When stars go BANG!

Some stellar explosions mark star death; others reveal greedy companion suns. Here's how these blasts compare. **by Francis Reddy**

Astronomers estimate that every second, somewhere in the observable universe, a star undergoes a supernova explosion. These stars are the source of chemical elements heavier than boron — like the calcium in our bones, the iron in our blood, and the sodium and potassium that orchestrate nerve impulses. So, while it's true that we are "star stuff," we're most deeply connected to those suns that end their days in explosions and scatter newly forged elements across the cosmos.

Supernovae leave behind the most extreme objects we know of. Neutron stars are no larger than Manhattan Island and contain more matter than the Sun. Stranger still are black holes, where gravity is so strong that not even light escapes. And at least some supernovae are linked to gamma-ray bursts (GRBs), the most powerful explosions in the universe.

Scientists have detected GRBs from as early as about 13 billion years ago, when the universe was 4 percent of its current age. They don't see supernovae as far in the past — the record is now about 12 billion years ago — but the nearest events offer important opportunities. Thanks to archival images and data, astronomers have been able to study 15 doomed stars before they blew up. Nearby supernovae also provide the best chance for catching the explosions long before they reach peak brightness in order to better understand how they unfold. "There is now a real push to locate and study supernovae as close to the start of the explosion as possible, ideally within the first 24 hours," says Stephen Smartt, an astronomer at Queen's University Belfast in Northern Ireland.

While scientists understand reasonably well the most common types of supernovae, new wide-field surveys are finding extreme examples that explode in unusual environments. One of those projects, the Palomar Transient Factory (PTF), has discovered

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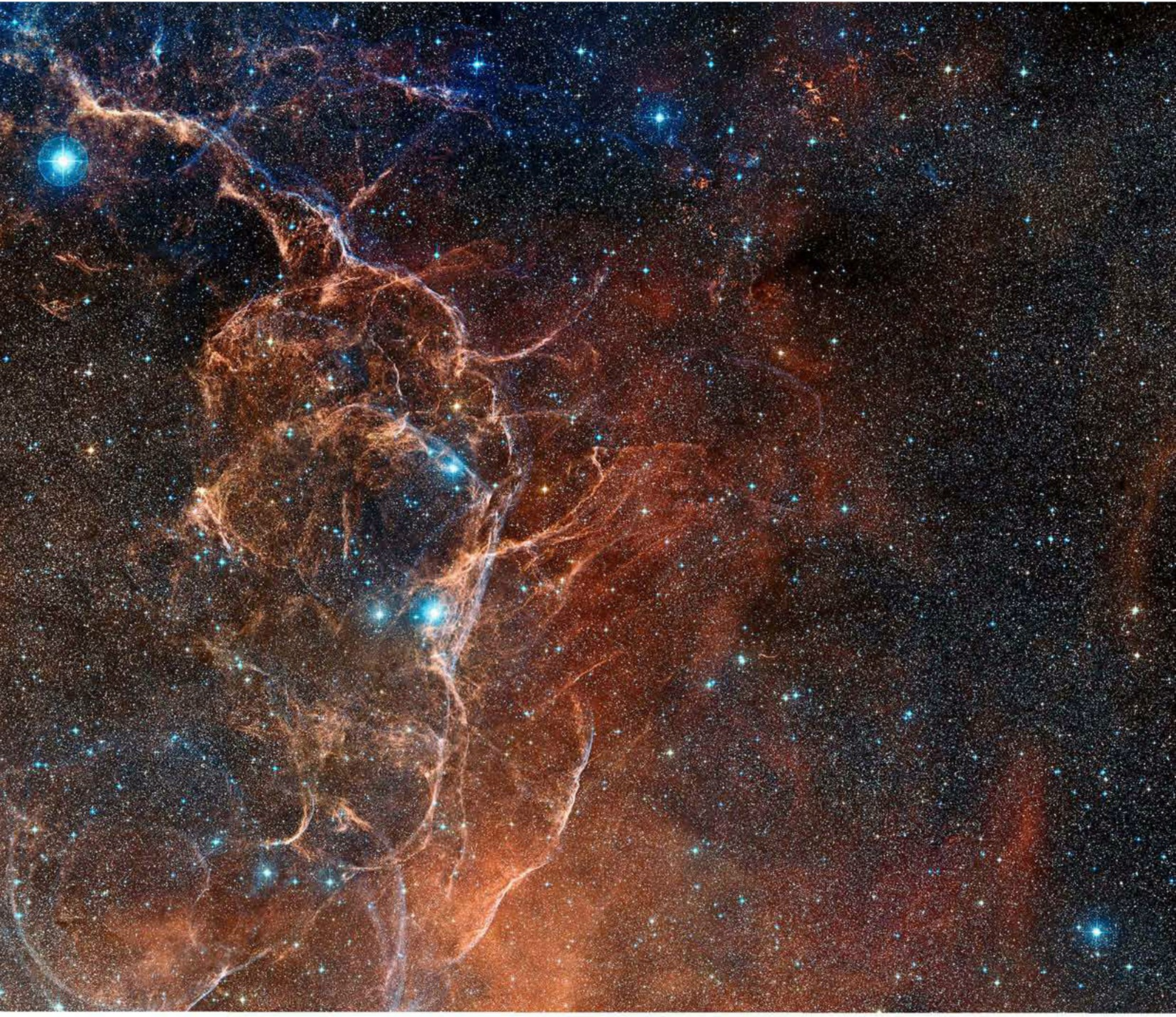


