DARK ENERGY'S NEW FACE

How are exploding stars changing our view of the universe's mysterious force?

by Steve Nadis

You never know what a day brings. Or a night. That's why Peter Nugent, an astrophysicist at Lawrence Berkeley National Laboratory in California, pushed himself August 24, 2011, to see what the Palomar Transient Factory (PTF) had turned up. Nugent's software sifts through data collected by the PTF — an automated wide-field survey that utilizes a 1.2-meter telescope at Southern California's Palomar Observatory — looking for changing objects in the night sky.

At the top of his priority list that day was a special kind of stellar explosion called a type Ia supernova. Such a finding is not unusual in itself — the PTF typically identifies about one new supernova each night. But the one Nugent found that day — a star that blew up in M101, a spiral galaxy 21 million light-years away — stood out from the pack. Dubbed SN 2011fe, it is, as Nugent puts it, "a once-in-a-generation event," the closest and brightest type Ia supernova seen in 25 years, and thus since the advent of modern, digital instrumentation.

Dazzling bursts in the sky that can sometimes outshine their own galaxies, type Ia (pronounced "one A") supernovae have fascinated and puzzled astronomers for centuries. But these objects recently have taken on far greater significance than mere curiosities: Observations of this class of supernovae led to the discovery that the universe's expansion is speeding up, for which the 2011 Nobel Prize in physics was awarded. Scientists theorize that "dark energy" is causing that acceleration. This finding ranks among the most scientifically important in the past century, yet it was based on the study of astronomical objects that still elude even the most basic of questions.

Cosmologists think dark energy dominates the universe, constituting about 72 percent of the total energy density, yet no one knows what it is. Many astrophysicists hope that if they can improve their understanding of type Ia supernovae, perhaps they can make cosmological measurements more precise and thereby gain a better understanding of dark energy, too.

Nugent felt confident that SN 2011fe could yield a wealth of information about these tumultuous celestial events — information that could advance our picture of both stellar evolution and cosmology. Fortunately, he caught the supernova just 11 hours after the explosion — the earliest detection ever for such an event. He sent an alert to the PTF consortium, and researchers promptly obtained follow-up observations with the Liverpool Telescope in the Canary Islands and NASA's Swift space telescope. Owing to this confluence of circumstances, SN 2011fe has become the best-studied type Ia supernova in history, providing an opportunity to solve some of the mysteries surrounding this violent and ultraluminous phenomenon.

SN 2011fe, **the closest and brightest type Ia supernova in 25 years, blasted into existence August 24, 2011, in spiral galaxy M101. Astronomers caught it just 11 hours after the star exploded and have carefully monitored its brightening and then fading light ever since. Such observations are helping them learn what causes these supernovae and how uniform the blasts are.** B. J. Fulton (LCOGT)/PTF/STScI

It starts from a cinder

Over the centuries, astronomers sometimes referred to such brilliant outbursts as "guest stars" — objects that appeared without warning and for no discernible reason, lighting up the heavens briefly before fading from view. More recently, investigators have come to believe that a type Ia supernova is the fiery explosion of a white dwarf — the dense inert core, composed almost entirely of carbon and oxygen, left behind after a star like the Sun sheds its outer hydrogen shell and contracts under the influence of gravity to an Earth-sized volume. The mostly dead white dwarf emits just a tiny fraction of the Sun's energy, although its luminosity changes spectacularly if and when it blows up; it then becomes 10 billion times as bright as our star.

Scientists think a type Ia supernova starts with a white dwarf that accrues additional mass through either a dramatic merger with another white dwarf or through a gentler process of siphoning off

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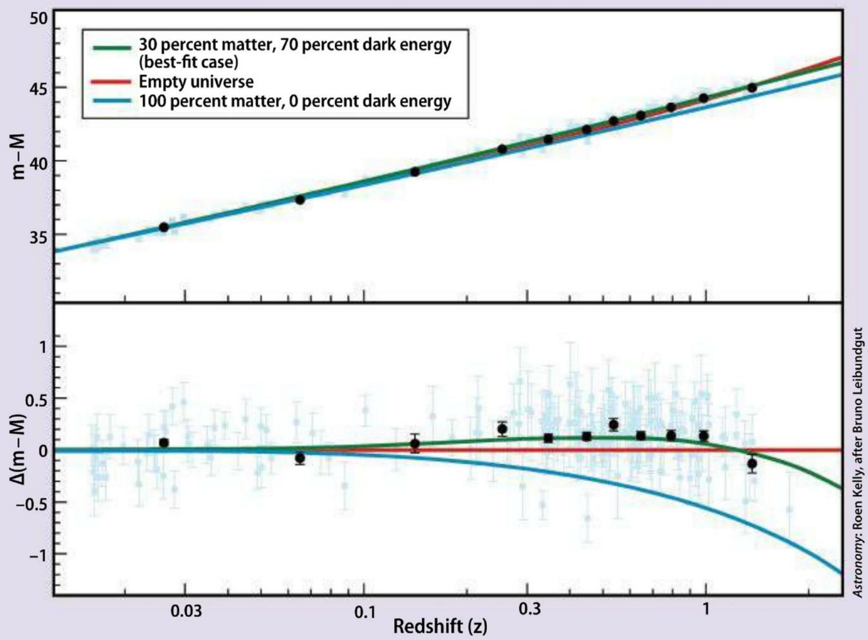
Determining the universe's composition



