ASTROPHYSICS

STELLAR FIREWORKS

Every year thousands of exploding stars appear in a bizarre assortment of forms. Astronomers want to know what makes them go boom

By Daniel Kasen
SUPERNOVA SIMULATION:
A stellar explosion is powered by a vast amount of magnetic energy spewing out of a rapidly spinning neutron star at the center.
ROUGHLY EVERY SECOND, SOMEWHERE IN our observable universe, another sun is destroyed in a stellar catastrophe—when a star pulsates, collides, collapses to a black hole or explodes as a supernova. This dynamic side of the universe, lost in the apparent calm of the night sky, has lately come to the forefront of astronomical research. For almost a century scientists have tried to trace what has happened over billions of years of cosmic evolution, but it is only recently that we have begun to parse celestial events on timescales of days and hours and so witness the volatile lives and deaths of stars.

Although in the past we have lacked tools to study these phenomena in detail, evidence of the universe’s transience has been around for millennia, going back at least to Chinese observations in A.D. 1006 of a “guest star” that became visible to the naked eye for a few weeks before fading away. The great astronomer Tycho Brahe recorded a similar event in 1572, as did Johannes Kepler about 30 years later. We now understand these apparitions to be the supernova explosions of stars. At their peak, supernovae can shine brighter than a billion suns, but because most occur very far away, they appear to us as dim specks of light, easily lost in a big sky.

Modern technology is now revolutionizing the study of the dynamic universe. Telescopes have become robotic and outfitted with high-resolution digital cameras that feed data to computerized image processing and pattern-recognition software. The machines monitor large swaths of sky on a regular basis, keeping a digital eye on anything that goes bump in the night. Over the past decade or so this newfound technological capability has enabled astronomers to discover thousands of new stellar explosions every year—each week we find as many new supernovae as had been seen in the entire 20th century.

Not only are we collecting more supernovae—we are uncovering bizarre new species. Some stellar explosions shine exceedingly bright, 100 times more luminous than ordinary supernovae; others are 100 times as dim. Some are colored deep red; others are ultraviolet. Some shine brightly for years; others fade away in a few days. Stellar deaths are turning out to be vastly more diverse than we had realized.

Astronomers are still trying to figure out what drives these odd stellar explosions. Clearly, they are telling us something important about the lives and deaths of stars and about physics under the most extreme conditions of temperature, density and gravity. By studying the full menagerie of supernovae, we hope to finally learn what causes stars to crumble and transform into dead stellar remnants such as black holes.

Supernovae also have something to teach us about our own origins. After the big bang the universe contained mostly the lightest of atoms: hydrogen and helium. According to theory, everything else we encounter—the calcium in our bones, the iron in our blood—was fused and expelled in exploding stars. Scientists used to think that run-of-the-mill supernovae created all of the heaviest elements, but the discovery of so many off-kilter explosions now suggests that different squares on the periodic table may have different points of origin. By observing large numbers of diverse supernovae, we are getting closer to pinning down how an assortment of stellar explosions may have contributed to the blend of elements that make up our planet and all its life.

STELLAR CATASTROPHE

TO UNDERSTAND HOW ODD some of the supernovae we are discovering are, let us first consider the typical supernova, which is itself a truly remarkable phenomenon. A star is a type of stable nuclear reactor: a massive ball of plasma, bound together by gravity and powered by nuclear fusion in its compressed core. The heat from fusion provides a pressure that counteracts the inward pull of gravity. A supernova explosion represents some kind of catastrophic instability in this balance of forces—the runaway victory of gravity over nuclear burning, or vice versa.