The Vela supernova remnant illustrates the beauty of a massive star's death. The stellar explosion occurred some 11,000 years ago; since then, the supernova's shock waves have collided with and compressed interstellar gas, causing it to glow. DAVIDE DE MARTIN/ANGLO-AUSTRALIAN OBSERVATORY/UK SCHMIDT TELESCOPE/DIGITIZED SKY SURVEY

more than 1,800 supernovae since 2009. Shri Kulkarni, the lead investigator on PTF, sums up the situation this way: "We have not been imaginative enough in understanding how stars die."

The big picture

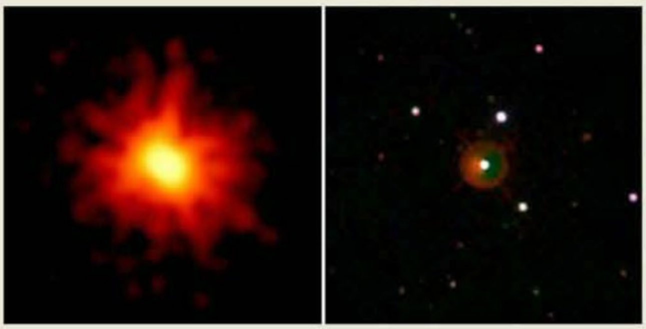
Nova derives from the Latin for "new star," a term that entered the scientific lexicon in 1573 when the great Danish astronomer Tycho Brahe reported on the previous year's brilliant example. A typical nova rapidly brightens by thousands of times and then, over a period of weeks, fades back into obscurity.

Astronomers now know that novae occur in binary systems where a normal star transfers matter onto a white dwarf — the dense Earth-sized remnant of a star like the Sun. Hydrogen gas piles onto the white dwarf and heats up until the layer eventually ignites in a runaway thermonuclear reaction that blows off the accreted gas, creating the nova outburst. The white dwarf itself remains intact and may undergo this process repeatedly. One of the best examples is RS Ophiuchi, a system where the white dwarf "goes nova" about every 20 years. For it to "go supernova" would require the white dwarf's complete disruption, a scenario that until recently was not thought possible in this type of system.

In 1934, long before the physical details of the nova process were clear, astronomers Fritz Zwicky and Walter Baade began referring to the most exceptional novae as "super-novae," and they made a convincing case that such events represent the collapse of an ordinary star into a neutron star.

At the time, observational proof that neutron stars even existed was 30 years away, but Zwicky and Baade's basic picture still describes the most populated supernova (SN) class. SN 1987A, the most recent "superstar" visible to the naked eye, dramatically confirmed this theory. Before-and-after images demonstrate that a star did disappear. Scientists also detected a burst of neutrinos —

A type Ia supernova explosion occurs once a white dwarf has collected enough mass from a companion to reach about 1.4 times the Sun's mass. Astronomers think the donor star can be a red giant (left), a normal star (middle), or another white dwarf. NASA/SWIFT/AURORE SIMONNET, SONOMA STATE UNIV.