According to measurements of distant type Ia supernovae, the universe's expansion is speeding up. These graphs show the surprising 1998 find; the green lines demonstrate the best-fit model of roughly 70 percent dark energy and 30 percent matter. (In the top chart, the y-axis plots apparent magnitude minus absolute magnitude. In the bottom, the y-axis shows the difference between the observed distance and that predicated in an empty universe.) Before this discovery, researchers expected to confirm that the cosmic mass could make the universe collapse (the blue lines show a theoretical cosmos without dark energy).

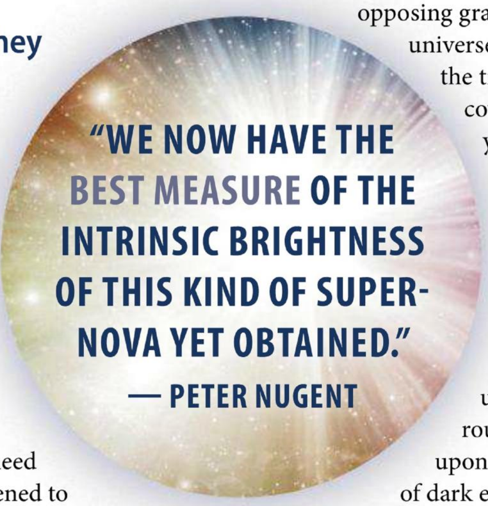
gas from a nearby stellar companion (either a red giant or a normal star). If the white dwarf gains enough material to reach a critical mass — the so-called Chandrasekhar limit, which is some 1.4 times the Sun's mass — it will undergo uncontrolled thermonuclear fusion, exploding with the energy of 100 trillion trillion hydrogen bombs while consuming almost all of its carbon and oxygen fuel in a matter of seconds.

Although the theory is by no means ironclad, many astrophysicists think type Ia supernovae all begin with a white dwarf of essentially the same mass (just shy of the Chandrasekhar limit) and at the same stage of stellar evolution. Both of these characteristics suggest that the luminosity of such events should be relatively uniform — an estimated 10^{36} watts at peak luminosity. If that reasoning holds, scientists can use these explosions as "standard candles" and judge celestial distances by how bright or faint they appear.

In the case of SN 2011fe, astronomers also got an independent check on distance owing to the presence of Cepheid variables in M101 — a class of luminous variable stars with a well-established relationship between intrinsic brightness and the pulsation period. Consequently, says Nugent, "We now have the best measure of the intrinsic brightness of this kind of supernova yet obtained."

