search & discovery

Overluminous supernovae push the Chandrasekhar limit

Their explosion mechanism may involve two white dwarfs rather than one.

Type Ia supernovae are explosions of white dwarfs, the carbon–oxygen remnant cores of medium-sized stars that have exhausted their hydrogen fuel. They're distinguished from other supernovae by the absence of hydrogen and the presence of silicon in their optical spectra. And they appear remarkably uniform—although not identical—which makes them useful to cosmologists as standard candles for gauging distances across the universe.

That uniformity has been attributed to a common formation mechanism: A white dwarf in a binary system accretes material from its companion star until it nears the Chandrasekhar limit of 1.4 solar masses ($M_\odot$). At that point, electron degeneracy pressure no longer supports the white dwarf against its own weight. When the center of the dwarf is sufficiently hot and dense, carbon fusion begins, which releases enough energy to unbind the star.

Several years ago researchers with the Supernova Legacy Survey spotted a supernova, SN 2003fg, that bore all the marks of being type Ia but appeared too luminous to have had a Chandrasekhar-mass progenitor.[1] But the data they gathered were sparse. Now three other research groups—from the Nearby Supernova Factory (SNfactory); the University of California, Berkeley; and the universities of Tokyo and Hiroshima in Japan—have collected detailed data on SN 2007if and SN 2009dc, two type Ia supernovae that were at least as luminous as SN 2003fg and shared some of its other unusual features.[2] The new data help point the way toward a better understanding of the physics of type Ia supernovae, which could yield a better standard candle for cosmologists.

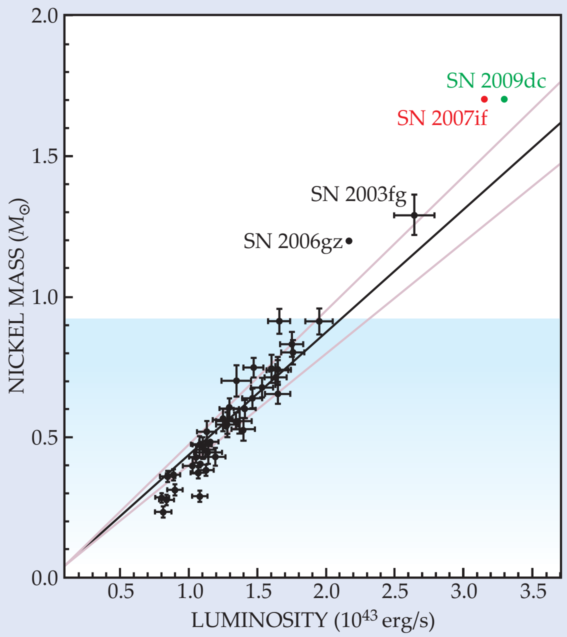

Figure 1. Overluminous supernovae SN 2003fg, SN 2006gz, SN 2007if, and SN 2009dc, compared with other type Ia supernovae from the Supernova Legacy Survey. The shaded blue region shows the range of nickel masses that can be produced by a Chandrasekhar-mass (1.4-$M_\odot$) white dwarf. Although error bars are not shown for the newer data points, intervening dust is a source of significant uncertainty. The luminosities shown for SN 2006gz and SN 2009dc both assume that much of the emitted light was absorbed by dust; the value for SN 2007if assumes no dust absorption. (Adapted from ref. 1.)

Nickel for your thoughts

Nuclear fusion in a type Ia supernova yields two classes of elements: intermediate-mass elements (such as silicon, calcium, and sulfur) and iron-group elements (iron, cobalt, and nickel). Nickel-56 decays into ^{56}Co and then ^{56}Fe. Those beta decays can produce enough light over the course of a few weeks to outshine the entire host galaxy—and to be visible to observers up to billions of light-years away.

Even if white dwarfs are all the same size when they explode, the explosions aren't identical, because they produce different amounts of nickel. Cosmologists have worked out an empirical relationship between the peak luminosity of a type Ia supernova and the time it takes to fade, which enables them to infer the supernova's distance and correlate that with its redshift. That the most distant supernovae are redshifted less than they would be if the universe were expanding at a constant rate implies that the expansion is accelerating—and that some 70% of the mass–energy content of the universe is a mysterious dark energy. (See PHYSICS TODAY, June 2001, page 17.)