NASA's Swift satellite imaged the extremely luminous afterglow of gamma-ray burst 080319B with its X-ray telescope (left) and its optical/ultraviolet instrument. NASA/SWIFT/STEFAN IMMLER, ET AL.

A NAKED-EYE GRB

At 2:13 A.M. EDT on March 19, 2008, alert observers fortunate enough to be looking toward the constellation Boötes at a dark site might have glimpsed gamma-ray burst (GRB) 080319B, one of the most luminous bursts in X-ray and gamma-ray energies and the brightest yet seen in visible light. The gamma-ray spike triggered NASA's Swift satellite, which alerted astronomers around the globe.

Two robotic wide-field optical cameras — TORTORA and Pi of the Sky, both located at observatories in Chile — automatically slewed to observe the burst's position. Both recorded the emergence of a dim star that, over a period of about 50 seconds, rose to a maximum brightness of magnitude 5.3 on the astronomical scale (or about three times brighter than the visual threshold) and then quickly faded to invisibility.

Incredibly, the light from this dying star had been traveling to Earth for 7.5 billion years. This was the birth cry of a black hole born when the universe was less than half its present age, long before the Sun was born.

Astronomers say the event was so bright because its particle jet happened to point almost directly toward Earth. They expect similar dead-on alignments with GRB jets to occur about once a decade, on average. — *F. R.*

particles that don't easily interact with matter, travel at nearly the speed of light, and carry away most of the energy of a stellar collapse — at Earth before the visible explosion. Depending on mass, composition, and other factors, such a core-collapse supernova may leave behind a neutron star or a stellar-mass black hole.

Spreading starlight into a spectrum of its component colors, rainbow-like, allows astronomers to see the absorption or emission of energy produced by elements in the star's gases, clues that reveal the stellar atmosphere's composition and motion. In 1941, Rudolph Minkowski found that the visible spectra of supernovae come in two distinct flavors at peak brightness: Type I supernovae show little evidence of hydrogen, while in type II blasts it is plentiful.

Until recently, the general picture was that a type Ia supernova arises from the detonation and total destruction of a white dwarf in a matter-transferring binary system with a normal star. In this scenario, the dwarf accumulates the gas rather than blowing it off in repeated nova explosions. All other supernovae — types Ib and Ic, which are associated with GRBs, and all type II — involve stars born with more than about eight times the Sun's mass. Such stars ultimately become unstable, collapse, and explode. The variations between different supernova types are what separate them.