The most common type of supernova occurs in moderately...
COLLISION: A neutron star (green) merges with a black hole in this simulation. The process is similar to what scientists think happens when two neutron stars coalesce—a scenario that could explain some underluminous supernovae. Here the neutron star gets distorted by the black hole's gravity (1 and 2). A bit of matter is ejected in a tail (3), and the rest wraps around the black hole (4). Ultimately almost all of the neutron star is swallowed.

sized stars containing 10 or more times the mass of our sun. These stars live for millions of years, continually fusing hydrogen into progressively heavier elements. Once they have burned their insides to iron, which is essentially nuclear ash, fusion cannot continue. Without this outward pressure, the innermost core of the star collapses under the pull of gravity and compresses a millionfold in volume, transforming into an ultradense nugget called a neutron star, which packs a mass greater than that of the sun into a region no more than a few miles across. The enormous energy released in the free fall blows apart the rest of the star.

To get a sense of the energy involved in a typical supernova explosion, imagine that our sun burned its entire supply of hydrogen—enough fuel to sustain it for more than 10 billion years—within a few seconds. That enormous amount of energy is quantified by its own physical unit: one bethe (named after Nobel Prize winner Hans Bethe). When a supernova explodes, the star's interior temperature rises above five billion degrees Fahrenheit, driving a supersonic blast wave that leaves in its wake a mess of freshly fused heavy elements, such as silicon, calcium, iron, and radioactive isotopes of nickel, cobalt and ti-

tanium. In a matter of minutes, the star blows apart into a cloud of ash and radioactive debris, expelled at 20 million miles per hour, or a few percent the speed of light.

Our own sun is, fortunately, too small to ever go supernova, but if it did, the first indication on Earth would be a brief flash of intense x-rays that would kill all life on the planet. Within a few minutes the solar debris cloud would double in size and become about 1,000 times brighter than the sun. After a few hours the cloud would engulf Earth, and a day later it would swallow Jupiter and Saturn. After a few weeks the solar ashes would spread across the entire solar system. By this time, the debris cloud would finally become translucent, and the bottlenecked-up light would flood out, reaching a peak brightness of about one billion solar luminosities before fading away.

Astronomers almost never catch the brief x-ray blast of a supernova explosion itself, and only rarely can we dig up an archived picture of the original star before it exploded. What we typically see is only the aftermath: that giant cloud of expanding, radioactive debris that glows visibly for weeks or longer. By examining the ashes, we try to piece together a story of what type of star was destroyed and why.
Among the zoo of weird supernovae recently discovered, perhaps the most dramatic are hyperenergetic explosions—what I will call ultranovae—that are more than 100 times as luminous as ordinary supernovae. They are the brightest and most distant supernovae ever discovered, visible most of the way across the observable universe. Such events are extremely rare; perhaps one goes off for every 1,000 ordinary supernovae. Astronomers have no conclusive evidence to explain why these blasts are so bright, but there are three leading theories. One of them may explain most or all of the ultranovae we see, but it is more likely that all three scenarios occur with some frequency.

**Particle-Pair Supernovae.** Naturally, many try to associate ultranovae with extremely massive stars. Theory suggests that very large stars are actually rather delicate characters, susceptible to a variety of instabilities. In particular, stars between 150 and 250 solar masses may become so hot in their cores that they generate a flurry of matter-antimatter particle pairs (namely, electrons and positrons). Producing these particles costs energy, which saps a star's outward pressure and causes its core, still loaded with combustible nuclear fuel, to fall in. The result would be disastrous. The compression of the core would accelerate nuclear fusion out of control, burning almost everything in sight. The sudden energy release—as much as 100 bethe's worth—would reverse the collapse and explode the star completely. Nothing would be left behind.

These most giant of nuclear explosions would produce debris clouds 1,000 times more radioactive than those of ordinary supernovae. Because the clouds are also thought to be extremely massive and opaque, the light would take a year or longer to diffuse out. We therefore expect the aftermath of these explosions to be extremely bright and long-lasting. A few of the recently discovered ultranovae have just these properties, leading some astronomers to claim that we have witnessed a giant star killed by an infestation of microscopic particle pairs. Others disagree, arguing that the data are better explained with different theories. Future observations of such bright and long-lived events will, it is hoped, better reveal the composition and speed of the stellar debris cloud and tell us whether this scenario truly does take place.

