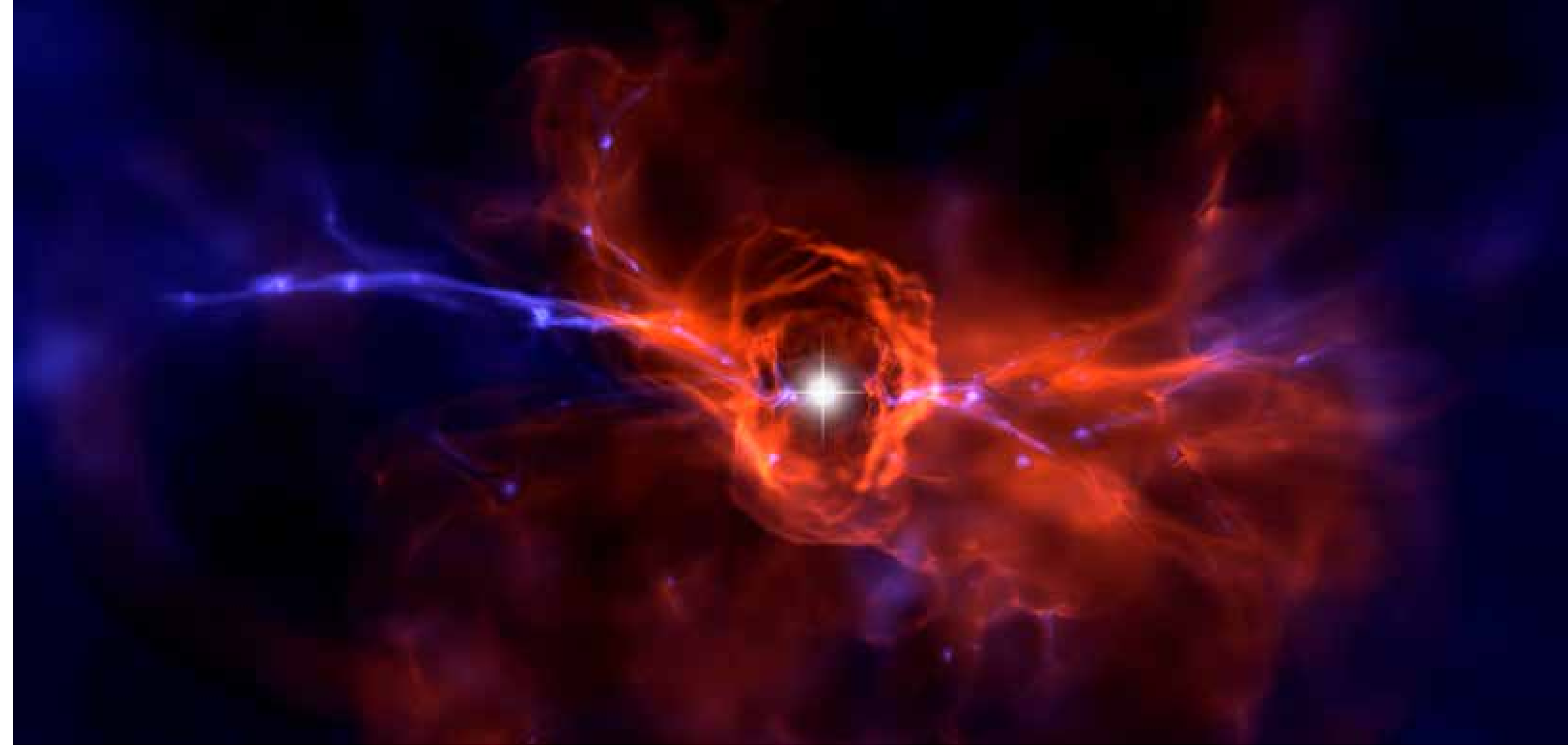


**In the early 19th century, Eta Carinae's (center) brightness varied significantly, peaking at roughly magnitude –1 in 1843. That event threw off an estimated 10 solar masses of material, which now takes on a dumbbell shape known as the Homunculus Nebula.** ESA/HUBBLE & NASA

## Where the wind blows

Regardless of the details, astronomers do know that after a supermassive star forms, it leads a brief but volatile life. Such a sun has strong stellar winds that create powerful outflows of material from its outer layers. "Unlike humans, these stars are born heavy and lose weight as they age," explains Crowther. "R136a1 has an estimated age of around 1.5 million years and has already lost an estimated 20 percent of its mass, or more than 50 solar masses." This means that even though it is the most massive star known today, R136a1 would have been more than 300 times the Sun's mass when it formed and might weigh as little as 100 solar masses at the end of its life in another 1–2 million years.





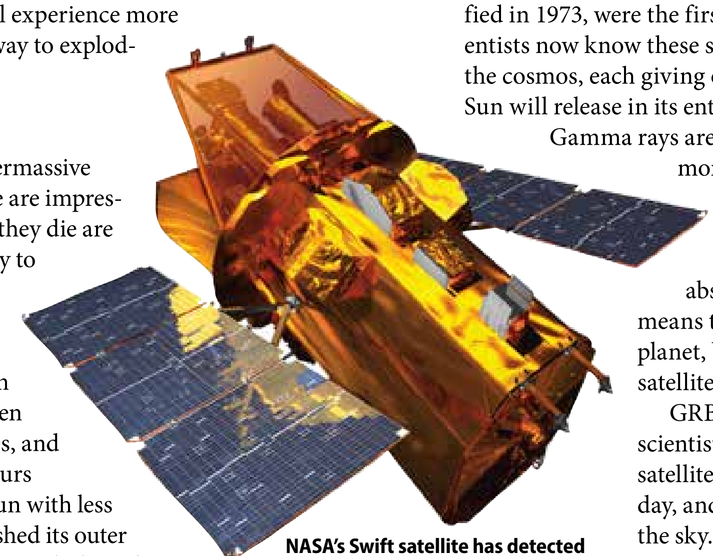
VISUALIZATION: RALF KÄHLER, TOM ABEL; SIMULATION: JOHN WISE, TOM ABEL

**The first stars in the universe, like that shown in this computer simulation, were likely objects with at least 100 solar masses. They burned through their primordial hydrogen and helium quickly and produced many heavier elements that they then spewed into space during their explosive deaths.**

Volatile winds also make massive stars unpredictable and prone to outbursts. Eta Carinae has undergone such flare-ups in the past: While it currently shines at about 5th magnitude, in the mid-19th century astronomers recorded a surge where the star reached nearly magnitude –1 — making it the second-brightest star in the night sky after Sirius despite being several thousand light-years farther from Earth. It remained that bright for years and eventually dimmed to 8th magnitude by the end of the century. Since the 1940s, Eta Carinae has been slowly brightening to reach its current magnitude. Astronomers are still not sure what exactly triggered the "Great Eruption," but they estimate the binary star shed about 10 stellar masses during this outburst; the material is still visible as the Homunculus Nebula that surrounds the system. Scientists think the binary star will experience more violent outbursts on its way to exploding as a supernova.

## With a bang

While the outbursts supermassive stars can have while alive are impressive, the outbursts when they die are truly spectacular. The key to the fabulous flare-ups is that every star eventually runs out of fuel to control the nuclear fusion processes in its core. When this happens, the star dies, and the sort of death that occurs depends on its mass. A sun with less than 8 solar masses will shed its outer layers and leave a planetary nebula with its dense remnant core, now called a white dwarf, in the middle; a star larger than that usually will explode in a supernova that can shine brighter than all the other suns in a galaxy combined. But not all supernovae are equal: A star with less than some 20 solar masses will leave behind a dense neutron-star core while a more massive one will collapse and create a black hole.



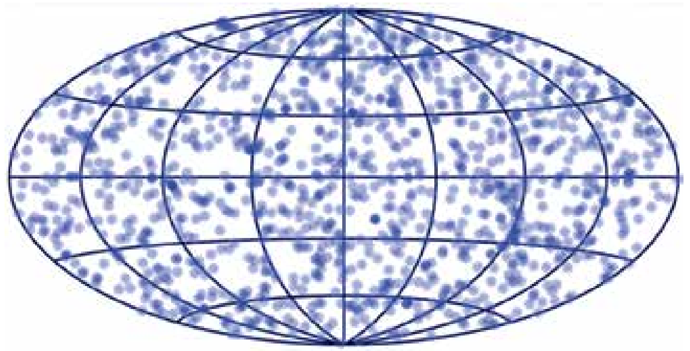
**NASA's Swift satellite has detected more than 900 gamma-ray bursts (GRBs). As soon as it senses a blast, it slews to observe it and also sends the GRB's coordinates to a network of other telescopes.** NASA E-PO/SONOMA STATE UNIVERSITY/AURORE SIMONNET

The formation of a black hole is a violent event — so violent that it can release a light signature seen across most of the visible universe. The blast that signals this catastrophic death was discovered by accident during the height of the Cold War. The U.S. military launched a series of satellites, known as the Vela project, to detect gamma-ray flashes in case the Soviets violated the 1963 Nuclear Test Ban Treaty. The Vela project never confirmed any atmospheric nuclear explosions, but it did detect gamma-ray flashes coming from above Earth — mysterious bursts from space that had unknown origins. These flashes, which the military declassified in 1973, were the first detected gamma-ray bursts (GRBs). Scientists now know these signals are the most powerful explosions in the cosmos, each giving off more energy in a few seconds than the Sun will release in its entire lifetime.

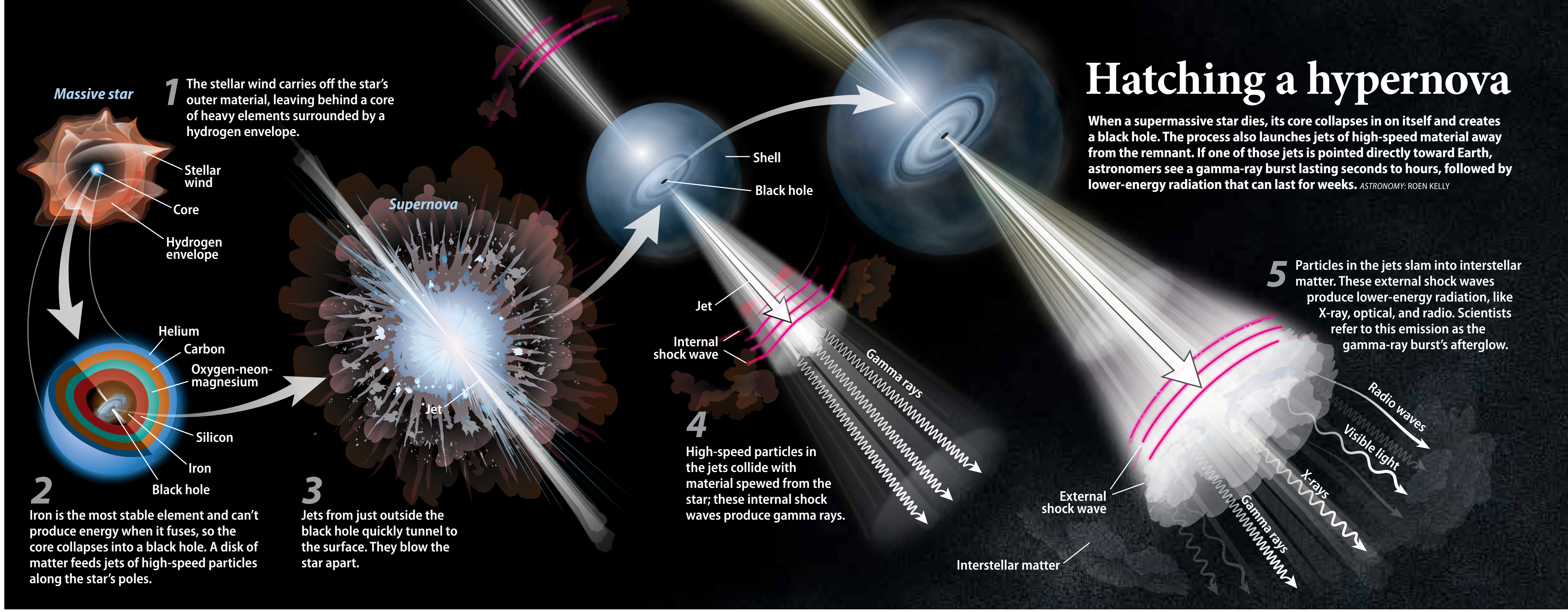
Gamma rays are the part of the electromagnetic spectrum more energetic than X-rays, and just one gamma-ray photon can pack thousands of times more energy than a visible-light photon. (Earth's atmosphere thankfully absorbs gamma rays, like X-rays, which means these flashes do not affect life on our planet, but it does mean astronomers must launch satellites to detect them.)