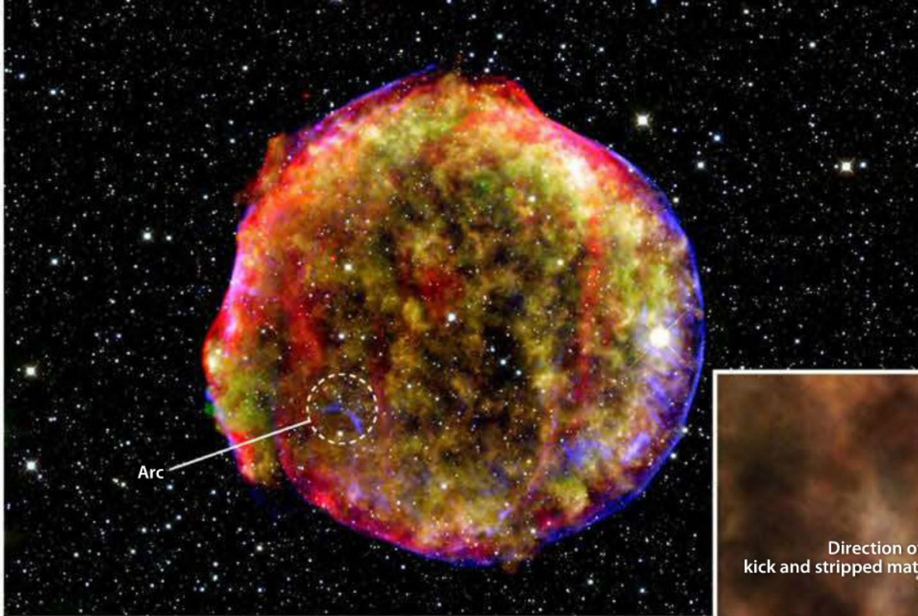
The supernova zoo

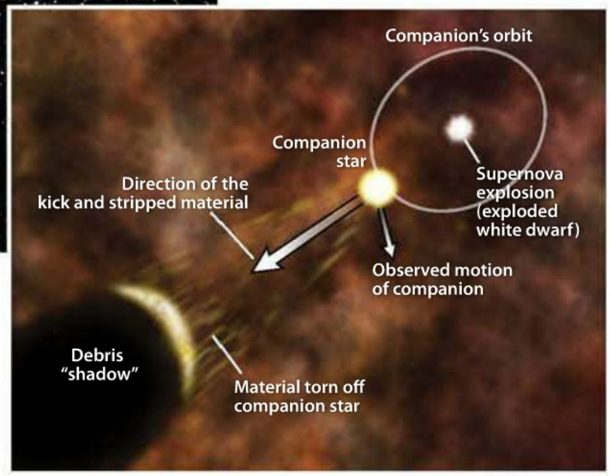
Astronomers determine a supernova's type in part by its spectrum and in part by its light curve, a graph of brightness changes. The energy driving a supernova's rapidly expanding gas comes mainly from three means: the radioactive decay of freshly synthesized elements, typically nickel-56; the shock wave heating the star's extended hydrogen atmosphere, if present; and the interaction between the supernova's ejecta and any hydrogen gas in the vicinity.

Type Ia supernovae tend to be brightest and most uniform, which is what makes them ideal probes of the distant universe. Their brightness stems from large amounts of radioactive elements produced in these blasts — specifically about one-third the Sun's mass of nickel-56. The white dwarf's carbon and oxygen support thermonuclear burning immediately, compared to core-collapse supernovae, which don't undergo this process as efficiently. Light-curve and spectral similarities point to white dwarfs as culprits of the exploding stars, and evidence has accumulated that they can expire in different ways than originally imagined.

The nearest type Ia in 25 years, SN 2011fe in spiral galaxy M101, occurred only 21 million light-years away. It showed none of the X-ray or ultraviolet emission expected from an explosion occurring in a binary system that included a normal star. Instead, this supernova likely formed when binary white dwarfs merged and exploded.

Also in 2011, another type Ia, dubbed PTF 11kx, exhibited an optical spectrum indicating that the supernova collided with preexisting shells of circumstellar gas about two months after the explosion. These gas shells are expected in recurrent nova systems like RS Ophiuchi, so apparently nova eruptions don't always blow off all of the material that collects on the white dwarf. It seems that both a sudden accumulation of mass via a merger and a much





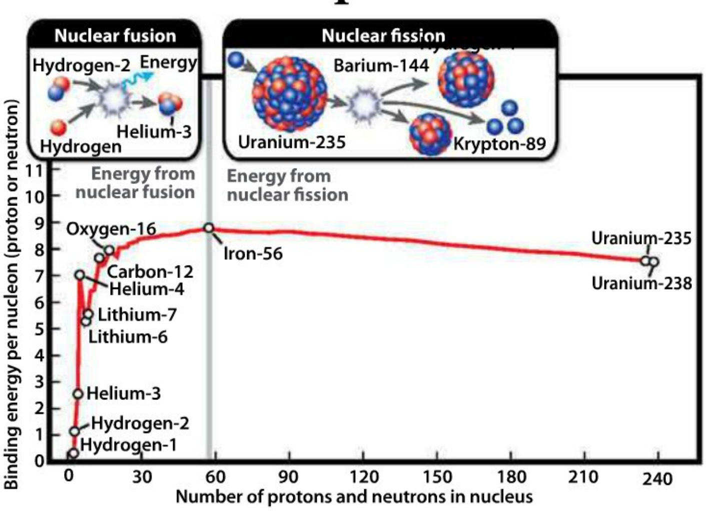
In November 1572, a "new star," resulting from the explosive death of a white dwarf, appeared in the sky. Since then, the stellar material has slammed into gas surrounding the site, creating the supernova remnant we see more than 440 years later. This explosion blew material (circled) off the companion star; the arc of gas blocked debris from the blast and creates a shadow in the outer region of the supernova remnant. SUPERNOVA REMNANT: X-RAY: NASA/CXC/SAO; INFRARED: NASA/JPL-CALTECH; OPTICAL: MPIA/CALAR ALTO/O. KRAUSE, ET AL.; ILLUSTRATION: NASA/CXC/M. WEISS

more gradual one via accretion can trigger a white dwarf's runaway thermonuclear explosion.