**False Alarm Supernovae.** An alternative idea to explain ultranovae is that they originate in stars slightly lower in mass (around 70 to 150 solar masses). These stars are thought to be subject to similar instabilities as their more massive brethren, but the conditions are often not as severe; after the star begins to crumble and ignite excess burning, it may rebound, reexpand and halt the nuclear reactions before they run out of control, recovering to live another day. In the process of regaining its balance, however, the star will likely blow off a good chunk of its outer layers, producing a supernova "impostor"—an outburst that resembles a dim supernova but in reality is just a near-death experience.

Stars that are in this mass range may go through several of these hiccups, each time losing a bit more matter, until they finally exhaust their nuclear fuel and explode like ordinary supernovae. When such a star finally does die, it will expel debris into an environment that is polluted with shells of material from previous outbursts. The violent collision of the supernova debris cloud with these shells should produce extremely bright fireworks that could explain some of the ultranovae. Automated surveys have recently recorded the manic last years in the life of a massive star. In 2009 astronomers noted what appeared to be a fairly ordinary, if dim, supernova. Named SN2009ip, it faded away in a few weeks and was largely forgotten. One year later, to everyone's surprise, another dim "supernova" was observed in the exact same location. Apparently the star was not dead yet. In 2012 astronomers saw a third outburst and then, a month later, a very luminous one.

Some scientists believe that the penultimate burst was the true death of the star while the final, most luminous flare resulted from the supernova debris cloud ramming into material from the previous near-death gasps. Others think that the star is still alive and will continue to entertain us with further outbursts. It will take a few years for the dust to clear, but for now we have seen the kind of violent instability we think makes up the end of life for some massive stars.

**Magnetic Supernovae.** Finally, an alternative line of thinking on ultranovae argues that their excessive brightness has less to do with extreme mass and more to do with extreme rotation. Stars that start off with more than 10 solar masses most likely produce ordinary supernovae that form neutron stars when they die. If such a star was initially rotating rapidly, the collapse might spin up the neutron star to extreme speeds, like a twirling figure skater who brings his or her arms in to accelerate. In principle, a neutron star can spin as rapidly as 1,000 rotations a second—much faster, and the star would be torn apart by centrifugal forces. The kinetic energy stored in such a massive, spinning top is enormous—up to 10 bethe.

How can this spin energy be tapped to power an ultranova? Neutron stars have immense magnetic fields that may transport the energy. To understand how, imagine spinning a refrigerator magnet in your palm. As you do so, you twist up the magnetic field surrounding it. Although you cannot see or feel it, a bit of your expended energy is carried off into space in the form of electromagnetic ripples. We think the same process occurs, on a much larger scale, around neutron stars. The most visually captivating example is the Crab nebula, the remains of a supernova reported by Chinese astronomers in A.D. 1054. Today the light we see from the nebula is powered by a spinning neutron star that generates a whirlpool of magnetized plasma. Over a period of 1,000 years the twisted-up magnetic field has extracted the neutron star spin energy and heated the surrounding gas, powering the beautiful display.

About five years ago my colleague Lars Bildsten of the University of California, Santa Barbara, and I suggested that a souped-up version of this process may explain the high luminosity of ultranovae. The neutron star would need to host magnetic fields 100 to 1,000 times stronger than the one in the Crab nebula and spin near the breakup speed limit. For such a star, nearly the entire spin energy could drain within a month, causing the supernova debris cloud to shine a million times more brightly than the Crab nebula. Although the numbers sound extreme, we have already observed some neutron stars with comparable magnetic fields (though none yet in the supernova stage). They are called magnetars, and they harbor the strongest known magnetic fields in the universe. Ultranovae may therefore sometimes signal the birth and prompt spinning down of a rapidly rotating magnetar.
Theories

Supernova Zoo

Supernova explosions, which signal the deaths of stars, come in a much wider variety than scientists thought. Recent observations have revealed supernovae that are 100 times brighter than usual, as well as underperforming blasts that are 1/100th as bright as the norm. Theorists have several ideas about what types of stars and situations give rise to some of these unusual eruptions.