GRB astronomy has come a long way since scientists initially found these blasts. NASA's Swift satellite now detects approximately one GRB a day, and the bursts originate from all directions in the sky. Astronomers also have determined that GRBs come in three types: short-duration bursts that last just milliseconds, long-duration ones that last minutes, and ultralong-duration bursts that can last hours. They know that the latter two types result from the death of a massive star, while

## GRBs occur everywhere



**Astronomers find gamma-ray bursts all over the sky. Some of these blasts result from the high-energy deaths of rare supermassive stars.** THE GAMMA-RAY BURST REAL-TIME SKY MAP (SONOMA STATE UNIVERSITY)




## Hatching a hypernova

**When a supermassive star dies, its core collapses in on itself and creates a black hole. The process also launches jets of high-speed material away from the remnant. If one of those jets is pointed directly toward Earth, astronomers see a gamma-ray burst lasting seconds to hours, followed by lower-energy radiation that can last for weeks.** *ASTRONOMY*: ROEN KELLY

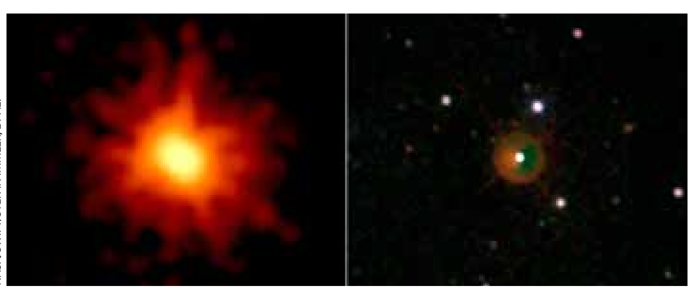
short-duration GRBs come from the violent merger of two neutron stars or a neutron star and a black hole.

When Swift, or another telescope, detects a GRB flash, astronomers receive that object's coordinates within minutes via text message and a network of instruments around the globe slews to view the object. A GRB's emission also rams into nearby material, which causes that material to glow in less energetic radiation. By studying these GRB afterglows in different wavelengths, astronomers have learned that the brightest and longest GRBs come from galaxies rich in star formation and that often a new, bright supernova will appear in the same location on the sky as a GRB. A supernova signals the death of a star, so this correspondence implies that the deaths of the most massive stars trigger some of the most violent and energetic phenomena in the universe; astronomers have a name for such an incident — a collapsar or hypernova.

As the core of a star collapses into a black hole, the remaining stellar material falls toward the center and swirls into a high-density accretion disk surrounding the stellar remnant. Through complex mechanisms not yet understood, matter from this accretion disk will be swept into jets of material at the poles of the star, and when the jets reach the star's surface, they will release gamma-ray energy in the direction of the jets. If one of these jets is aimed directly at Earth, telescopes see a long- or ultralong-duration GRB.

## Record breakers

GRBs are rare — a galaxy the size of the Milky Way will have only a handful every million years or so. To find more of them, astronomers must look far from our galaxy. The more distant an object is from Earth, the longer the light has been traveling to reach us and thus the further back in time that object existed. One GRB holds the record for the farthest object seen with the unaided eye: On March 19, 2008, the beam from GRB 080319B was so powerful that its afterglow reached a visual magnitude of 5.3 for approximately 30 seconds. Anyone who happened to be looking at the right spot in the constellation Boötes at the time under dark skies would have seen the glow of a star dying 7.5 billion years ago.



NASA/SWIFT/STEFAN IMMLER, ET AL.

**On March 19, 2008, NASA's Swift satellite detected the gamma-ray burst (GRB) from a massive star's explosion. The blast was so bright that anyone at a dark site and looking at the constellation Boötes could have seen it. This image shows the observed X-ray afterglow from Swift (left) and the GRB's optical afterglow.**

But that's not the only GRB that holds a record: The most distant object that astronomers have directly detected was a GRB that exploded a mind-boggling 13.2 billion years ago, and its light just arrived at Earth in 2009. The supernova that spawned this blast occurred just 620 million years after the Big Bang, when the first galaxies were beginning to form.

Those two GRBs are long-duration types. In recent years, astronomers also have detected ultralong-duration GRBs that appear to come specifically from supermassive stars. Astronomers detect the gamma-ray signal from these objects for hours instead of several minutes. They believe that these ultralong bursts result from the same mechanisms that create long GRBs — that is, jets from a star collapsing into a black hole — except the star is especially wide and massive. This process could happen for a massive or supermassive star that does not have powerful winds that spew its outer layers over time, so such a star holds onto its gas and has a radius as large as Jupiter's orbit. Because the edge of this sun is so much farther out than a star that has shed much of its material, it takes longer for the explosion to propagate through the star. The black hole also has more material to feed on, powering an ultralong-duration GRB.

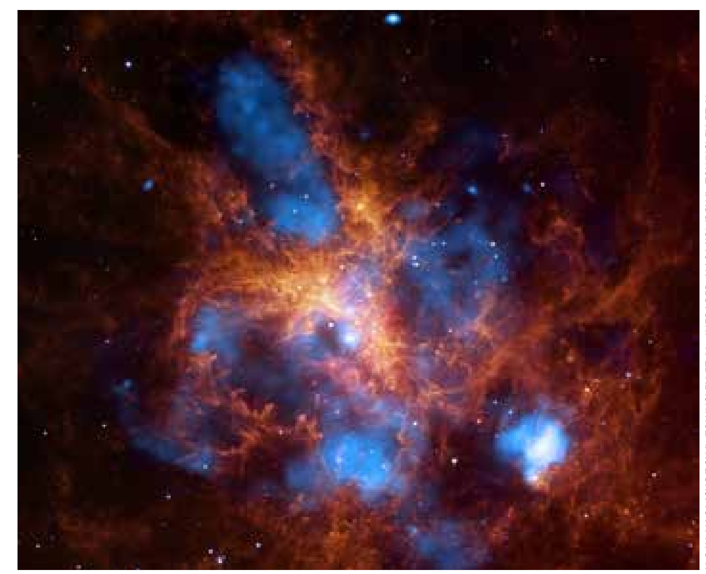
## The earliest rock stars

Such GRB glimpses are intriguing to astronomers who want to learn about the first generation of stars in the universe, called Population III. The chemical composition of the cosmos was different in the first few hundred million years, and thus so were the stars that were born from that material. The universe held the basic elements that formed just minutes after the Big Bang — roughly 75 percent hydrogen, 25 percent helium, and a few trace "metals." (Due to their rarity compared to hydrogen and helium, all elements above helium in the periodic table are metals according to astronomers.) Metals are more efficient at cooling a dust cloud than pure hydrogen, and at cooler temperatures, smaller stars form. In a metal-free environment, however, the dust cloud will be warmer, and computer simulations show stars that form in such environments will be much more massive than those seen today, growing to a few hundred solar masses.

No one is quite certain exactly how big these first stars were because astronomers don't yet have the capability to observe them directly; so far they have only hints of these suns in stray light lensed by the intense gravity of intervening galaxies. Astronomers hope NASA's upcoming James Webb Space Telescope will provide the first glimpses of Population III stars.

Scientists estimate that these first stars, due to their truly supermassive size, would have lived just a million years before exploding as brilliant supernovae. But before these blasts occurred, these stars would have fused in their cores the first 26 elements on the periodic table, including carbon, oxygen, silicon, and iron. Population III stars left their mark as the first suns to inject metals into the universe, but in this way they also doomed themselves: They spread these elements so effectively throughout the cosmos that astronomers do not see any metal-free stars today.

The brief but brilliant lives and deaths of supermassive stars have played, and continue to play, a huge role in star formation around them. "They are the motors of the galaxy because when they explode as supernovas, they dynamically and chemically enhance their surroundings," explains Lucas Ellerbroek of the University of Amsterdam. "They put a lot of extra metals into their environment, and although it's never been proven, it's thought the supernovas trigger other waves of star formation."



X-RAY: NASA/CXC/PSU/L. TOWNSLEY, ET AL.; INFRARED: NASA/JPL/PSU/L. TOWNSLEY, ET AL.

**The massive stars in 30 Doradus shed material and radiation, which then plow into nearby gas. These collisions heat the gas to millions of degrees, which emits X-rays, shown as blue in this composite image.**

Such stars also have affected us directly. It is possible that in whatever long-forgotten nebula our Sun formed, the material initially clumped because of the life and death of a nearby supermassive star. More tangibly, virtually every element on Earth was fused in a star's core long ago — from the carbon in your body to the oxygen you breathe and the silicon in your computer — in a chain of events that stretches back to the first stars in the universe. Supermassive stars are rare, but they are crucial to the universe's evolution and have played a key role in shaping both our lives and those of stars and galaxies across the cosmos.

No one knows which of our galaxy's stars will be the next supernova, but here's a rundown of some famous stars with explosive potential. by Francis Reddy

# Five stars that could go BANG

Each second in the core of our Sun, about 600 million tons of hydrogen nuclei become rearranged into 596 million tons of helium nuclei. These 4 million "missing" tons get transformed directly into energy and, ultimately, sunshine. Every object astronomers regard as a "normal" star is doing something similar, producing energy to support itself against its own weight through one or more types of nuclear fusion reactions. Each of the naked-eye stars we see on a clear evening can be described accurately as a gravitationally contained thermonuclear reactor. And about once or twice a century, on average, one of these fiery cauldrons in our galaxy becomes unstable and explodes.

The result is a supernova — a blast that can reach a luminosity more than 10 billion times greater than the Sun and appear bright enough at its peak to outshine the combined light of all the stars in its host galaxy. The explosion may destroy the star entirely, or it may leave behind a crushed remnant of the stellar core in the form of the most extreme objects scientists know of — neutron stars no bigger than a city and black holes with gravity so strong that even light can't escape.

As far as astronomers can tell, the Milky Way's supernova production line seems to be running a bit behind. The last naked-eye supernova likely was noticed only by John Flamsteed, the first Astronomer Royal of England, while cataloging stars in August 1680. He noted a star in the constellation Cassiopeia that a later generation of astronomers couldn't find, but its position is suspiciously close to the expanding debris of the young supernova remnant Cassiopeia A. Dimmed by distance and interstellar dust, the Cas A supernova attracted no attention because its brightness never would have exceeded 3rd magnitude, and it faded to near the limit of naked-eye visibility by the time Flamsteed recorded it.

A more recent supernova lacked an earthly audience altogether. Radio and X-ray measurements tracking the expansion of G1.9+0.3,

**The nearby IK Pegasi binary system harbors a white dwarf (foreground) and a normal star, but one day the latter sun will swell into a red giant. When it does, material will flow onto the white dwarf and cause it to explode as a type Ia supernova.** RON MILLER FOR *ASTRONOMY*

The last supernova visible from Earth with naked eyes was Supernova 1987A, the "spiky" star to the right of center in this image. The blast occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way, and lit up southern skies in February 1987. ESO

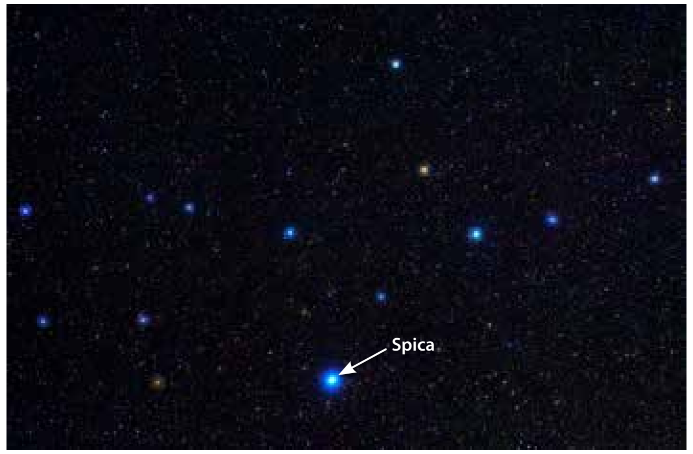
a remnant located toward the bustling center of the Milky Way in Sagittarius, reveal that light from its explosion would have washed over Earth less than 150 years ago. The most recent supernova known in our galaxy might have been seen around the 1860s if intervening dust hadn't totally obscured its light.