The other type I supernovae result from the collapse of a massive star. Type Ib spectra contain helium lines while type Ic do not, but both exhibit strong oxygen, magnesium, and calcium features. Because they're often difficult to distinguish, astronomers sometimes group them together as type Ib/c.

Meanwhile, some type Ic explosions show broad spectral lines that indicate rapid motion and an unusually powerful event. One example is SN 2003dh, which emerged from the "afterglow" of GRB 030329. A GRB's "afterglow" is the slowly fading emission produced when high-speed ejecta strikes interstellar gas. The rising light of SN 2003dh in the aftermath of a GRB helped cement the link between these blasts. This type likely marks the demise of hot Wolf-Rayet-type stars born with more than 25 times the Sun's mass; such stars shed large amounts of material during their lifetimes.

What the "iron peak" means



Iron is the heaviest element a star can produce by nuclear *fusion*. The process of fusing light elements together to create a heavier one (such as hydrogen to helium) releases more energy than it takes to fuse the nuclei. However, it takes more energy to fuse iron nuclei than the energy released. To produce energy past the "iron peak," one needs to split apart the nuclei — this is nuclear *fission*, instead of fusion. In the plot shown, the y-axis is the amount of energy needed to keep protons or neutrons together in the nucleus, and the x-axis specifies how many of those particles the nucleus holds. *ASTRONOMY*: ROEN KELLY

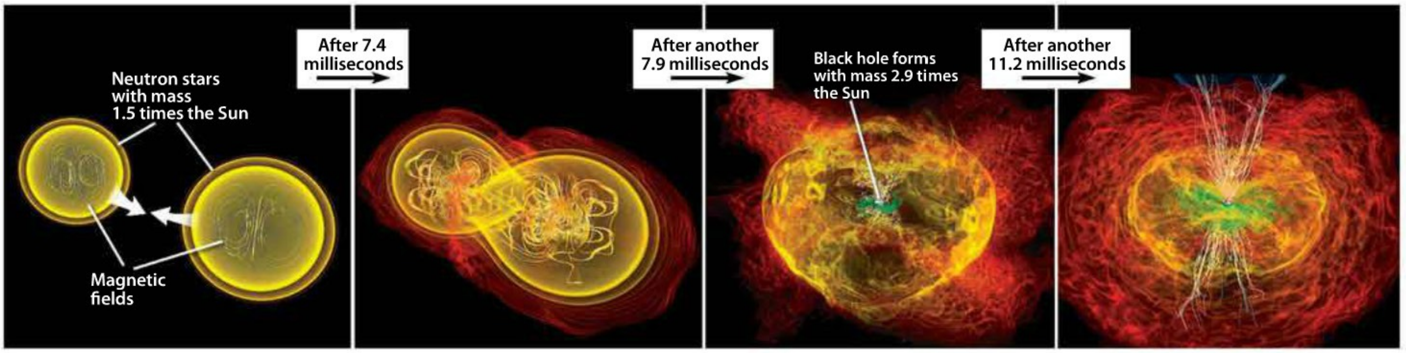
While astronomers study spectral lines to differentiate type I supernovae, they analyze the light curves of type II because their spectra all show hydrogen. The most common stellar explosion by volume in the universe is type II-P, so named because the declining supernova's light pauses for a while, resulting in a plateau-like feature. The plateau points to an extended hydrogen envelope, such as those found around red and blue supergiant stars like Betelgeuse and Rigel, respectively. Type II-P supernovae include SN 2005cs in the Whirlpool Galaxy (M51), where a red supergiant exploded, and SN 1987A, where archival images revealed a blue B3-type star.

Type II-L supernovae are both brighter and rarer than type II-P. Their light curves show a linear decay (hence the "L") after they reach peak brightness, so the type II-L progenitors don't possess extended atmospheres. These stars may have lost their envelopes to a close companion. A famous example is SN 1979C in spiral galaxy M100, where a steady X-ray source now likely indicates the presence of the youngest known black hole in our galactic neighborhood.