Farther than they should be

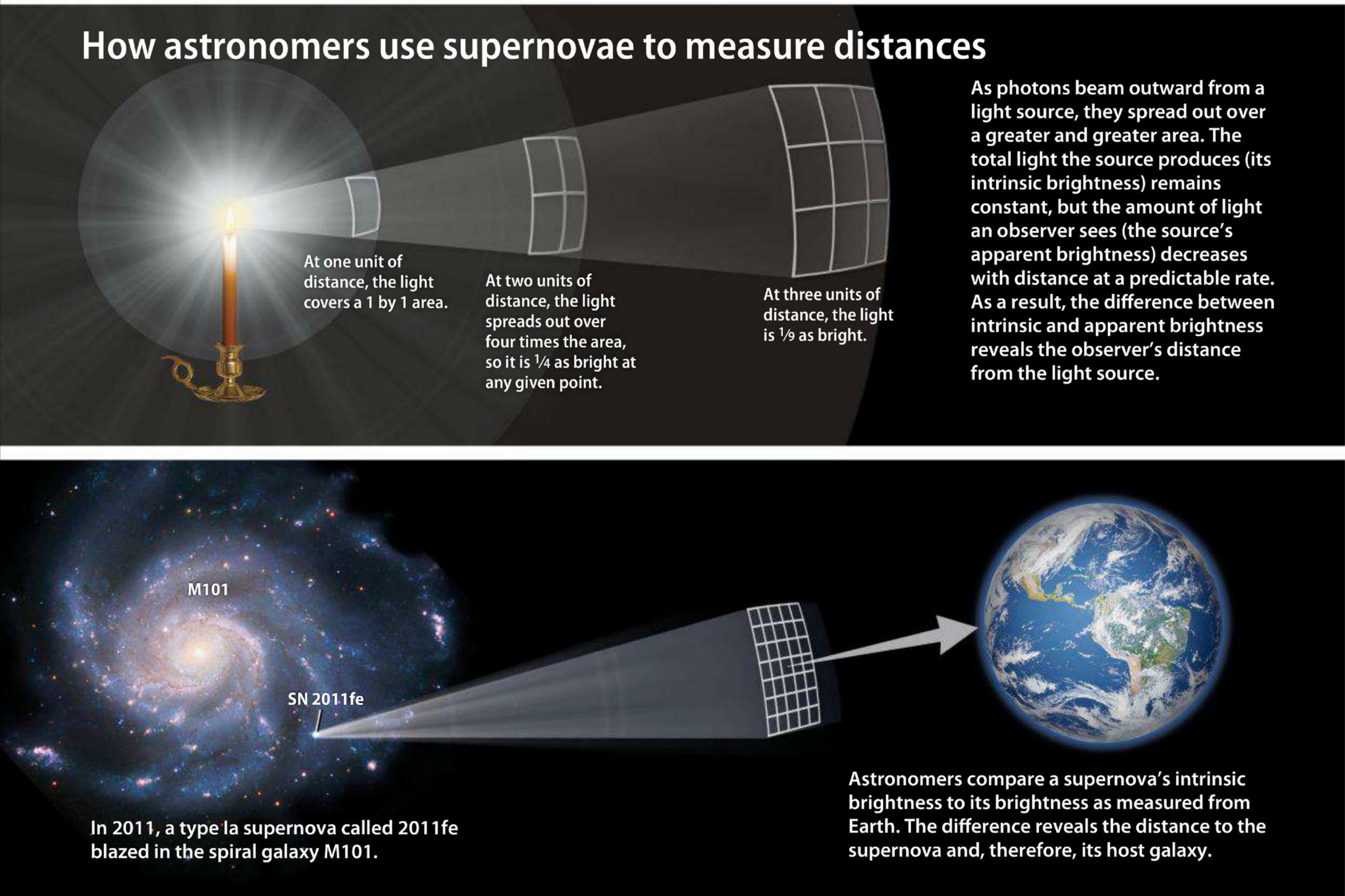
For the purposes of cosmology, the brightness of a supernova reveals its distance and, by extension, the time when the light left on its journey toward Earth. But that's just half the story. Cosmologists also need to know what happened to the light during the course of its travels — how much its wavelength was stretched (or "redshifted") by the expansion of the universe. To get this information, astronomers look not only at the luminosity of a supernova and its remnants but also at the spectrum, or characteristic colors, of the light it emits.



Basically, a supernova gives off much of its light in a specific blue wavelength that corresponds to the explosion's temperature. The wavelength of light that telescopes detect is physically tied to the universe's size. If the universe has stayed the same size during the journey, the light won't change its wavelength. But if the universe has grown bigger in the interim, the wavelength will get bigger, too, and the peak color will shift toward the red end of the spectrum. The more the universe grows, the redder the light gets. The trick then is to find supernovae at different distances from us — say at 1 billion, 3 billion, and 5 billion light-years away — determine what has happened to their emitted light in that period, and thereby chart the expansion history of the universe.

Two teams carried out an analysis of this sort: Saul Perlmutter at the University of California, Berkeley, on one side and Adam Riess of Johns Hopkins University in Baltimore, Maryland, and Brian Schmidt of the Australian National University in Weston Creek on the other. While the teams expected to measure the deceleration of the universe's expansion due to the gravity of cosmic mass, they were surprised to find that rather than slowing down, the universe's expansion is actually *accelerating*. Some unseen, mysterious substance — dubbed "dark energy" because of its unknown nature — is opposing gravity and pushing the universe apart. That's what the trio of researchers discovered more than 10 years ago, and that's what earned them the Nobel Prize.

Their work was momentous, concrete, and inspired, and their prizes are well-deserved. But uncertainties still surround the supernovae upon which scientists' view of dark energy largely rests. In fact, the more astrophysicists look, and the better they understand these explosive type Ia supernovae, the more they realize that cosmology's so-called



A "standard candle" is a type of object that has a known luminosity. Thus, astronomers gauge the object's distance by how bright it appears — fainter standard candles must be farther away. For decades, scientists considered type Ia supernovae such a tool, but recent findings suggest that there might be slight differences in how they form, and therefore not all of these blasts have consistent luminosities. *Astronomy*: Roen Kelly; M101: B. J. Fulton (LCOGT)/PTF/STScI

standard candles may have varying characteristics. "They don't all look alike," says UC Berkeley astrophysicist Daniel Kasen. "Recent observations have shown an interesting, and disturbing, range of diversity. … The big question is how standard are these supernovae, and how well can we standardize them?"