This sums up the inventory of known Milky Way supernovae in the past 400 years. For the past century, astronomers seeking to understand the mechanisms that drive these explosions and the stars that produce them have gathered information from supernova remnants in our galaxy and supernovae in other galaxies. For most supernovae, a short fuse is lit when stars born with more than about six to nine times the Sun's mass run through a series of fusion fuels and finally exhaust them, leading to the collapse of their cores, the formation of a neutron star or black hole at their centers, and explosions that blast the overlying stellar layers outward at high speed. Less frequent types result from nuclear processes that sap energy from stellar cores before they run out of fuel, forcing an early collapse, or that tip a delicate balance in favor of runaway thermonuclear reactions.

Thankfully, no stars doomed to end their lives as supernovae lie near enough to the solar system to pose a significant threat to Earth in the immediate future. Yet many famous stars are fated to explode and, when their time comes, will put on quite a show for earthly observers. But which ones? And how soon?

## Proximity bombs

Two stars top any list of potential near-Earth supernovae. The closest by far is the 6th-magnitude binary system IK Pegasi. The primary component is a normal star of spectral type A weighing about 1.7 solar masses, and its companion is a heavy white dwarf,

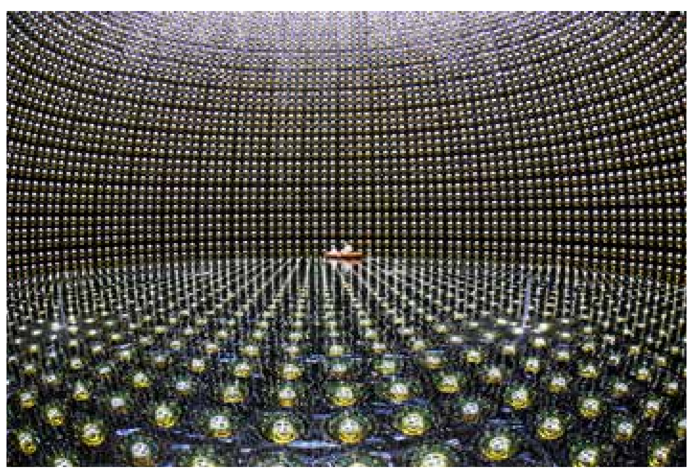



The blue giant star Spica in Virgo looks like a good supernova candidate. At a distance of just 260 light-years, it is the nearest star to Earth with the potential to become a type II supernova. BILL AND SALLY FLETCHER

a compact stellar remnant weighing about 1.2 Suns yet only about as big as Earth. White dwarfs represent the end state for low-mass stars like the Sun and no longer are capable of generating energy through stable internal nuclear reactions. However, when a white dwarf's mass teeters near a physical limit of around 1.4 Suns — the exact number depends in part on its composition — a thermonuclear runaway suddenly will blast it to smithereens and produce what astronomers call a type Ia supernova.

There's only one way this can happen for IK Pegasi. The aging primary star eventually will expand so much that its atmosphere will stream onto the white dwarf, where matter may accumulate and slowly nudge the object toward its explosive demise. According to an evolutionary model of the system by Martin Beech at the University of Regina in Saskatchewan, Canada, some 1.9 billion years will pass before the fireworks begin. Long before this happens, the citizens of Earth will be facing much bigger problems thanks to the steadily increasing luminosity of the aging Sun. In half the time it'll take for IK Pegasi to explode, Earth no longer will be inhabitable.

A different sort of nearby supernova may come from Spica, the 1st-magnitude luminary of the constellation Virgo and among the hottest stars we see. Located about 260 light-years away, this blue star has 12,000 times the Sun's luminosity and weighs in at about 10 solar masses, which makes it the nearest star potentially capable



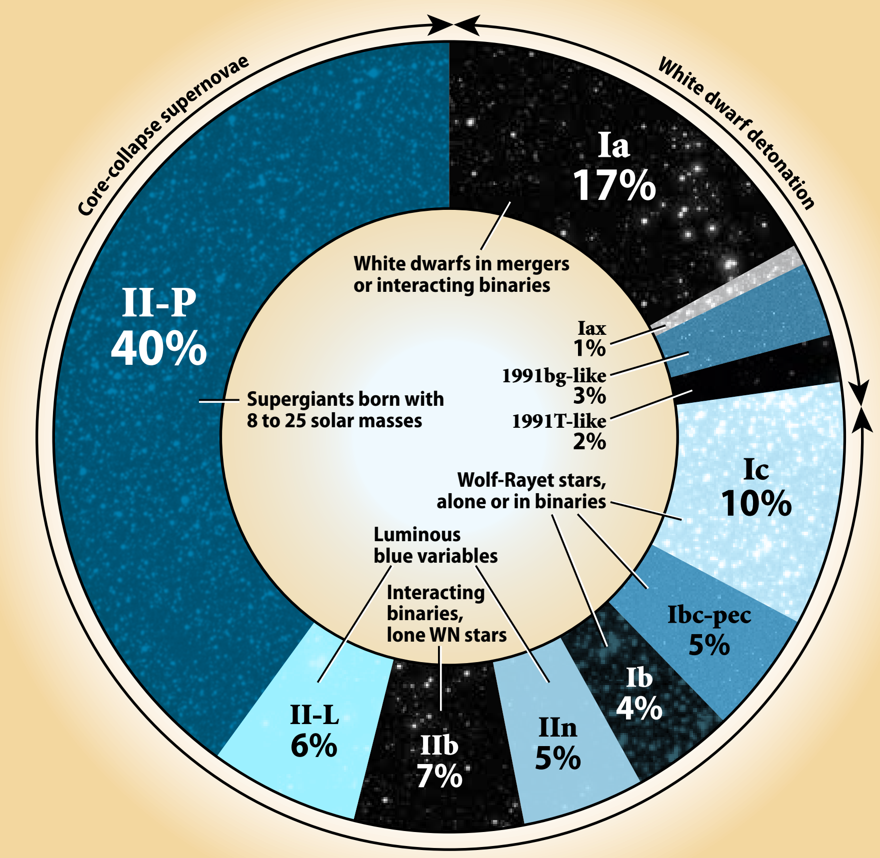
When Betelgeuse explodes, it will send an immense wave of ghostly neutrinos in all directions. Neutrino detectors, like Super Kamiokande in Japan seen here, would be the first instruments to detect the star's demise. KAMIOKA OBSERVATORY/INSTITUTE FOR COSMIC RAY RESEARCH/UNIVERSITY OF TOKYO

of producing a type II supernova, in which the star's core collapses. But a variety of factors complicate Spica's future. First, it spins about 80 times faster than the Sun, and second, it has a close companion, another blue star of about 7 solar masses. This secondary is so close that it takes only four days to complete an orbit — a period about 90 times faster than Earth revolves around the Sun. The mutual gravitational pull of these huge stars warps them into distinctly oval shapes.

Like the Sun, both members of this system still fuse hydrogen in their cores, but Spica may be close to polishing off its allotment and starting its evolution into a giant. Its distorted profile and rapid spin guarantee that it will transfer some portion of its outer layers to its partner, with additional mass lost to space. "The now more massive component will lose about 7 to 8 solar masses, and the now less massive star will likely accrete 50 to 80 percent of that," says Norbert Langer of the University of Bonn in Germany. "Therefore, the now less massive star will probably explode as a supernova."

If Spica's weight loss takes it below the core-collapse threshold, it would form a white dwarf. Millions of years later, when its companion similarly evolves, it will return to Spica some of the mass it received, but the end result of this stellar oversharing is unclear. Perhaps the system will end up much like IK Pegasi, with white-dwarf Spica bypassing its fate as a type II supernova to explode instead as a type Ia.

### The wheel of supernovae




This chart breaks down the frequency of different supernova classes determined by detailed searches covering a large volume of the local universe. Type II-P explosions, caused by the collapse of massive stars with large atmospheres, are the most common and best understood. Type Ia supernovae from exploding white dwarfs are the next most common, although astronomers have started to recognize additional subtypes. Very massive luminous blue variables like Eta Carinae and S Doradus one day may explode as type II-L or IIn supernovae. *ASTRONOMY*: ROEN KELLY; ADAPTED FROM W. LI, ET AL. (2011)

Another consequence of rapid rotation is to reduce the star's luminosity and central temperature, which means it behaves as if it has a lower mass than it really does. For stars, mass is destiny: The more they have, the brighter they shine and the faster they run though their fuel supply. Nuclear fusion transforms hydrogen into helium, producing energy in the form of gamma rays and neutrinos, which are ghostly particles that travel at nearly the speed of light and rarely interact with matter. Once the hydrogen is depleted, the star's core contracts and heats until the accumulated helium "waste" ignites, producing energy by fusing helium nuclei into carbon and oxygen. The recycling program ends here for stars around the Sun's mass, which end up as carbon-oxygen white dwarfs.

More massive stars tap into a sequence of fuels to extend their energy-producing lives. As each runs low — first hydrogen, then helium, carbon, neon, oxygen, and silicon — the core contracts, heats up, and ignites waste from the previous reactions. But once silicon fusion begins and an iron-nickel core starts to form, the star's days are numbered and a core collapse is imminent.

Some massive stars won't live long enough to reach this point. For stars born within a narrow mass range — 9 to 9.25 solar masses if they have a chemical composition similar to the Sun — the fatal blow comes toward the end of carbon fusion, when the core contains a mix of oxygen, magnesium, and neon. At a critical density, the magnesium and neon nuclei begin capturing electrons before the core reaches a temperature hot enough to initiate neon fusion. This electron-capture process removes pressure support from the core, which then collapses under its own weight and produces a weak type II supernova. Could Spica's crazy spin place its effective mass in the right range for this to occur? If so, it would become a supernova sooner than in the other scenarios, although still millions of years from now.

While the closest supernova candidates won't supply us with a bang any time soon, many other stars in our corner of the galaxy are likely to explode in the astronomically near future. Among them are a few truly famous names.

## Betelgeuse, Betelgeuse, Betelgeuse

If there were a poster child for supernova progenitors, it would be Betelgeuse, the magnitude 0.6 red supergiant that marks the right shoulder of Orion the Hunter. Suggestive of its true physical size, Betelgeuse has the largest angular diameter of any star other than the Sun despite a distance of 640 light-years. If this behemoth were placed at the center of our solar system, it would engulf all planetary orbits inside Jupiter's. Amazingly, this actually understates

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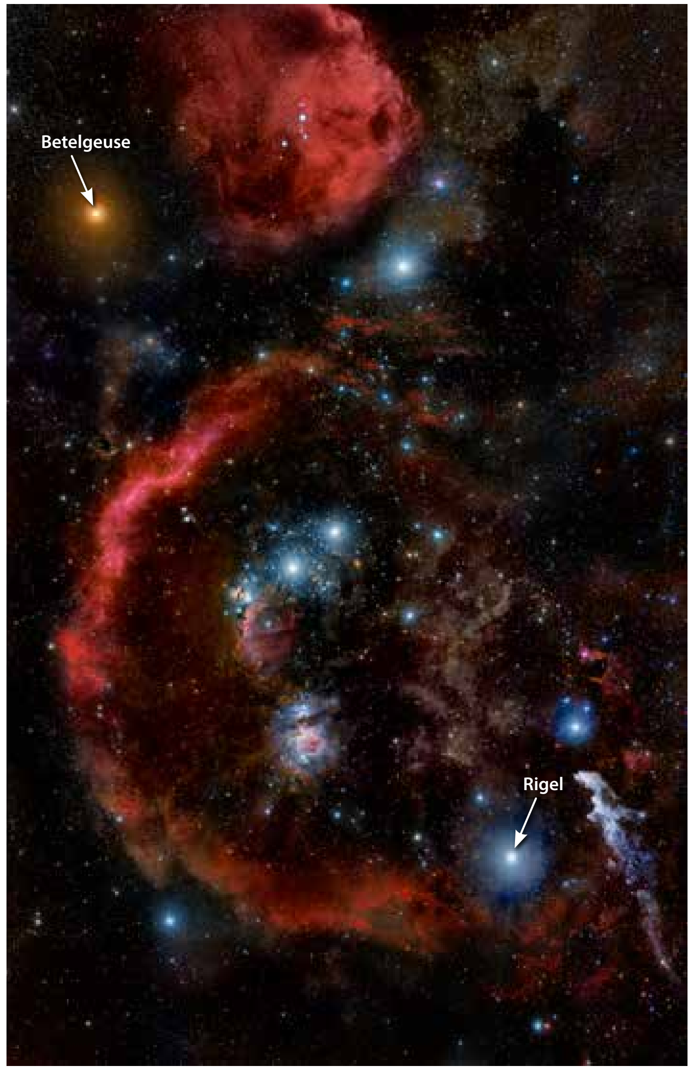


**The gaudy constellation Orion harbors one of the closest and most imminent supernova candidates: Betelgeuse, which forms the Hunter's right shoulder. Rigel, the figure's left knee, also might explode one day.** ROGELIO BERNAL ANDREO

the star's influence. In 2009, astronomers using the European Southern Observatory's Very Large Telescope imaged a giant plume of gas extending at least six times the star's diameter, equivalent to the distance between Neptune and the Sun, and a complex nebula of irregular dusty arcs reaching some 16 times farther. Astronomers estimate that, all told, the star's extensive mass loss affects the environment out to a light-year or more from its surface.