Next, type IIb supernovae pull a bait and switch. Initially, hydrogen lines are abundant, but they weaken and disappear as helium lines emerge, creating a type Ib spectrum. An explosion from a lone Wolf-Rayet star or from a star in an interacting binary may explain why type IIb progenitors have lost most, but not all, of their hydrogen atmospheres. The explosion responsible for the Cassiopeia A supernova remnant was of this type, according to a study of its light echoes, which let modern astronomers study the blast years later as its light shines on nearby gas and dust clouds.

Finally, the rarest and most diverse class of core-collapse supernovae is type IIn, so named for narrow emission lines in their spectra. The light curve and spectrum indicate interactions between the expanding supernova and a dense, hydrogen-rich environment around the star. An example is SN 2005gl in NGC 266, which astronomers think originated with a luminous blue variable star weighing much more than 50 solar masses. Known for short lives punctuated by bright eruptions that eject lots of gas, these stars explode within cocoons of their own making.

When neutron stars collide



Scientists think that short-duration gamma-ray bursts (GRBs) result from two neutron stars (or a neutron star and a black hole) colliding and merging. Recent computer simulations of the former scenario show that the neutron stars' combined magnetic field can produce jetlike structures capable of powering a GRB.

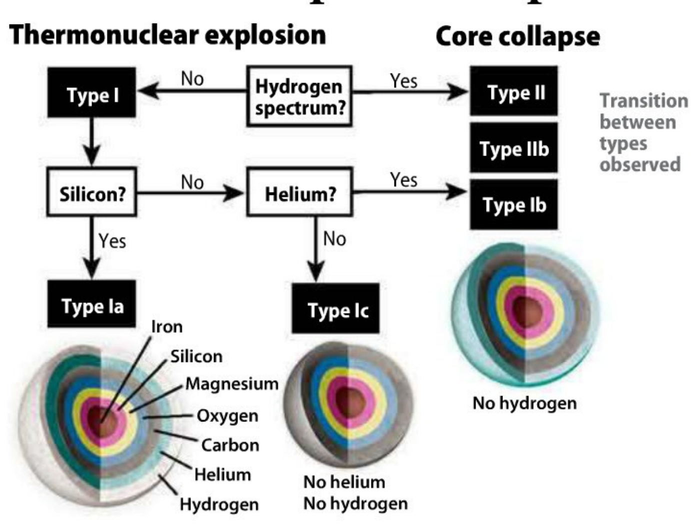
EXCEEDINGLY BRIGHT

During the past decade, scientists have discovered 18 supernovae that would normally be classified as type IIn or Ic but are 10 or more times brighter. Avishay Gal-Yam, an astrophysicist at the Weizmann Institute of Science in Israel, has proposed a classification extension to include these superluminous supernovae (SLSN). SLSN-I, the brightest subtype, is poor in hydrogen, SLSN-II is rich in hydrogen, but a third variant, called SLSN-R for "radioactively powered," may be the best understood.

The first well-observed SLSN-R is SN 2007bi, a blast that also happens to be the first convincing case of a "pair instability" supernova. Stars initially born with more than about 130 times the Sun's mass develop hot oxygen cores that produce extremely energetic gamma rays. The radiation possesses so much energy that when two gamma rays collide, they transform into an electron and a positron — a matter-antimatter pair.

This process lowers the core's pressure, it begins to collapse, and then a runaway thermonuclear reaction blows the star to smithereens, with no neutron star or black hole left behind. Amazingly, SN 2007bi may have produced as much as five times the mass of the Sun in radioactive nickel. — *F. R.*

How to read supernovae spectra



To characterize a supernova, astronomers analyze its spectrum and look for hydrogen, silicon, and helium, as well as how the star's brightness changes over time. This diagram shows how the cores of stars that produce different types of supernovae compare. *ASTRONOMY*: ROEN KELLY, AFTER MARYAM MODJAZ

Stellar recycling

For stars, mass is destiny: The more they have, the brighter they shine and the faster they use their fuel supply. Nuclear fusion transforms hydrogen into helium and produces gamma rays, the highest-energy form of light. Once the hydrogen in the core is depleted, the star's core contracts and heats until the accumulated helium "waste" ignites, fusing helium nuclei into carbon and oxygen to produce energy. In the Sun's mass range, the recycling program ends here.