Matters of adjustment

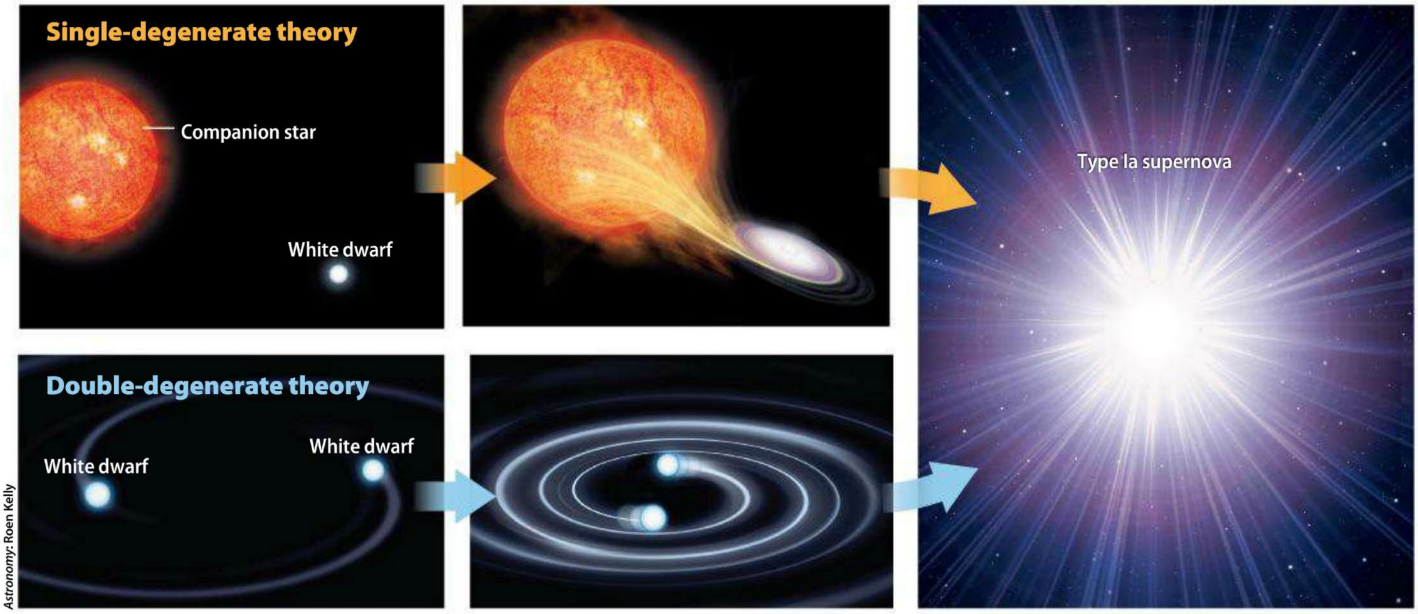
Astrophysicists have long known that various adjustments have to be made to calibrate these standard candles. In 1993, Mark Phillips (now based at Las Campanas Observatory in Chile) found a correlation between a type Ia supernova's intrinsic brightness and the width of its "light curve" — a measurement of how fast the blast's luminosity rises and falls over time. Phillips found that brighter supernovae have broader light curves, meaning that they take longer to reach their maximum brightness and longer to fade away. Researchers already take this relationship into account to make such supernovae useful cosmic yardsticks.

Color also must be factored in: The presence of dust can make type Ia supernovae appear redder and dimmer, as Phillips, Riess, and UC Berkeley physicist Robert Tripp showed separately in the 1990s. To compensate for the phenomenon of dust reddening — similar to the red sunsets one sees on smoggy evenings — astronomers noticed that these supernovae all have about the same color a couple of months after reaching their peak brightnesses. If a particular supernova deviated from that and looked redder than usual, it was presumably due to dust, thus warranting an additional correction to the distance calculation.

Today, the astrophysics community recognizes that further refinements are needed. The brightness of the explosions, for example, may depend on the star's environment, its composition (and ratio of heavy elements), and other factors. But just fine-tuning isn't enough.

Bigger problems

Until recently, astrophysicists have been embarrassingly ignorant about some of the most basic features of type Ia supernovae. "The nature of the type Ia explosion and the progenitors involved have remained elusive, even after seven decades of research," explains Andrew Howell of the University of California, Santa Barbara. Kasen puts it in even blunter terms: "The main thing we don't know is: What is the system that is exploding, and why does it explode?"



A type Ia supernova results from the detonation of a white dwarf — a stellar cinder that's the core of a once Sun-like star. The white dwarf gains material one of two ways: either by stealing material from a companion star (the "single degenerate" case) or by colliding with another white dwarf (the "double degenerate" case). In the single degenerate theory, the explosion leaves behind the companion star, and thus scientists search for evidence of this remnant.

Fortunately, there's been considerable progress on the observational front, especially in the past year, with answers already obtained to some of those "elusive" questions. Nugent's team, which found traces of high-speed carbon and oxygen in the spectrum of light fleeing SN 2011fe's blast site, provided "the first direct evidence that a type Ia supernova does indeed start with a carbon-oxygen white dwarf," he says.