Born about 8 million years ago with an estimated 20 solar masses, Betelgeuse is approaching the end of its life. Like most stars in its mass range, this monster is destined to cycle through a full suite of nuclear fuels until it produces an iron core, which will then collapse to produce a type II-P (for "plateau") supernova and a neutron star. Although astronomers can't peek "under the hood" to see what's actually happening in the star's core, they can estimate its status using observations and evolutionary models. This research suggests Betelgeuse will go supernova sometime between 20,000 and 100,000 years from now.

Here's how the event will play out for earthly observers. Facilities designed to detect neutrinos will notice a brief burst associated with the collapse of the star's core. Astronomers first saw such a signal in Supernova 1987A, a peculiar type II-P explosion in a neighboring galaxy called the Large Magellanic Cloud; it remains the closest stellar explosion seen in centuries. For a similar 10-second burst, says Michael Richmond at the Rochester Institute of Technology in New York, "The flux of energy in neutrinos coming from Betelgeuse would be roughly 1,000 times larger than the flux coming from our Sun." Since neutrinos can travel through a light-year of solid lead without bumping into a single atom, he notes, this boon to astrophysics will come with no threat to Earth and its inhabitants.

**This artist's impression depicts Betelgeuse, a leading supernova candidate. Observations show that the star has a large bubble boiling at its surface and an enormous plume of gas that would stretch across our planetary system.** ESO/L. CALÇADA

The next signal will be an ultraviolet or, possibly, weak X-ray flash as the supernova's shock wave breaches the star's visible surface. That will be followed by a rapid increase in the blast's visible light. Some two weeks after the explosion, Betelgeuse likely will reach a peak visual brightness exceeding magnitude –10.5, appearing as a single searing point of light brighter than a quarter Moon and easily visible during the day. A key feature of type II-P events, which are the most common type in our part of the universe, is that the subsequent fading levels off for many weeks. This occurs as the expanding shock wave traverses the star's vast hydrogen envelope, ionizing the gas and creating an opaque surface that prevents us from seeing visible light from the inner parts of the shredded star. As the shock wave speeds through, the atoms recombine, form more transparent neutral hydrogen, and let astronomers see deeper layers.

Once the plateau phase ends roughly 100 days after peak brightness, Betelgeuse will fade more rapidly. Still, based on expectations for a typical type II-P supernova, it will remain visible in daylight with a brightness exceeding magnitude –5 even a year after the explosion. After two years, Supernova Betelgeuse still may rival Sirius, now the night sky's brightest star.

But the show won't be over then. Astronomers will have an unprecedented view of the formation of a young supernova remnant and neutron star. Roughly 6 million years after the explosion, a much diminished shock wave will reach the solar system, according to a study led by Michelle Dolan and Grant Mathews at the University of Notre Dame. They calculate that the solar wind, an outflow of ionized gas from the Sun, will hold the shock wave in check, preventing it from penetrating closer than about 2½ times Earth's orbital distance, and that the shock will take more than a thousand years to pass by.

And Betelgeuse might not be the only supernova progenitor in Orion. Astronomers were thrown for a loop when SN 1987A erupted from a blue supergiant star rather than a red one. It was an unusual explosion, and researchers have speculated that the progenitor star may have been either a fast rotator or blew up when it merged with a companion star. Various studies have shown that under the right conditions, a blue supergiant can explode long before it evolves to the red supergiant stage. This suggests that Rigel, located opposite Betelgeuse at Orion's left knee, may possibly end its days as a type II-P supernova. If it does, its peak visual brightness would exceed magnitude –9, slightly dimmer than Supernova Betelgeuse due to its greater distance of about 850 light-years.

**This artist's rendering shows the RS Ophiuchi binary system shortly after the white dwarf (right) has gathered enough material from its red giant companion to erupt as a nova (as it last did in 2006). Eventually, the white dwarf may accumulate enough mass to explode as a supernova.** CASEY REED

## Vela superstar

Wolf-Rayet stars are born with masses at least 25 times greater than the Sun and, as a consequence, burn through their fuel allotment much faster than stars like Betelgeuse and Rigel. They run so hot that intense stellar winds already have stripped away their vast hydrogen atmospheres, which constitute most of their birth mass, and even whittled away much of the helium layer below, laying bare some of the byproducts of advanced nuclear fusion reactions. These stars come in three flavors based on their enrichment of nitrogen (WN), carbon (WC), and oxygen (WO). They radiate much of their light in the ultraviolet, so despite high temperatures, they aren't especially bright optically.

The 2nd-magnitude star Gamma$^2$ Velorum is a binary system in the constellation Vela that contains the closest Wolf-Rayet star to Earth. Located at an estimated distance of 1,100 light-years, the primary is a superhot giant star weighing about 30 solar masses. Its WC companion probably weighs about 9 Suns now but started out with 25 to perhaps 40 solar masses. Some astronomers estimate the system is more than 5 million years old, which would mean a star in this mass range should be in its twilight years. The WC star eventually will form an iron core, collapse, and explode, but it isn't at all clear what that explosion will look like or whether it will leave behind a neutron star or black hole.

The optimal case requires a quickly rotating core, which might let the WC star produce an especially energetic type Ic supernova peaking at a visual magnitude as high as –10, rivaling the blast from much-closer Betelgeuse. These explosions also are associated with long-duration gamma-ray bursts — brief, intense flashes of the highest-energy radiation powered by a black hole formed inside the star during collapse. But it's impossible to be more definitive about what may happen at Gamma$^2$ Velorum: Wolf-Rayet stars are rare, and astronomers don't truly understand the progenitors of type Ic supernovae.


ALAN DYER

**Gamma$^2$ Velorum harbors a Wolf-Rayet star with the potential to explode as a supernova. This superhot massive star lies in the southern constellation Vela.**

## From nova to supernova

Our last candidate, RS Ophiuchi, belongs to a different type of binary system. This close stellar duo contains a white dwarf that undergoes repeated outbursts called novae, which are in effect a supernova's little cousin. They occur when hydrogen from a normal star flows onto the dwarf, gradually piles up as a surface layer, eventually reaches a flash point, and explodes in a runaway thermonuclear reaction. Only the accumulated gas erupts, leaving the white dwarf unharmed and ready to begin the process again. Systems producing so-called classical novae may take 10,000 years between outbursts. But RS Ophiuchi is a much rarer system called a symbiotic recurrent nova, which pairs a red giant with a white dwarf. The dwarf star accumulates gas so quickly that it's ready to pop in a matter of decades.

Until recently, astronomers thought these eruptions blew off all of the accumulated mass, preventing the white dwarf from growing toward the 1.4-solar-mass tipping point needed for a type Ia supernova. But the validity of this assumption is now in doubt.

RS Ophiuchi lies about 5,200 light-years from Earth and "goes nova" every couple of decades, most recently in 2006. Measurements from the latest outburst suggest the white dwarf is relatively close to its mass limit. If it exploded, its peak brightness could exceed a visual magnitude of –8, roughly the brightness of a four-day-old Moon seen as a single brilliant point.

An important aspect of RS Ophiuchi that no direct observations can establish is the compact object's composition. Is it a carbon-oxygen or an oxygen-neon-magnesium white dwarf? If the latter, then as the dwarf grows toward its mass limit, the electron-capture process will cause a collapse to a neutron star and a weak supernova.

Despite their violence, supernovae transformed a sterile universe into one hospitable to life, scattering heavy elements made in the foundries of massive stars and forged in the blasts themselves. Whether it's RS Ophiuchi, Gamma$^2$ Velorum, Betelgeuse, or some other star, the light from the next naked-eye supernova may already be on its way, bringing a cosmic delight to skywatchers and a scientific bonanza for astronomers.

The brown dwarf Gliese 229B looms above the surface of a hypothetical rocky planet. The brown dwarf, which likely sports a turbulent atmosphere, orbits the ruddy low-mass star Gliese 229A depicted at right. *ASTRONOMY*: ROEN KELLY

# The little stars that couldn't

Brown dwarfs — objects that form like stars but without enough mass to fuse hydrogen — are shedding light on the births of both stars and solar systems. **by Jesse Emspak**

Brown dwarfs were once called failed stars — more massive than planets but without enough heft to ignite hydrogen fusion and shine under their own power. In recent years, astronomers have learned that they are among the most complex objects in the sky: Pressure has crushed their interiors into super-dense states scientists call "degenerate" while their cool atmospheres may harbor clouds of iron and silicon. They could hold the keys to understanding why solar systems form the way they do and serve as clocks for determining ages throughout the galaxy — if astronomers can pin down how they change with time.

"They show us that our [stellar] evolutionary models are wrong," says Emily Rice, an astrophysicist at the American Museum of Natural History and the College of Staten Island in New York City. Brown dwarfs have had a habit of defying expectations, and their sheer variety keeps them interesting, she says. "There are a lot of big ideas and open questions [surrounding them]."

**The faint light of low-mass brown dwarf TWA 5B shows as a small dot above center. TWA 5A, a pair of Sun-like stars that orbit so closely that their glows merge, dominates this visible-light view.** ESO

## From theory to reality

Astronomer Shiv Kumar, then at NASA's Goddard Space Flight Center Institute for Space Studies in New York, first proposed the existence of brown dwarfs in the 1960s. Kumar constructed models of low-mass stars and found the mass limit for objects capable of fusing hydrogen — about 0.07 solar mass for a gas cloud with a similar composition to the Sun and about 0.09 solar mass for one made of pure hydrogen. Such an object would contract until it reached a certain size, where the pressure exerted by degenerate electrons — they occupy all of the lowest possible energy states in the gaseous interior — would halt the collapse. At the time, Kumar called them "black dwarfs," but that name already was taken by white dwarf stars that had cooled to the point where they no longer shine. In 1975, Jill Tarter, then a newly minted Ph.D. and now

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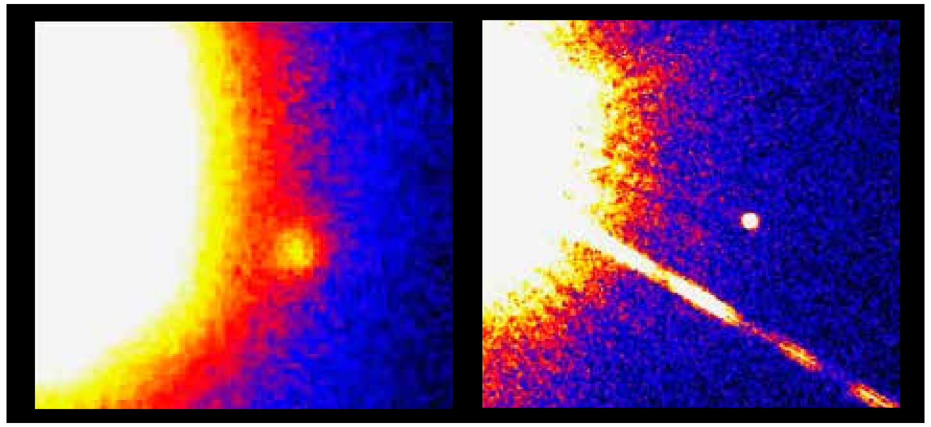


**Brown dwarf Gliese 229B turned up in 1995 as a blip next to its bright companion, Gliese 229A, through Palomar Observatory's 1.5-meter telescope (left). The Hubble Space Telescope resolves it more clearly (right).** LEFT: T. NAKAJIMA (CALTECH)/S. DURRANCE (JHU); RIGHT: S. KULKARNI (CALTECH)/D. GOLIMOWSKI (JHU)/NASA

at the SETI Institute in Mountain View, California, proposed the name "brown dwarf," and the moniker stuck.