Ordinary
In a typical supernova, the core of a star weighing 10 or more times the mass of our sun collapses into a dense remnant called a neutron star, and the outer layers explode in a supersonic blast wave.

Birth star: 10 or more solar masses

Neutron Star Collision
When two neutron stars crash together, scientists think most of their mass will create a black hole, but a small part may escape to power an under-bright "kilonova."

Birth star: 10 or more solar masses

Magnetar
The collapse of a rapidly rotating star may produce a highly magnetized neutron star, called a magnetar, that taps the spin energy to power an ultraluminous supernova.

Birth star: 70-150 solar masses

False Alarm
A star may begin to go supernova but regain its balance, blowing off just some of its outer layers. When this star finally does explode, the debris will hit the previously shed layers, creating an ultrabright flash.

Birth star: 150-300 solar masses

Particle Pair
The hot cores of very massive stars may give rise to pairs of matter and antimatter particles that precipitate a premature blast. The energy would destroy the star and prevent a black hole from forming.

Birth star: 300-1,000 solar masses

Complete Collapse
The most massive stars might produce a whimper rather than a bang because their extreme gravity would pull nearly their whole mass into something denser than a neutron star, a black hole.

Birth star: 300-1,000 solar masses

Illustration by Jen Christiansen

Trillion
These scenarios lead to supernovae that are significantly brighter than normal

Magnetar-powered supernova

False alarm supernova

Particle-pair supernova

Ordinary supernova

Undernovae
Neutron star collisions and the deaths of the most massive stars in the universe could lead to underperforming explosions

Neutron star collision (kilonova)

Complete collapse

Brightness (solar luminosities)

0 1 10 100 1,000

Duration (days)
CRAB NEBULA: This supernova remnant is powered by a spinning neutron star that injects a whirlpool of magnetized plasma (visible in blue).

UNEXPECTEDLY DIM
ON THE OPPOSITE END of the spectrum from ultranovae, astronomers have also recently discovered the strange phenomenon of underperforming supernovae. Wide-field surveys have found peculiar supernovae that are 100 times as dim as ordinary events. Scientists debate what causes these weak outbursts but suspect some are, surprisingly, the muffled last gasps of the most massive stars to have ever lived.

FAILED SUPERNOVAE. It is unclear just how massive a star can get, but conceivably some may be as large as 300 to 1,000 times the mass of the sun (even larger than the very massive stars we think might explode because of particle pairs). One might expect these mammoths to produce the most spectacular supernova explosions of all. Actually they are probably duds. The gravity of such a star is so strong that once it becomes unstable, total collapse is inevitable. The infall should eventually tear a hole in spacetime itself, forming something denser than a neutron star: a black hole.

Theoretical models show that the bulk of the star will be swallowed by the black hole and suddenly disappear from sight. This hypothetical nonevent has been called an unnova. Automated surveys are looking for unnovae in a backward way: searching not for a sudden light in the sky but for a bright star that goes lights out in an instant.

Although they fail to make a bang, some of these black hole-forming stars may at least manage a whisper. The cores of cer-
tain giant stars are surrounded by a loose, puffy halo of hydrogen gas. As the bulk of such a star gets sucked below the black hole horizon, the halo of gas may heat up and blow away, leading to a faint glow. The death of a very big star would then produce, ironically, a remarkably weak and dim supernova.