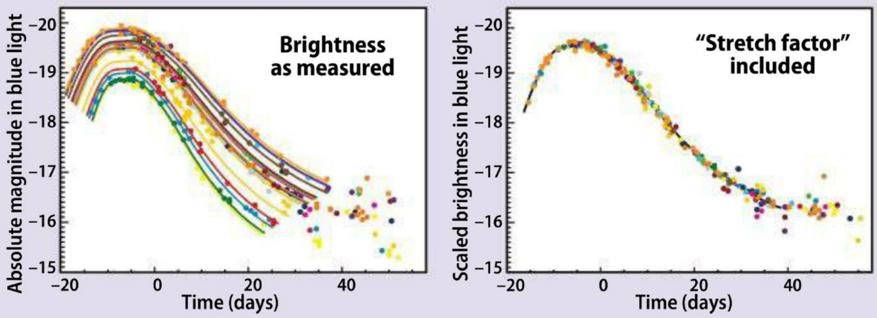
A subsequent analysis led by UC Berkeley astronomer Joshua Bloom and published in January 2012 confirmed that the object that blew up was a carbon-oxygen white dwarf. That finding was based on a fortuitous observation of M101 taken by The Open University graduate student Stefan Holmes using the 17-inch PIRATE telescope on the island of Mallorca off Spain's coast just four hours after the explosion. The supernova was not visible in the image, which places tight constraints on the size of the progenitor star, as theoretical models show that bigger progenitors create brighter glows from the supernova's expanding shock wave. The non-detection by PIRATE — given the telescope's size and Earth's distance from M101 — indicates that the star must be small, less than 1⁄50 the Sun's diameter. Thus, it could be only a white dwarf or a neutron star. "Since we see carbon and oxygen in the explosion, and a neutron star can't emit that, that leaves a white dwarf as the only possibility," explains Nugent, a coauthor of that study.

Nailing down the progenitor's identity, at least in this one case, is helpful to theorists trying to model these explosions "because there are only so many ways you can blow up a carbon-oxygen white dwarf," notes University of California, Santa Cruz, astrophysicist Stan Woosley.

Drawing on the PIRATE observations, Bloom and his colleagues also determined that SN 2011fe's companion star must, with few caveats, be a diameter less than 1⁄10 that of the Sun, making a white dwarf again the most likely candidate.

Even stronger confirmation of the "double-degenerate theory," which holds that a type Ia supernova is triggered by the merger of two white dwarfs, came in a January 2012 paper by Bradley Schaefer and Ashley Pagnotta of Louisiana State University in Baton Rouge. Schaefer and Pagnotta looked for a companion star to the remnant of a supernova (SNR 0509–67.5) that detonated in the Large Magellanic Cloud about 400 years ago. If the companion to the exploding white dwarf was another star, such as a main sequence star or a red giant — the so-called "single-degenerate" case — it should have survived the blast. No stars would remain after the cataclysmic union of two white dwarfs. Studying archival images of the remnant taken by the Hubble Space Telescope, Schaefer and Pagnotta found no signs of a companion star some