Yet it took until 1995 to finally see one, when astronomers discovered Teide 1 in the Pleiades star cluster. After that, the sightings came thick and fast — astronomers now have identified more than 1,000 brown dwarfs thanks to better detectors, particularly in the infrared part of the spectrum where brown dwarfs radiate most of their energy. The big players include the Two-Micron All-Sky Survey (2MASS), the Spitzer Space Telescope, and the Wide-Field Infrared Survey Explorer (WISE).

With greater numbers, however, has come greater complexity.

**In fact, the only place that water clouds have been definitely observed beyond the solar system is on cool Y-class brown dwarfs.**

## Acting your age

Stars fuse hydrogen into helium during most of their lives, a stage scientists refer to as the "main sequence." A star's size depends on the balance between the inward pull of gravity and the outward push of gas pressure caused by heat. Heavier stars go through their stores of hydrogen faster, and thus are more luminous, and a star's color and size tend to stay the same until it's almost out of fuel. Once you know a star's mass, intrinsic luminosity, and color, it's not difficult to put constraints on how old it is and how long it will live.

But brown dwarfs behave differently. Lacking the mass of stars, they don't generate the necessary heat and pressure at their cores to turn hydrogen into helium. The core may get hot enough to fuse deuterium, a heavy isotope of hydrogen with one neutron, or even lithium. But neither process lasts long because such elements form only a tiny percentage of a brown dwarf's mass. Electron degeneracy puts a lower limit on the size of the dwarf, which cools slowly as it radiates away its internal heat.

Astronomers classify brown dwarfs as L, T, and Y, running from hottest to coolest. Theoretically, this sequence also should run from youngest to oldest, reflecting the dwarfs' slow cooling.

"Stars stay on [the main sequence] and at an absolute brightness and color for a long time," says Adam Burgasser, an astrophysicist at the University of California, San Diego and head of its Cool Star Lab. While it's possible to put a lower limit on a star's age, the evidence is indirect until they start moving off the main sequence. "But the luminosity of a brown dwarf is the main thing we measure — it's more directly accessible — so if that is time variable, it's a much better clock."

**The young brown dwarf TWA 5B (top) emits X-rays. The 1-million-year-old object spins quickly, which tangles its magnetic field and heats the atmosphere to millions of degrees. TWA 5B orbits the close binary TWA 5A (bottom). A visible-light image of this system appears on p. 25.** NASA/CXC/CHUO UNIVERSITY/Y. TSUBOI, ET AL.

The problem is getting a good handle on a brown dwarf's mass and, from that, the rate at which it cools. A massive brown dwarf will lose heat much more slowly than a less massive one.

The difficulty of determining a brown dwarf's mass stems from their location — they often exist in isolation. A companion star or planet makes the task easy because scientists can measure the dwarf's gravitational pull and thus its mass. So the key, says Burgasser, is to find lots of brown dwarfs in binary systems. "A lot of work is being done to make that a reality," he adds.

Another way to learn a brown dwarf's age is to measure its surface gravity. By breaking down an object's light into individual colors, a spectrum can show not only what compounds are in the brown dwarf's atmosphere but also the gravitational force there. In stronger gravity fields, spectral lines broaden because the atmospheric gases are more compressed and therefore the molecules move more rapidly. So, by looking at the width of spectral lines, scientists can estimate a brown dwarf's surface gravity, which in turn tells them how much it has contracted and thus approximately how old it is.

## True colors and stormy weather

Meanwhile, some astronomers strive to see into the atmospheres and come up with models that describe the clouds there. Brown dwarfs are cool enough to have weather, but it isn't like anything on Earth.

For a brown dwarf, cloud composition depends on temperature. Younger objects are relatively hot, sometimes up to about 3,000 kelvins. As the dwarf cools, different compounds will condense. At higher temperatures, the clouds might be made of silicon or iron, while lower temperatures mean clouds of methane or water. In both cases, a lot of complex molecular chemistry takes place.

In fact, the only place that water clouds have been definitely observed beyond the solar system is on cool Y-class brown dwarfs. Jackie Faherty, an astronomer at the Carnegie Institution of Washington and the American Museum of Natural History, recently published a study of a particularly cool dwarf with a temperature of only about 250 K (–10° Fahrenheit) and a mass of six to 10 Jupiters. "What I think that I have is the first object that there's verifiable evidence of water clouds outside our solar system," she says. The object, cataloged as WISE 0855–0714, lies only about 7 light-years from Earth.

Another way of using a brown dwarf's atmosphere to get at deeper truths involves looking at how much light it lets through. Kay Hiranaka, a graduate student at Hunter College in New York City, is working on how to identify a brown dwarf's age by how deep into the dwarf an observer can see. A younger, warmer brown dwarf will tend to have a thicker atmosphere. As the dwarf cools, heavier elements will condense into larger droplets and dust grains that eventually rain out of the atmosphere. So, as a brown dwarf ages, it should become less cloudy, making it easier to see light from deeper in the interior.

## Adding complications

But the story of brown dwarf atmospheres isn't so simple. Hunter College astronomer Kelle Cruz (Hiranaka's advisor) has been studying the spectra of low-mass brown dwarfs using 2MASS data for more than a decade. In a 2009 study published in *The Astronomical Journal*, she found that while many of these objects had spectra that looked normal, some showed absorption lines that didn't match expected strengths, and the overall light coming from the dwarf was either bluer or redder than it should be.

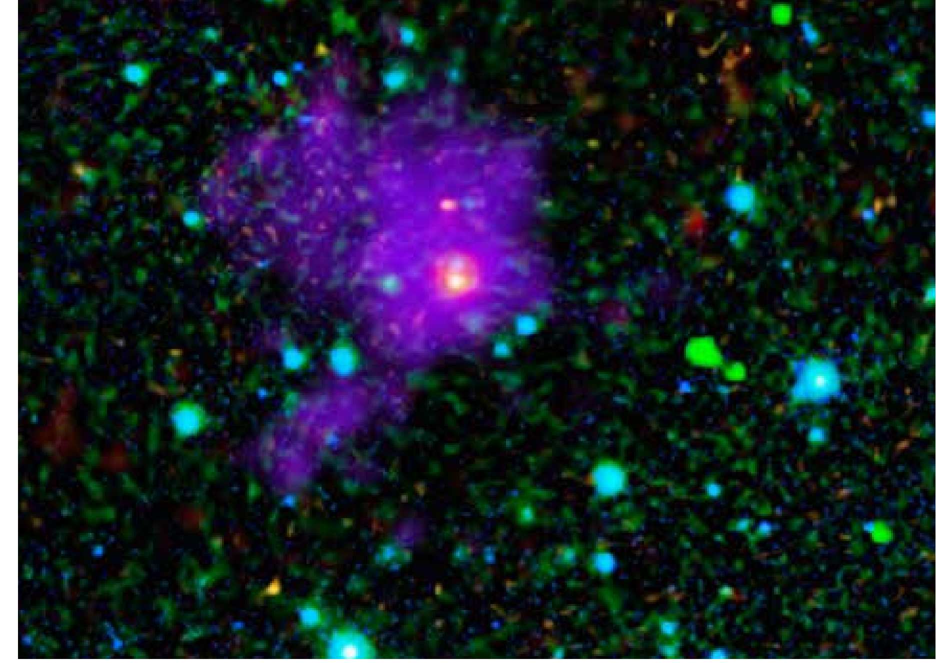
For example, Cruz found that the spectral lines for sodium, cesium, rubidium, potassium, iron hydrides, and titanium oxide were weak while those for vanadium oxide were relatively strong. These results differ from most brown dwarfs of the same class but with higher surface gravities.

Another odd aspect of the spectra was lithium, the third-lightest element. In ordinary stars, lithium atoms fuse with hydrogen to create two helium nuclei, so the lithium gets depleted quickly. No object below 65 Jupiter masses (0.06 solar mass) can build up enough heat to fuse lithium, which means that it should show up in absorption spectra. Many of the low-mass objects Cruz and her colleagues studied failed the so-called lithium test, however, because they showed none of this element.

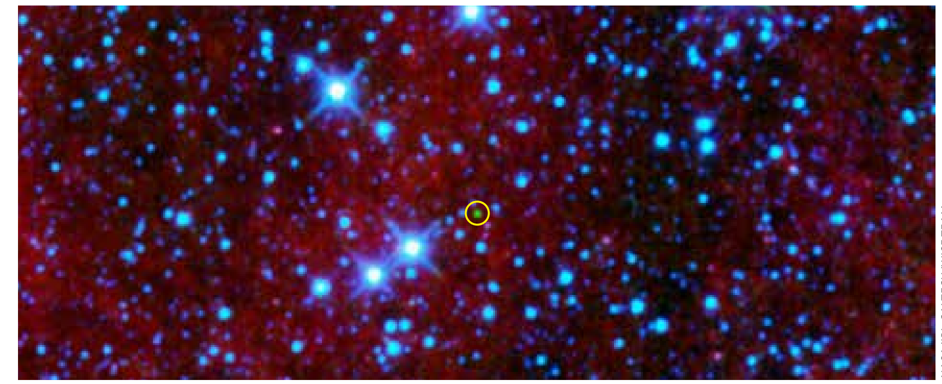
Cruz's team considered various explanations for the lack of lithium and concluded that the dwarfs' low gravity is the likely culprit. Cruz says clouds also may help block lithium's signature. For example, a brown dwarf with lots of dust particles in its atmosphere might preferentially scatter shorter wavelengths of light where the lithium lines occur.

Clouds also have been a focus of Stanimir Metchev, an astronomer at the University of Western Ontario in London, who studied brown dwarf rotations to learn more about these atmospheric phenomena. By tracking the brightnesses of the dwarfs, he could use the variability to map visible features. "It's the oldest technique in astronomy," he says, "just measuring the total brightness over time."

"The bottom line from our study of weather on brown dwarfs is that virtually all of them have spots on their surfaces, perhaps not much unlike the weather systems that we observe on Jupiter and other

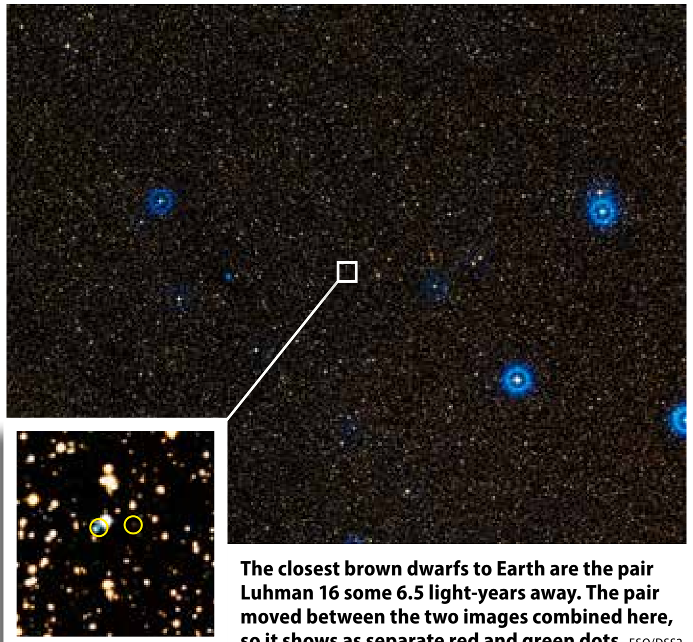


**NASA's infrared-sensitive Spitzer Space Telescope captured this pair of brown dwarfs (at center) lurking in the confines of the dark nebula Barnard 213. Brown dwarfs are cool objects that radiate most of their energy at infrared wavelengths.** NASA/JPL-CALTECH/D. BARRADO (CAB/INTA-CSIC)