**COLLIDING NEUTRON STARS.** Another type of underluminous eruption might come from a very different kind of extreme event: the collision of two neutron stars. Massive stars are frequently born as orbiting pairs. These stars will go supernova one after the other, and if the pair is not plum flang apart, what remains is a binary system of two neutron stars (or a neutron star and a black hole or two black holes). Over time, the two compact objects should spiral in closer and closer, ultimately colliding and coalescing into a larger black hole. This process was recently confirmed by the discovery of gravitational waves produced in the merger of two black holes. When neutron stars meld, calculations suggest that the extreme gravitational forces (about 10 billion times the pull of Earth's gravity on our bodies) are strong enough to strip off about 1 percent of the stars' skin and fling it out into space (the remaining 99 percent goes into the black hole).

This small bit of material that escapes the black hole most likely is peculiar stuff—a vaporized sea of disassociated particles, mostly neutrons, along with some protons and electrons. As the gas decompresses, the particles should begin to bind together into heavier nuclei. The protons will repulse one another because of their positive electric charge, but the neutrons have no charge and will attach to other particles more easily. By progressive addition of neutrons, the nuclei should grow heavier and heavier, producing a shower of elements across the lower half of the periodic table, such as gold, platinum, and mercury, mixed into a pool of assorted radioactive waste, including uranium and thorium. Neutron star collisions are one of the few places in the universe scientists think these heavy elements can be formed.

The abundance of radioactive material should cause the debris cloud to glow like a supernova. But because of the relatively small mass involved (less than 1 percent of that found in a supernova), we expect the light to be about 100 times as dim as an ordinary supernova and to last for only a few days. Recent theoretical work I did with my graduate student Jennifer Barnes at the University of California, Berkeley, suggests that the peculiar composition of heavy metals in such clouds should give the glow a distinctive color, either a deep-red or infrared hue. The phenomenon has been called a kilonova.

Lately astronomers may have, for the first time, seen this radioactive red "smoke" from a neutron star collision. In June 2013 a brief burst of gamma rays alerted astronomers to a possible nearby neutron star merger. They pointed the Hubble Space Telescope at the site and caught a brief infrared glow. A few weeks later it was gone. The data are scarce but consistent with theoretical predictions of what a kilonova should look like. If this identification is correct, it is the first time we have directly witnessed the production of heavy, precious metals. We would like to observe more such events to better determine the amount of metals these explosions synthesize and whether they can account for all, or only part, of the abundance of gold, platinum and other heavy elements in the universe.

**CHAOTIC COSMOS**

Our study of the dynamic universe has just begun. Within a decade or so new automated telescopes such as the Zwicky Transient Facility coming online near San Diego, the Large Synoptic Survey Telescope being built in Chile and the Wider Field Infrared Survey Telescope that NASA plans to launch into space will be able to scan most of the sky every few nights, discovering hundreds of times as many supernovae as we currently do. Meanwhile modern supercomputers are becoming capable of running out detailed three-dimensional simulations of these events, allowing us to visualize what may go on deep in the cores of exploding stars.

Data gathered in the coming years will challenge our theories about the many types of stellar deaths. Each scenario described here is physically plausible but unproved. With more observations of unusual supernovae, we hope to pin down which of these explosive possibilities are, in fact, realized in nature. Most likely, the universe will turn out to be stranger than we have imagined, revealing even more exotic phenomena than we have dreamed up so far.

Ultimately we will also be able to tell a richer narrative of the stuff that makes up our bodies and the world around us. The gold ring on your finger, for example, has a history that goes back beyond the time of your ancestors. That material probably first floated in the iron furnace of a massive star that falttered, collapsed and compressed into a dense neutron star. Much later, after maybe a billion years, the neutron star might have crashed into another compact star, spewing a cloud of radioactive waste out into space. That cloud, rushing at 60 million miles per hour, would have traveled more than 1,000 light-years across the galaxy, mixing with other gases along the way, until it eventually settled into the crust of planet Earth. Some time later people dig up that stellar rubble, shaped a ring and began to tell their own stories.

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The death of a very big star would produce a remarkably dim supernova.