More-massive stars can tap into a sequence of fuels to extend their energy-producing lives. As each runs low — first hydrogen, then helium, carbon, oxygen, neon, and silicon — the core contracts, heats up, and ignites the waste from the previous reactions. But once silicon fusion ignites and an iron-nickel core begins to form, the star's days are numbered. Nuclear fusion in elements heavier than iron soaks up more energy than it releases, and thus iron is the end of the line. (See diagram at the bottom of p. 25.)

For stars born between nine and 100 times the Sun's mass, energetic gamma rays begin cracking iron nuclei into helium nuclei and free neutrons, a cooling process that saps any temperature gain in the contracting core. At masses near the lower end of this range, energetic electrons begin merging with the protons in iron nuclei, which drops the core's internal pressure despite its contraction.

But stars with some 7 to 10 solar masses may explode long before they can produce iron. During carbon fusion, these stars produce cores with a mix of oxygen, magnesium, and neon. At a critical density, the magnesium nuclei begin capturing electrons before the core gets hot enough to start neon fusion, ultimately producing a weak type II supernova with a much smaller yield of heavy elements. Possible examples include SN 1054, which produced the famous Crab Nebula in our galaxy, and SN 2008S in NGC 6946.

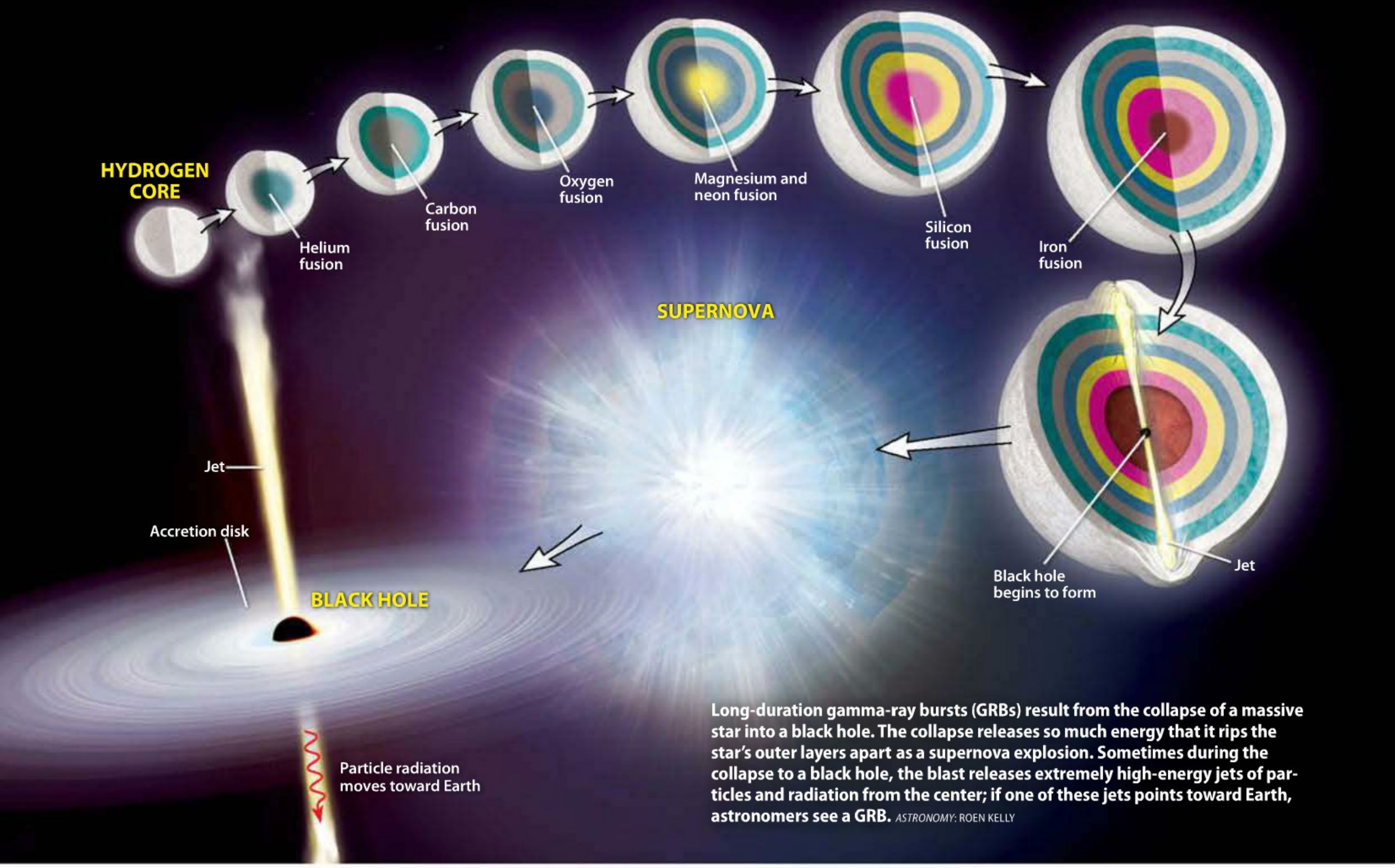
Jets and gamma rays

Scientists first recognized GRBs in 1973 after satellites capable of detecting them became available. Because they occur about once a day, on average, astronomers have cataloged thousands of bursts; clearly, not every supernova creates a GRB, or researchers would find them in much greater numbers.

GRBs are sudden, intense flashes of radiation with peak energy in the gamma-ray part of the spectrum. GRBs occur anywhere in the sky and typically last seconds. They produce jets of matter moving near light speed, and all evidence points to a gravitational power source associated with the formation of a stellar-mass black hole.

Earth's atmosphere screens out gamma rays, so spacecraft must detect GRBs. Two NASA missions, Swift and the Fermi Gamma-ray

From a supernova to a gamma-ray burst



Long-duration gamma-ray bursts (GRBs) result from the collapse of a massive star into a black hole. The collapse releases so much energy that it rips the star's outer layers apart as a supernova explosion. Sometimes during the collapse to a black hole, the blast releases extremely high-energy jets of particles and radiation from the center; if one of these jets points toward Earth, astronomers see a GRB. *ASTRONOMY*: ROEN KELLY