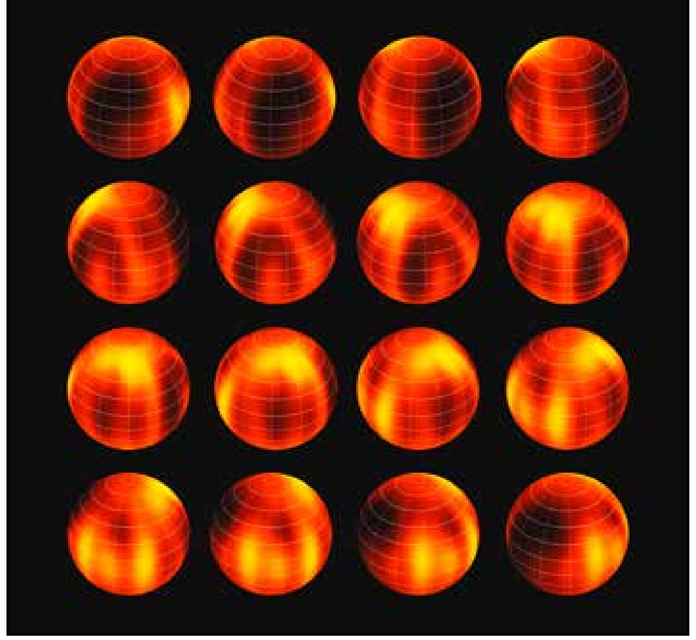


NASA/JPL-CALTECH/WISE TEAM

**NASA's Wide-Field Infrared Survey Explorer has turned up hundreds of brown dwarfs. The emerald-green object at center is one of the coolest the telescope has found, glowing at about 600 kelvins.**



The closest brown dwarfs to Earth are the pair Luhman 16 some 6.5 light-years away. The pair moved between the two images combined here, so it shows as separate red and green dots. ESO/DSS2



Astronomers used the European Southern Observatory's Very Large Telescope to make these weather maps of the nearby brown dwarf Luhman 16B, one of a pair discovered in 2013. The 16 equally spaced views record one full rotation of Luhman 16B. ESO/I. CROSSFIELD

giant planets in the solar system," he says. "The state-of-the-art understanding before our survey was that spotted brown dwarfs may be confined to a narrow temperature range, between 1,300 and 1,500 K, where their atmospheres were expected to undergo the greatest changes because of the disruption of silicate [dusty] clouds. Our survey has shown that these clouds are visible in all brown dwarfs, not on just those special ones."

In addition, Metchev found that younger, hotter brown dwarfs show a greater temperature contrast between regions than older ones. Temperature contrasts across a dwarf's surface provide the driving force for storms that can be every bit as violent as those on Jupiter or Saturn, and possibly many times that size.

Clouds on brown dwarfs also can add complexity to the models for how the luminosities of these objects change over time. Astronomer Trent Dupuy of the University of Texas at Austin recently found evidence that the models are off, perhaps by as much as a factor of two. He looked at a binary system for which he could get an accurate mass for the dwarf and checked its luminosity against available models. He found that the dwarf was too bright given the system's estimated age.

Dupuy thinks a big reason is that the clouds are irregular — no planet or dwarf is uniformly cloudy everywhere. At the same time, clouds act like a blanket and help the dwarf hang on to more energy. Models, he says, tend to assume that temperatures are uniform across the surface.

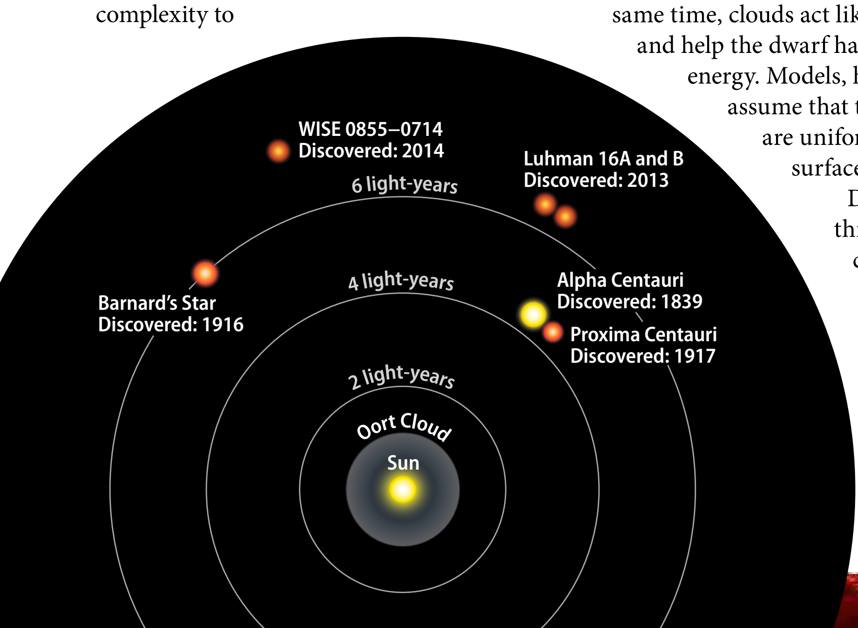
Dupuy doesn't think the discrepancy is too bad. Saturn, for example, is also hotter than it should be according to models that work well for Jupiter. "On the one hand, they are a factor of two off," he says. "On the other, it's only a factor of two."

The brown dwarf ISO-Oph 102 (circled) resides in the colorful Rho Ophiuchi star-forming region. A thin dusty disk (not visible in this wide-field view) surrounds the young dwarf and shows up at radio wavelengths. ALMA (ESO/NAOJ/NRAO)/DSS2

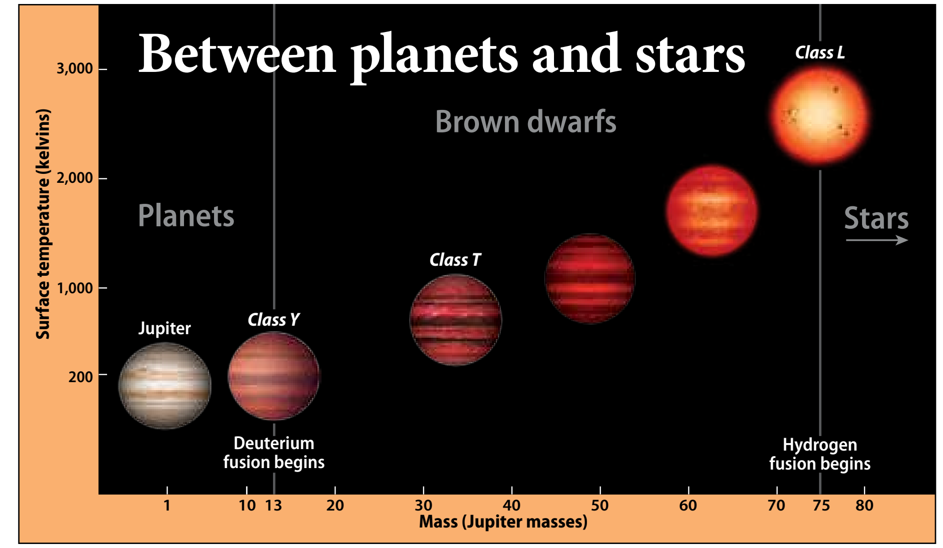
## Spin doctors

Metchev and his colleagues found that the rotational periods of brown dwarfs don't match theory either. As a body gravitationally contracts, the law of conservation of angular momentum dictates that it will rotate faster, like a spinning figure skater who pulls in her arms. Although the researchers found that a significant fraction of brown dwarfs spin in about 10 hours or more, Metchev says the expected average should be even faster. Without tidal forces — from a planet orbiting the brown dwarf or the dwarf circling a star — there are not many ways to slow down a rapidly rotating object.

One possibility would be for the dwarf's magnetic field to couple with the interstellar medium. The problem with this idea is that there might not be enough matter to generate a coupling strong enough. "Within about 300 light-years of the Sun, we're in a local bubble," says Metchev. "A long-ago supernova cleared this region."




Brown dwarfs seem to be ubiquitous, with astronomers estimating our galaxy holds one for every six stars. The solar neighborhood boasts three brown dwarfs — Luhman 16A and B and WISE 0855–0714 — located within 7 light-years of our solar system. *ASTRONOMY*: ROEN KELLY




Brown dwarfs occupy the broad range of objects from roughly five to 75 times the mass of Jupiter, though the boundaries are somewhat fuzzy. The biggest and hottest (class L) define the limit at which hydrogen fusion begins (larger objects are stars), while the coolest and smallest (class Y) transition into gas giant planets. All the intermediate class T objects can fuse deuterium. *ASTRONOMY*: ROEN KELLY

## How low can you go?

These problems connect with how brown dwarfs are born in the first place. Before they were discovered, it wasn't clear how they could form at all.

University of Western Ontario astronomer Shantanu Basu, who studies star formation, says that most scientists around 1990 said that forming a star would require a gas cloud of at least one solar mass. But most stars are smaller than the Sun, so clearly it's possible to generate objects with lower masses, perhaps through fragmentation. But can you get down as low as a brown dwarf?

"It's actually rather hard to get something that low mass to collapse directly," says Basu. He adds that the debate now is whether brown dwarfs form "top down," from collapsing gas clouds as stars do, or "bottom up," by accreting matter like planets. The evidence is not conclusive, and it's possible that both processes occur.

Astronomer Kevin Luhman at Pennsylvania State University isn't so sure. "I think that observations indicate that most brown dwarfs probably form in the same manner as stars, through the gravitational collapse of a cloud core," he says. "They are just born from smaller molecular cloud cores than stars."

It's possible, he adds, that turbulence within the gas cloud causes some parts of it to turn into stars and others into brown dwarfs. Through surveys of star-forming regions, he has found objects as small as 0.005 solar mass (about five Jupiters).

Basu notes that a protostar's accretion disk can contain a lot of mass, so it's possible that brown dwarfs form the same way as gas giant planets. If so, some of these bodies should get ejected into deep space as they get jostled. This could happen even before they have fully formed — creating clumps of half-contracted matter that eventually will form free-floating brown dwarfs.

If true, a large number of free-floaters should exist in star-forming regions and at the periphery of local star systems. The problem with confirming such objects is that their ejection speeds would tend to be slow, on the order of a mile per second, which is equivalent to moving a light-year in a few hundred thousand years. So, it would be difficult to tell if a brown dwarf formed in place or elsewhere.

Basu hopes new observations with the Atacama Large Millimeter/submillimeter Array in Chile will reveal brown dwarfs in the dust disks surrounding stars. Isolated brown dwarfs have been observed, though it's not clear yet if they were ejected from a parent system. "We don't have any observations of the early stages, the first 10,000 years," he says.

**Metchev found that younger, hotter brown dwarfs show a greater temperature contrast between regions than older ones.**

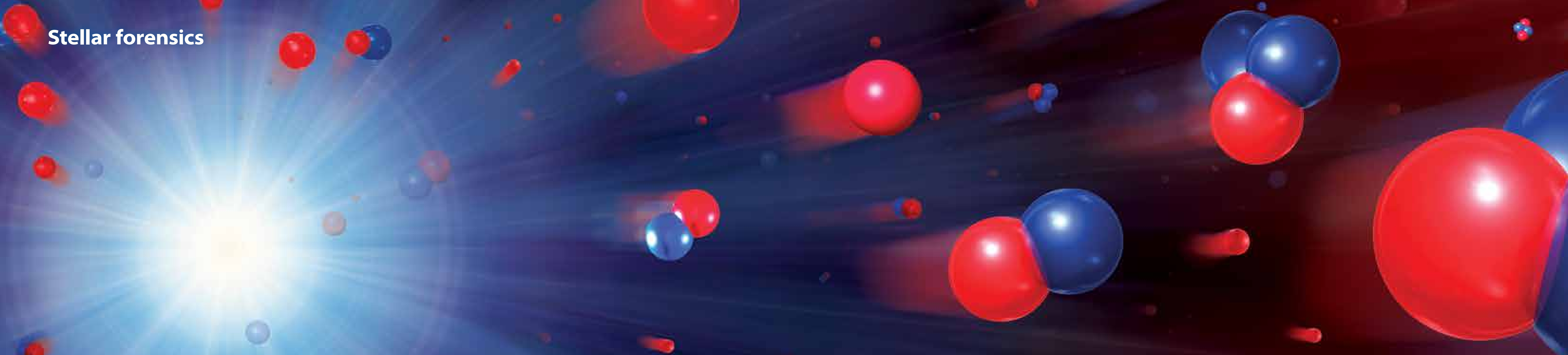
## Planet stand-ins

The fuzzy boundary between brown dwarfs and giant planets is part of what makes these objects worthy of study, says Faherty. "Some of these would be without question a planet [if they orbited a star]."