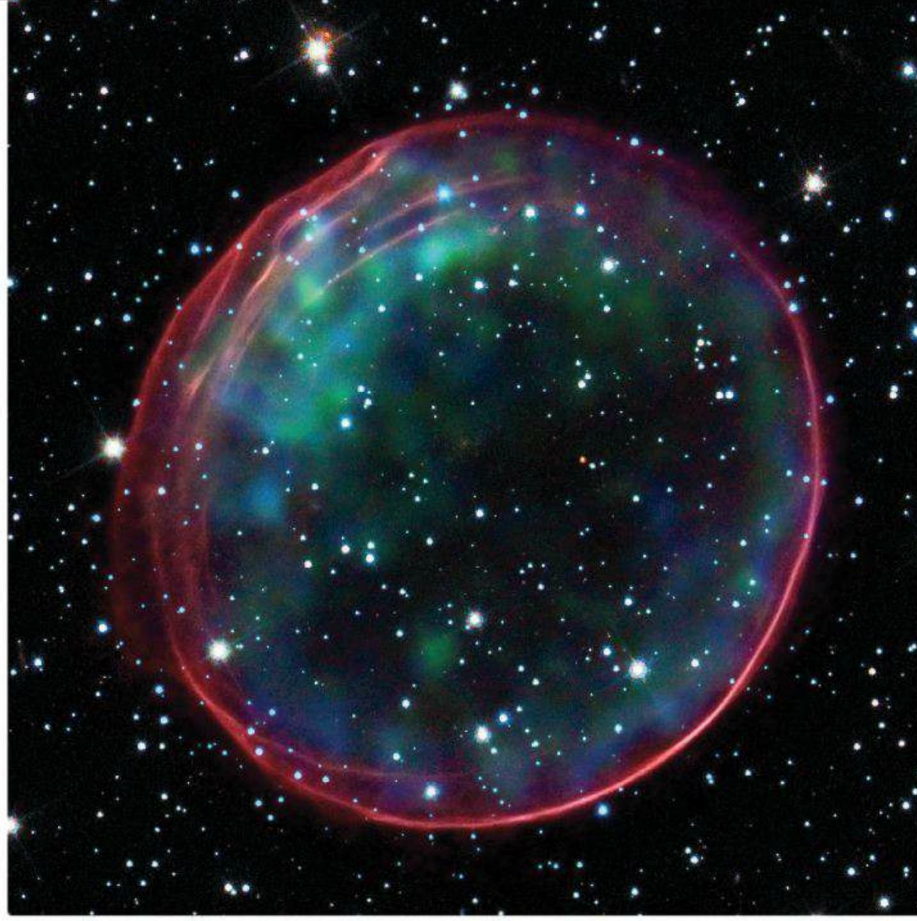
Comparing candles



All type Ia supernovae's light curves have strikingly similar shapes, except for a difference in scaling factor. Scientists in the 1990s found that the brighter this type of object is, the longer it takes to reach its maximum luminosity and then fade. *Astronomy*: Roen Kelly, after Saul Perlmutter, et al.

4 magnitudes fainter than nature would allow, thus ruling out all single-degenerate models and leaving a double-degenerate system as "the only remaining possibility."

"This conclusion seems sound," concurs University of Barcelona astronomer M. Pilar Ruiz-Lapuente. The study's chief limitation, according to Schaefer, "is that we have this incredibly decisive result for just one supernova. If this one progenitor class dominates all type Ia supernovae, then we've solved the whole problem. If there are two progenitor classes, then we've only solved half the problem."



NASA/ESA/CXC/SAO/The Hubble Heritage Team (STScI/AURA)/J. Hughes (Rutgers University)

SNR 0509–67.5 doesn't contain a star in its center, which leads astronomers to believe that the supernova that formed this colorful remnant resulted from the merger of two white dwarfs.

A type Ia supernovae division?

A 2011 paper by Mark Sullivan of Oxford University in the United Kingdom and collaborators, which analyzed 472 type Ia supernovae, suggests that these events may subdivide into two categories, depending on whether the supernova occurs in a massive galaxy with a high rate of star formation or in a lower-mass galaxy with less star formation. The different mix of stars in those galaxies could lead to different white dwarf companions. "Even after you make the usual corrections for the light curve width and color, these supernovae still differ in brightness depending on the kind of galaxy they come from," says Howell, a study co-author.

While some may lament the need to continually refine astronomers' standard candles, Nugent considers it a good thing: "We might now be able to subclassify two supernovae that otherwise look the same — depending on the kind of host galaxy or the companion star — all of which can lead to increasing precision in cosmology." Right now, distance measurements of type Ia supernovae are accurate to within about 6 percent; new approaches can improve on that mark.

Ryan Foley of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, has developed a method to make these supernovae even better standard candles. While astronomers have traditionally assumed that some explosions are redder than others simply due to the presence of dust, Foley has shown that some of the color variation may be intrinsic to the supernova itself. He measured the speed of the material ejected from more than 300 type Ia supernovae, both nearby and far away, and found that objects with faster "ejecta" were redder while those with slower ejecta were bluer. So the standard color adjustment apparently needs some adjustment itself.

> **"THERE ARE ONLY SO MANY WAYS YOU CAN BLOW UP A CARBON-OXYGEN WHITE DWARF."**
> **— STAN WOOSLEY**

Forecast the future

Every improvement in accuracy will help unravel the dark-energy enigma. The latest data, based on Sullivan's supernovae survey and other work, suggest that dark energy is the "cosmological constant" — an inherent property of space itself that remains invariant over time and does not get diluted as the universe expands. If this picture holds, our universe will expand into the indefinite future at an ever-increasing clip, with galaxies driven farther and farther apart. "But if we've been making mistakes," notes Foley, "if there's a fundamental difference, say, between nearby and distant supernovae that we've overlooked, that could be enough to make something that looks like a cosmological constant no longer constant."

Additional supernovae observations, compiled by existing programs like the PTF and the upcoming Large Synoptic Survey Telescope and the proposed Wide-Field Infrared Survey Telescope, will undoubtedly clarify the picture. At the same time, new supercomputer calculations, carried out by theorists like Woosley and Kasen, will help show the extent to which asymmetries in the explosion can affect the luminosity of type Ia supernovae. "We are on the cusp of being able to make measurements that can tell us the ultimate fate of the universe," says Howell. "Even though it looks like the universe is filled with this vacuum energy, the so-called cosmological constant, we have to keep on it and make sure we get the right answer."

Visit www.Astronomy.com/toc to learn about the different types of supernovae.

Astronomy's experts from around the globe answer your cosmic questions.