Space Telescope, are among the latest in a long line of satellites designed to catch these extreme outbursts; they average about 90 and 240 detections a year, respectively. New burst positions are quickly communicated to astronomers around the world. This gives large ground-based telescopes an opportunity to catch the burst's afterglow, capture its spectrum, and from that determine its distance.

Scientists divide GRBs into short and long classes, with the boundary being two seconds, but the observed range runs from milliseconds to minutes. Short GRBs likely form when a binary composed of dual neutron stars (or perhaps a neutron star and a black hole) merge to make a black hole. While circumstantial evidence favors this model, clean-cut proof has been elusive, says Tsvi Piran, an astrophysicist at the Hebrew University in Jerusalem.

In most cases of long GRBs, a supernova typically emerges out of the fading afterglow. As a star's core collapses into a black hole, oppositely directed particle jets form — through processes not yet fully understood — and blast outward at nearly the speed of light. The jets drill all the way through the collapsing star. When they breach the surface, satellites see a burst if the jets are favorably oriented toward Earth. The jets continue into space while the star begins to expand as a supernova.

The most extreme burst detected so far is GRB 080916C on September 16, 2008. It exhibited both the greatest total energy and the fastest motions ever observed, and ground-based afterglow observations determined its "redshift" was about 4.35, meaning the star exploded some 12.2 billion years ago. The slowest possible speed of matter that produced the gamma rays is 99.9999 percent the speed of light.

In some cases, GRBs are near enough to Earth that astronomers should see emerging supernovae — but don't. Piran suggests that a collapse to a black hole likely is still involved: "Such a collapse might produce a weaker outgoing shock than a regular [core] collapse to a neutron star, and as such there may not be a supernova." The resulting jet may fail to escape the star's outer layers but could nevertheless produce a weak GRB before the entire star disappears into the black hole it created.

Even as astronomers pick through clues from the latest supernova or GRB, they are mindful that questions still outnumber answers. They say that the next big leap in understanding stellar blasts will come from losing their "electromagnetic chauvinism," the reliance on the information carried by the light emitted from supernovae and GRBs. Light is, after all, a secondary product of the great shifting masses in core collapse or merging binaries.

Scientists will look for strong signals from neutrinos or oscillations in the fabric of space-time called gravitational waves — data straight from the heart of a merger or dying star. They will provide a true scientific bonanza, and astronomers have reason to believe that this leap is just years, not decades, away.

SEE A GALLERY OF SUPERNOVA REMNANTS AT **www.Astronomy.com/toc.**