And their masses can get close to some of the Jupiter-class worlds found by the Kepler space telescope. "It's a gateway to understanding giant exoplanets," she says.

"One reason brown dwarfs are interesting is that they allow us to study the process of star formation over a very wide range of masses, from 100 solar masses to 0.005 solar mass [and perhaps lower]," says Luhman. "At the same time, we can examine how planet formation varies over that same range of masses for the central 'sun.' By doing so, we can test theories for star formation and planet formation since those theories often make predictions that depend on the stellar mass."

That's part of what makes the study of brown dwarfs so exciting, says Faherty. When we study the origins of these objects, "We're playing detective for something [that happened anywhere] from 10 million to 3 billion years ago."



# The hunt for stars' hidden fingerprints

Examining current stars is giving astronomers a look at past generations.

**by Liz Kruesi**

The study of the universe cannot depend solely on observations of celestial objects, on computer simulations of cosmic history, or on mathematical equations. Instead, it is a combination of the above — plus crucial laboratory measurements. One cannot interpret distant cosmic objects without a foundation of basic physics.

Perhaps no area of astronomical research showcases this relationship better than stellar spectroscopy — spreading out the light from a star into its constituent wavelengths (or colors), and using that data to interpret many of the star's properties. Spectroscopy combines atomic physics, stellar astrophysics, and observational astronomy.

If you know what to look for, you can find clues to the previous generation of stars in a spectrum. In this sense, stars are fossils, preserving the composition of the objects that came before them.

*Contributing editor* ***Liz Kruesi*** *is a freelance science writer in Austin, Texas. She thanks the previous generations of stars that made the elements that comprise her.*

Astronomers learn about suns that lived and died generations ago, seeding the cosmos with rich chemistry, including the materials necessary for life.

Some of these chemical elements are difficult to find and eluded detection until recently; others are still missing. Scientists are working together to gather data to fill in the gaps. Their goal is nothing short of knowing the cosmic origin of every element, building up a more complete picture of star formation and stellar death, and tracking how the periodic table of elements evolved in our universe.

## An intertwined history

Early learning about the composition of stars relied on the advancement and collaboration of physics and chemistry experiments, and on building better astronomical instruments. In the early 19th century, German scientist Joseph von Fraunhofer invented the spectroscope and spread sunlight into its constituent rainbow — and puzzled over dark lines he saw within the Sun's light.

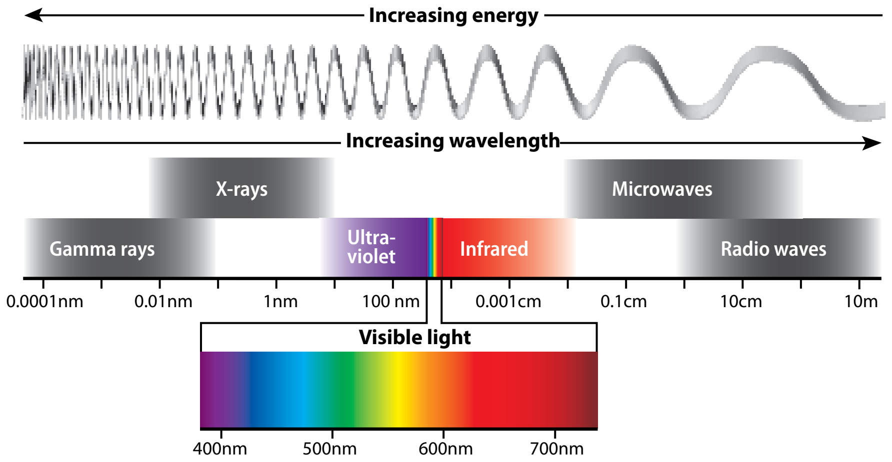
In the middle of that century, Gustav Kirchhoff and Robert Bunsen realized, after comparing solar observations with laboratory chemistry experiments, that those lines mark specific elements. Each line corresponds to a wavelength absorbed by an element's atoms. With that information, the physicists identified more than a dozen chemical elements in the Sun's spectrum.

Other astronomers at the time began to study stars to try to tease out the compositions of those distant lights.

Fast forward to the end of the 19th century when Harvard College Observatory astronomers began collecting and studying the spectra of tens of thousands of stars. The missing colors — the dark absorption lines — varied in strength among different stars. This difference became the perfect tool to categorize these stars. The work, led by Annie Jump Cannon, is today's cornerstone of stellar classification, and the missing colors — revealing the elements present in each star — allowed astronomers to decipher a host of characteristics about these objects. For example, from the width of those lines, researchers can figure out how fast a star is spinning.

**A few minutes after the Big Bang, protons and neutrons began to combine into deuterium (heavy hydrogen) and helium nuclei, although most of the material was still hydrogen nuclei (protons). The temperature at this time was about 1 billion kelvins.** ASTRONOMY: ROEN KELLY

## The electromagnetic spectrum




**The color, energy, and wavelength (distance between wave crests) of any kind of electromagnetic radiation are all related. Green light, for example, has a shorter wavelength than orange, so it is more energetic. Gamma rays contain the most energy, and radio waves have the least.** *ASTRONOMY*: ROEN KELLY

## THE ULTRAVIOLET ELEMENTS

In their survey of the cosmos, Ian Roederer of the University of Michigan, Chris Sneden of the University of Texas at Austin, and their colleagues are searching for elements whose spectra contain strong ultraviolet lines.

So far, the team — using the Hubble Space Telescope to collect data — has found and measured the following 12 elements that show strong ultraviolet lines in their spectra:

| | |
|---|---|
| Boron-5 | Tellurium-52 |
| Phosphorus-15 | Lutetium-71 |
| Germanium-32 | Osmium-76 |
| Arsenic-33 | Iridium-77 |
| Selenium-34 | Platinum-78 |
| Cadmium-48 | Gold-79 |

But knowing what materials made up each star answered only part of the riddle. Other questions remained. How did those elements form, and why were their ratios different in different stars?

Work in the first half of the 20th century began to address these questions, and in 1957, scientists realized that nearly all elements heavier than hydrogen, helium, and lithium are created within stars during their lives and their explosive deaths. While astronomers had an idea of the general processes needed to make the elements, they puzzled over the details: Why would some stellar environments form much more of a specific element than others, and at what point in the explosion did certain elements form?

### Chemical fingerprints

Each element leaves its fingerprints in stellar spectra, but getting to those telltale signals can be difficult. The youngest stars are made of material that has been processed through several generations, and thus have thousands of overlapping fingerprints. Separating out each line to measure how much of each element makes up those stars is not possible.

Stars from the universe's early days are made of less complex mixtures of material, and thus have fewer signals to sort through. When scientists examine the oldest stars they can study, they are measuring the elements that formed out of the spewed debris of the first stars. That data lets them know how those first stars lived and died, setting in motion the chemistry of the entire cosmos.

But these older and more pristine stars are rare because most would have already died in our 13.8 billion-year-old universe. (Astronomers have found only five stars that each hold 1⁄100,000 or less the amount of heavy elements that our Sun contains.)

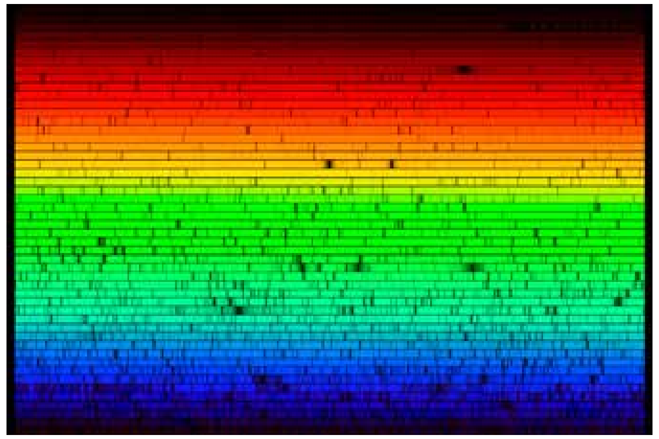
### Inside the star

Gravity compresses the gas of a star like the Sun in such a way that deep in its core, temperatures reach 27 million degrees Fahrenheit (15 million kelvins). Because of the high pressure, atomic nuclei (mostly hydrogen's sole proton) are in close proximity. The temperature ensures that the atoms' electrons are unattached and that the nuclei are moving at high speeds and colliding.

A series of nuclear reactions converts four protons into one helium nucleus (two protons and two neutrons), two electron antiparticles, two ghostlike neutrinos, and a bit of energy in the form of gamma radiation. That energy radiates away from the star's core, and its outward pressure opposes the in-fall from gravity.

The radiation travels from the center of the star through its densely packed gas and finally penetrates the surface, free to journey to astronomers' telescopes. During its journey through the star, each gamma ray interacts with nuclei and electrons. The particles can either reflect or absorb the gamma ray, re-emitting it in the latter case. Each interaction causes it to lose a bit of energy. That means that the star's light scientists detect can range from high-energy gamma rays down to low-energy radio waves.

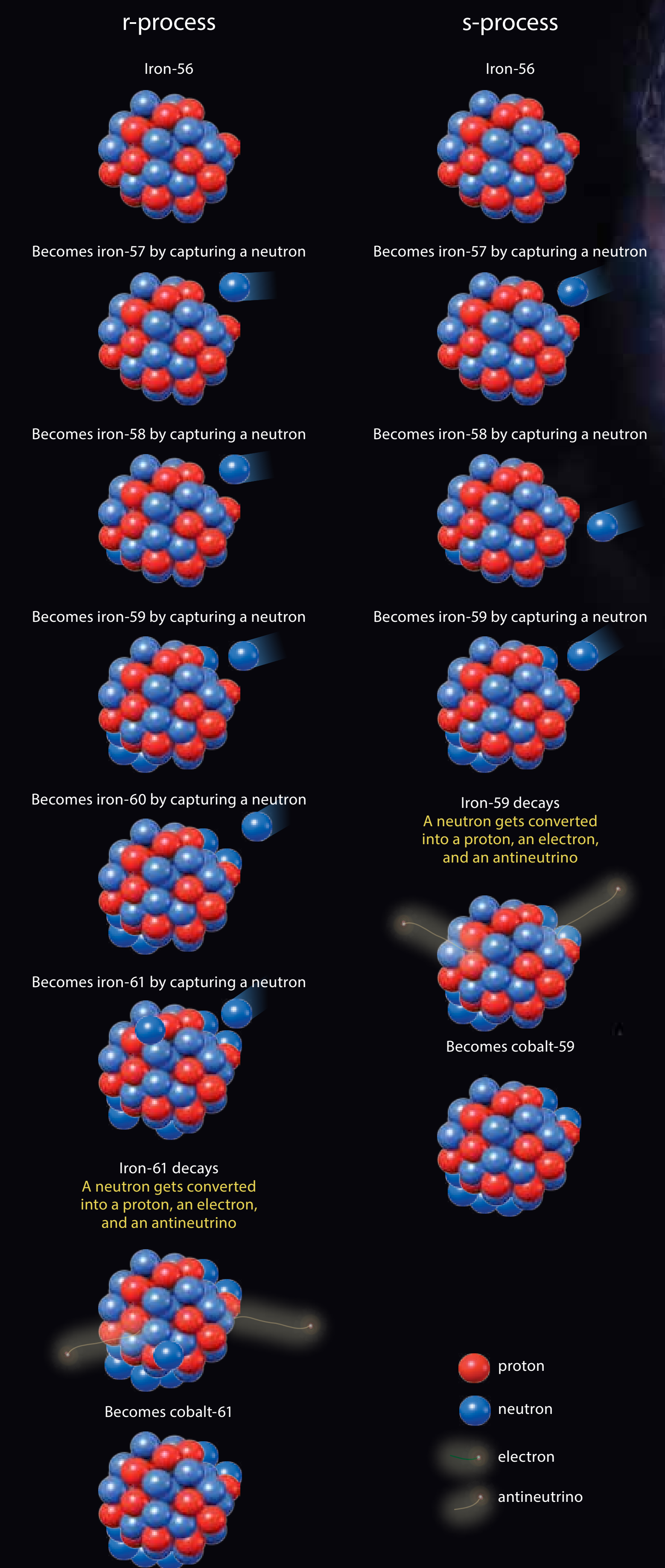
The detected light also reveals what type of gas is in that star. The temperature of the star's inner gas layers is cooler the farther out from the core one studies. When there is a cooler clump of gas in front of a radiation source, an atom in the clump can absorb some of the light. It does so at very specific colors, which are characteristic to what element the gas is.