The lunar shadow

Q: What determines the length of totality during a solar eclipse? — **Richard Vaun,** Holley, New York

A: Totality occurs within the Moon's shadow, as cast by the Sun, falling onto Earth. So, because the Moon moves at different speeds in its orbit around Earth and the planet moves at different speeds in its orbit around the Sun, the shadow sweeps through space at differing rates.

Further, we live on a rotating planet, so how fast Earth's surface at a particular spot moves through space factors into totality's length. At the equator, Earth completes one spin about its circumference of 24,901 miles (40,074 kilometers) in 24 hours, making the speed roughly 1,000 mph (1,600 km/h). Near the poles, a point on Earth's surface moves around the planet's spin axis much more slowly.

The Moon's shadow sweeps across Earth's surface during the August 11, 1999, solar eclipse. The length of totality depends on where on the planet's surface the shadow falls, how far away the Moon is from Earth, and how far Earth is from the Sun at that time. CNES/Mir 27 Crew

So, the longest totalities occur when the Moon's shadow crosses Earth near the equator, the Moon is closest to our planet, and Earth is farthest from the Sun. The theoretical maximum is about 7½ minutes, but that won't happen until the next century, and now the longest totalities are around 6½ minutes.

In 1973, the speed of the shadow across Earth slowed enough that a supersonic Concorde could keep up with it for 74 minutes, although the eclipse was high overhead and holes (with windows) had to be cut into the airplane. — **Jay M. Pasachoff,** Hopkins Observatory of Williams College, Williamstown, Massachusetts

GRAVITY, THE TRAVELER

Q: If the Sun suddenly disappeared, it would take about eight minutes for Earth to become dark (due to the speed of light). How long would it take to feel the absence of the Sun's gravity? — **John Boliek,** Hockessin, Delaware

A: According to Albert Einstein's general theory of relativity, if the Sun were to suddenly disappear, Earth would feel the absence of the Sun's gravity in the same time it would take for it to "feel" the absence of the Sun's light. So, about eight minutes. That's because removing the Sun would launch a set of gravitational waves from its location that would carry the information about the Sun's absence to Earth; according to our current understanding, gravitational waves travel at the speed of light. The reason for this coincidence is that, as far as we know, both electromagnetism (i.e. light) and gravity have what's called "unlimited range" — that is, the strength of either force declines by the distance to the source squared. — **Marc Kuchner,** NASA's Goddard Space Flight Center, Greenbelt, Maryland

UNDER LIGHT-POLLUTED SKIES

Q: How do light pollution filters work? Do they actually help? — **Kyle Norris,** Peoria, Arizona

A: Light pollution reduction (LPR) filters work because many outdoor lighting sources do not shine evenly across the visible spectrum. Instead, they emit radiation at only a few distinct wavelengths. For instance, a high-pressure sodium streetlight radiates principally in yellow wavelengths. **LPR filters suppress those and similar wavelengths while allowing others through.**

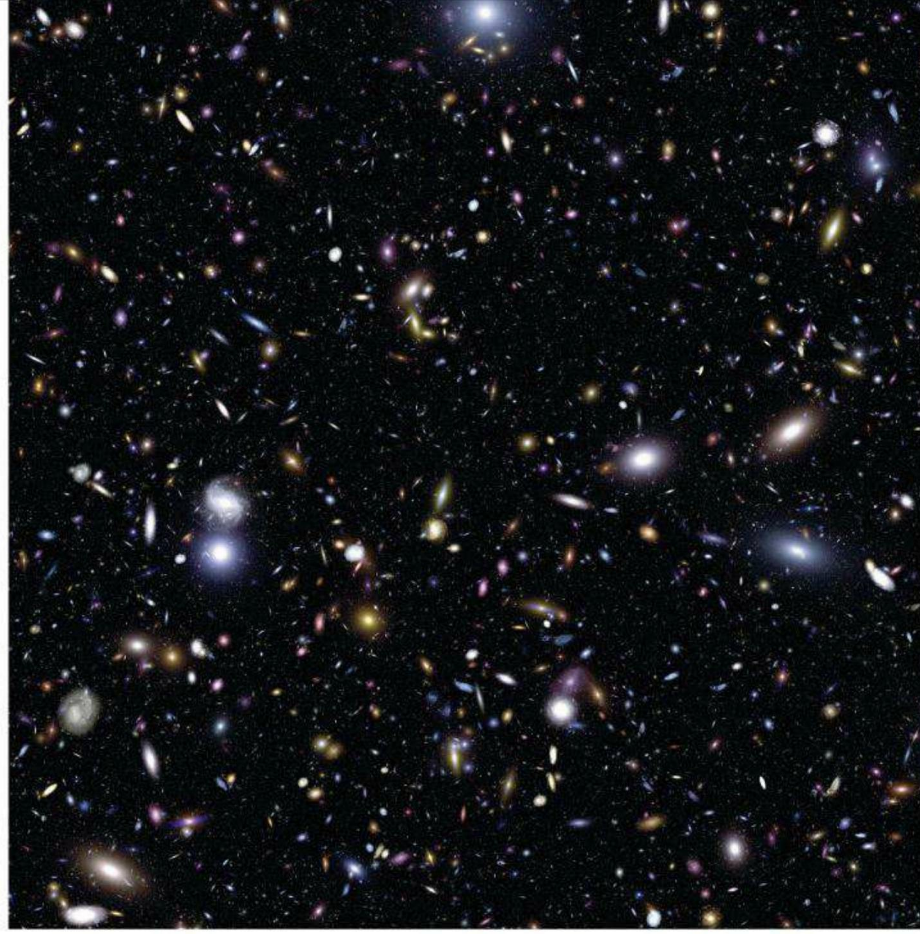
LPR filters don't reduce all forms of light pollution, despite their name. They do little to reduce the impact of car headlights, lights directed onto buildings, and other fixtures using incandescent bulbs that (unfortunately for astronomers) emit all visible wavelengths.