**The Sun's spectrum was the first studied in detail. In this image, wavelength increases on each line from left to right, and from bottom to top. Each of the 50 rows covers 6 nanometers, creating a complete spectrum across the visual range from 400nm to 700nm.** N. A. SHARP/NOAO/NSO/KITT PEAK FTS/AURA/NSF



# Nature's recipe for creating elements




*ASTRONOMY*: RICK JOHNSON AND ROEN KELLY

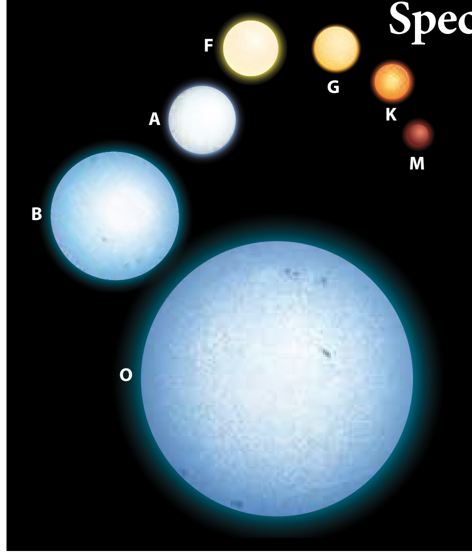
The universe began as a pretty dull place — lots of hydrogen and helium, but little else. Things began to grow interesting after the first stars formed. These ancient ancestors of the stars we see today fused hydrogen into helium in their cores. Later, they and their offspring created more complex atoms, including carbon, oxygen, and nitrogen.

The heaviest stars forged ever more exotic elements, up to iron-56 (a nucleus containing 26 protons and 30 neutrons). But that's as far as fusion goes. Creating heavier elements requires an influx of neutrons. Let's look at how stars turn iron-56 into isotopes of cobalt. The same methods produce heavier elements as well.

Deep inside evolved stars, nuclear reactions create lots of neutrons. When iron-56 captures a neutron, it becomes iron-57. Another capture produces iron-58, and another iron-59. Each neutron capture takes about a year — so scientists dub this the s-process (for slow). Iron-57 and iron-58 are fairly stable, but iron-59 decays to cobalt-59 in a month, before it can capture another neutron.

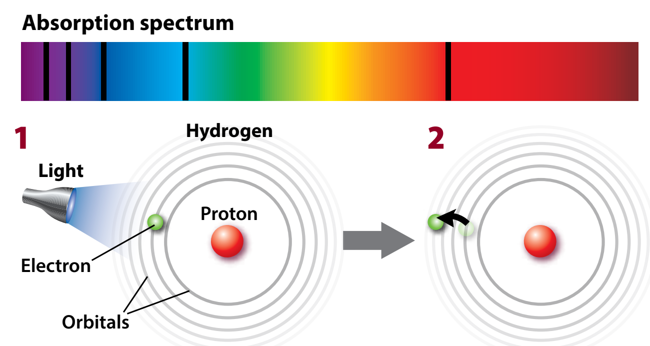
To get past this roadblock, you need a high flux of neutrons, like that found in supernovae. Iron-59 adds one neutron to make iron-60 and a second to form iron-61. That then decays to stable cobalt-61. Scientists call this the r-process because it happens so rapidly. The same process creates the heaviest elements. — *Richard Talcott*

## Spectral types




Stellar spectral classes range from the hottest, bluest stars to the coolest, reddest ones. O-type stars have surface temperatures in excess of 30,000 kelvins, whereas M-type stars have surface temperatures as low as 2,500 kelvins, cool enough for some molecules to exist within them. *ASTRONOMY*: ROEN KELLY

## Forming absorption lines




**A single electron orbits a hydrogen atom's nucleus. The electron usually stays in a level with a certain energy. Diagrams 1 and 2 show the electron absorbing just the right wavelength of energy to move to a higher level. A cloud of gas (such as a star's atmosphere) shows an absorption spectrum.** *ASTRONOMY*: ROEN KELLY

Each color is precisely the wavelength that the element needs to boost an atom's electron to another energy level. When a whole lot of atoms absorb that color of light, less of that wavelength gets to telescopes. Stellar spectroscopists look for those "missing" colors in the light that began at the center of the star, and those missing colors tell them what elements make up the star.

But just knowing these elements doesn't tell you much about stellar evolution. For that, astronomers need to calculate how many atoms of each element lie in that star. It's these kind of details that still drive today's stellar astrophysicists, like University of Michigan's Ian Roederer, University of Texas at Austin's Chris Sneden, and their collaborators.

An atom absorbs energy at a specific wavelength, which boosts an electron to a higher energy level. Some transitions are more likely than others, a phenomenon called the "transition probability." Each atom creates an ultra-faint fingerprint. The more atoms of the element that are present in addition to how likely it is for that energy-level jump to occur means a more visible fingerprint, which shows up as a stronger absorption line.

To best understand what they're seeing in the spectrum, Roederer and Sneden collaborate with an atomic physicist who specializes in this work. "Jim Lawler has been painstakingly measuring these properties in the laboratory for decades," says University of Oklahoma's John Cowan, another astrophysicist in this collaboration. And his work is absolutely crucial to calculating how much of each element is in the star.

### Extra pathways

The number of protons in an atom's nucleus defines its chemical element identity. Most of the elements up to iron (26 protons) are created through fusion within a star's core, where pressures and temperatures are extreme. But after iron, it takes more energy than fusion generates to create heavier elements. A star still can make them, however, in so-called neutron capture processes. There's the slow pathway, called s-process, and the rapid pathway, called r-process.

"The definition of slow means that if a neutron is grabbed by some nucleus, then it becomes too neutron-rich for stability," says Sneden. "The neutron will turn itself into a proton and you've gone up one in the periodic table." In this s-process, time passes between the nucleus grabbing extra neutrons and the neutron decaying into a proton. "Any adjustment the neutron has to make has time to do it before another neutron comes along," Sneden adds.

The rapid process doesn't have such a leisurely schedule. Instead, "a great flux of neutrons just obliterates a nucleus," he says. The r-process happens in energetic, violent events when a massive star collapses and rebounds as a supernova explosion. "This flood of neutrons," Sneden adds, "will glom onto heavy-element nuclei, and in a second or two the neutron flood stops, and furiously there will be decays back to stability." Some astronomers think the rapid neutron capture process also can occur when two neutron stars slam into each other, but this theory has only recently become popular.

The heavy elements made during these neutron-capture processes are rarer than those made in the cores of stars because these processes happen for briefer amounts of time. They also require higher temperatures — up to hundreds of millions of degrees — and such conditions are extremely rare.

### The hidden elements

Using ground-based telescopes, astronomers have studied a plethora of elements like iron, carbon, oxygen, hydrogen, and helium. But Earth's atmosphere limits the wavelengths that pass through it, and not all elements have spectral lines that lie in these gaps. (Or sometimes they do, but those lines are much less likely and the resulting spectral line is therefore too weak to see.) Several of the elements invisible in optical light lie in the ultraviolet (UV) part of the spectrum.

Most UV radiation doesn't make it through Earth's atmosphere, and while that's good for human DNA, it's not great for astrophysicists who look for that light. They need a telescope in space to view it. Currently, there's only one telescope that can be used to look for it — the Hubble Space Telescope.

The push to find the "invisible" elements finally moved forward when Hubble launched. While Roederer and Sneden lead the charge now to detect these elements and calculate their abundances, the work began in the 1990s with Sneden, Cowan, Francesca Primas, Doug Duncan, Ruth Peterson, and David Lambert.

To figure out which element to go after, the scientists look at databases and publications from the physics community that provide the energy-level transitions of each element and at what wavelengths these occur. They're looking for unsearched-for elements with strong spectral lines in the ultraviolet range. "Our marching plan has been to work our way through the periodic table of elements," says Cowan.

First, they select a few elements to study, and then pick an ideal star to observe. They choose specific stars out of the large sky surveys that people like University of Notre Dame astrophysicist Tim Beers have completed. In his four-decade career, Beers has captured low-resolution spectra of millions of stars. From those observations, Sneden's team can find the stars with cleaner spectra and fewer heavy elements. That usually means the ideal star is older and thus was created when fewer heavy elements existed.

The researchers have a few additional requirements, too: "We're looking for stars that are bright enough to us, close enough, and [have] the spectral lines strong enough that we can see," says Cowan. They also need stars that haven't evolved too much to make their own stew of chemical elements.

The next step, says Roederer, is to apply for Hubble time to get a detailed UV spectrum of that ideal star. Once the proposal is accepted and the data collected, it's time to analyze. But it's not easy. "The ultraviolet spectrum of a star, like any in our study, is, to put it bluntly, a mess. It's a composite of thousands upon thousands of lines — the signatures of dozens of elements," says Roederer.

To work through that spectrum, the astronomers compare it to computer models of other stars. These simulations factor in chemical composition and the elements' atomic transitions as well as different layers (indicated by different temperatures) of the star's atmosphere. Researchers are trying to reproduce in their computer model the same spectrum they observe with Hubble. Their model goes into the fine details: "We correlate the strength of an absorption line — if you wish, the depth of an absorption line — to actually measure the number of atoms that could be responsible for that depth," says Primas.

They compare each computer-generated spectrum to the observed one and create a plot, called a "best fit," of how much they differ. The one that matches the closest can then tell them the amount of each element.

"From there, then you've got something you can actually do some science with," says Roederer.

**Supernovae — the explosions of the most massive stars — seed the cosmos with metals (elements heavier than hydrogen and helium). Such events also create the heaviest elements by the r-process, where the explosion showers the nuclei of already heavy elements with neutrons.** NASA/JPL-CALTECH

### Science of the stars

The most exciting science that astronomers are using these abundance measurements for is to unravel the details of the previous star and its explosion that produced some of the material the observed star grew out of. "It's one thing to say some massive star blew up and it made these elements," says Beers, but what the research is moving toward is being able to say what the mass of that star was, if those elements formed through the r-process during the blast or the s-process from material piling up on one object stolen from another. "That's the real driver to understanding, keeping in mind we're all talking about laboratories that blew up 13.5 billion years ago," says Beers. "It's the ultimate CSI."

By knowing how much of each element a supernova contributed to a next-generation star, astronomers can constrain evolution models. When they have this information for tens of elements, they can further narrow down which models make sense and which don't.

Researchers also are shifting to stars that formed from the explosions of the first generation of stars, those with less heavy-element material. These stars formed from less processed material and can give clues to the first round of stellar evolution.

Although it's not possible to go back in time to look at the first stars, the collaboration between atomic physics, spectroscopy, computer modeling, and stellar astrophysics is providing a way to use today's relics from that epoch. Such collaborations were critical more than a century ago when scientists first began interpreting what elements existed in stars, and while the techniques have evolved and advanced, they have done so together to push forward the understanding of the cosmos. ◑

### A FUTURE LACK OF TOOLS

The Hubble Space Telescope has opened up this field of hunting the missing elements because it is sensitive to ultraviolet (UV) wavelengths, a regime not accessible from the ground. The telescope has two UV instruments, which Roederer, Sneden, and their colleagues say are crucial to this work. But Hubble has operated for 26 years, and it won't live forever. The major concern among researchers in this field is, what happens next?

There are no UV instruments in development at NASA or the European Space Agency. The Russian and Spanish space agencies are collaborating on a project called World Space Observatory-Ultraviolet, which will have a 1.7-meter telescope that can study UV wavelengths between 115 and 310 nanometers. While the agencies claim the telescope is in the production stages, the project's website hasn't been updated in over two years — and a launch date is nowhere to be found. *— L. K.*