Another common fallacy is that these filters make sky objects look brighter. Filters only subtract light, dimming everything. In the process, however, the background sky and field stars darken more than the target. This boosts the *contrast*, making celestial objects easier to spot.

Some amateurs believe these filters dim the view so much that they can't use them with small telescopes. That's also not true. Any telescope can benefit from these filters.

Under urban and suburban skies, LPR filters perform best on bright nebulae. **While a filtered view seldom shows more detail than an unfiltered one, or reveals an otherwise invisible target, LPR filters improve the visual aesthetics by darkening the background sky.** And even from a dark site where there's no light pollution, nebulae tend to look a bit better.

If you live under a dome of light pollution, consider adding an LPR filter to your equipment arsenal. Once you start using filters, you'll be amazed at what you've been missing. It's the same pleasant experience as putting on your "shades" on a sunny day. **— Michael E. Bakich,** Senior Editor



More galaxies closer to the moment of the Big Bang will be visible to the James Webb Space Telescope (JWST). The infrared observatory will see farther away, and thus further back in time, than the Hubble Space Telescope has because its mirror will be much larger than Hubble's and infrared radiation probes earlier epochs due to cosmic redshift. A simulated JWST deep field is shown here. NASA

INTO THE UNKNOWN

Q: Are there plans to further the Hubble Space Telescope's capacity to look even deeper?
— Mike Martinez, Eagan, Minnesota

A: The Hubble Space Telescope has made the deepest views of the universe that it can, which have been pretty deep and far back in time.

Before NASA launched Hubble in 1990, ground-based telescopes could see clearly only about halfway across the universe. Astronomers knew there must be an "undiscovered country" of primeval galaxies out there, but seeing them required a space telescope to push back the frontier. The pinnacle of that success is the Hubble Ultra Deep Field (HUDF) image, which pushed to 29th magnitude and allowed astronomers to see 95 percent of the way across the universe. HUDF has revealed a feeble glow of a galaxy that existed only 480 million years after the Big Bang.

It took a whopping 500 Hubble orbits around Earth to make the HUDF. To go little more than twice as faint, to 30th magnitude, would require 3,000 Hubble orbits — that's nearly all of Hubble's allocated observing time for one year.

At that faintness, the telescope would receive only one photon per minute from distant galaxies. Hubble cameras are state of the art but still cannot perform well with such an anemic trickle of starlight. Electronic "noise" in the telescope's solid-state detectors would begin to overwhelm the faint starlight.

Given the diminishing return on the orbits that would be needed, there are no plans to push Hubble's views fainter. The observing time would be more productively spent doing several "deep fields" on different areas of the sky to see if the distribution of galaxies in the universe really does look essentially the same in all directions.

NASA is building the James Webb Space Telescope (JWST) that, because it has a larger mirror than Hubble, will see 10 times fainter than Hubble in infrared light once it launches in 2018. The universe's expansion reddens light from distant objects, and thus the JWST will observe back in time with its infrared vision. **— Ray Villard,** Space Telescope Science Institute, Baltimore, Maryland

ATMOSPHERIC EFFECTS

Q: Why do some stars appear to flash a variety of different colors when you look at them through a telescope? **— Dominic Snyder,** Glen Rock, Pennsylvania

A: Earth's atmosphere is made of layers of gas, and light from distant objects must pass through it to get to our telescopes.

Differences in gas can make light bend, or refract. Think of an object seen through air rising from an asphalt road on a hot day. That warm air slightly warps light, and you see this distortion. Also, rainbows are a result of sunlight refracted in atmospheric water droplets. **So, Earth's atmosphere will bend some colors from especially bright stars more so than others, which makes the source look like it's flashing colors. — Liz Kruesi,** Associate Editor

Send your questions via email to: **askastro@astronomy.com**; or write to **Ask Astro, P. O. Box 1612, Waukesha, WI 53187.** Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.