The Supernova Legacy Survey found SN 2003fg to be too luminous either to fit the cosmologists' empirical relationship or to have come from a Chandrasekhar-mass white dwarf. The team estimated that it contained about 1.3 $M_\odot$ of Ni alone. Other elements that must have been present boosted the estimated total mass to at least 2.1 $M_\odot$.

Luminosity wasn't the only strange thing about SN 2003fg. Its spectrum included strong carbon absorption lines that are weak or absent in a typical type Ia supernova. And the material ejected by the explosion was cast off at a relatively low speed of 8000 km/s—as inferred from Doppler line shifts—rather than the more usual 10 000 to 12 000 km/s.

How could a white dwarf be so heavy—or its explosion so luminous? It could have been spinning very fast, so that centrifugal force helped to balance gravity. It could have been the product of two white dwarfs orbiting each other and merging. Or it could have been an ordinary Chandrasekhar-mass white dwarf exploding asymmetrically, with the bright side facing Earth. Observations of other similar supernovae would help to narrow the possibilities.

One such candidate, SN 2006gz, was observed in 2006 and described a year later.[3] But it wasn't as extreme a case as SN 2003fg. Classifying SN 2006gz as super-Chandrasekhar relied on the assumption that a shroud of dust made it appear less luminous than it really was. And although it had the carbon spectral lines seen in SN 2003fg, it lacked the lower-velocity ejecta.

New candidates

As their names suggest, SN 2007if and SN 2009dc were observed in 2007 and 2009. Both were suspected of being too bright. But analysis of SN 2007if had to wait, because no host galaxy was visible in the images of the supernova. Spectral lines from the host galaxy are necessary to determine the supernova's redshift (and thus estimate its distance) and to interpret the supernova's own spectra. Only in 2009 was a galaxy observed where SN 2007if had been.

Both new supernovae are much closer to Earth than SN 2003fg was. And the research groups were on the lookout for overluminous type Ia supernovae, so they collected more complete data. Both SN 2007if and SN 2009dc were at least as luminous as SN 2003fg, as shown in figure 1, although the presence or absence of intervening dust creates significant uncertainty. Both have the lower-velocity ejecta and the carbon lines that SN 2003fg had.

To test the possibility that the overluminous supernovae are asymmetrical explosions with their bright sides facing Earth, the Tokyo–Hiroshima researchers collected polarimetry data on SN 2009dc.[4] An aspherical supernova ought to produce polarized light, as the radiated photons scatter off ejected matter. But the researchers found no significant polarization.

The SNfactory and Berkeley groups compared their data with several published theoretical models. Both groups conclude that merging white dwarfs provided the best match. A rotating white dwarf probably couldn't grow massive enough, nor could its explosion produce enough Ni, to be as luminous as SN 2007if or SN 2009dc. It's unlikely that even the bright side of an asymmetrical explosion would be bright enough. And neither of the single-dwarf scenarios explains the relatively slow ejecta or the carbon lines.

Two white dwarfs can, of course, be more massive than one. And low-velocity ejecta can arise from a high-mass system simply because of the greater gravitational force holding them back. But Richard Scalzo, lead author of the SNfactory paper on SN 2007if, figures that the lower velocities could also be due to a collision between the ejecta and a C–O envelope created in the merger.

Compared with slow accretion by a single white dwarf, the merging of two white dwarfs, shown schematically in figure 2, is a violent process. The less massive star is thought to get shredded by tidal disruption, with some of its mass ending up as a diffuse disk or envelope around the newly merged white dwarf at the center. When that white dwarf explodes, the ejected material slams into the envelope, creating a dense shell that slows the ejecta. And the carbon in the shell could show up in the supernova spectrum.

Based on that scenario, Scalzo computed the effects of varying the system's parameters—including total mass, envelope mass, and elemental composition of the fusion products—to see which combination best matched the SNfactory observations of SN 2007if. He obtained a mass estimate for the whole system—not just a lower bound based on the Ni mass—of about 2.4 $M_\odot$, with 1.6 $M_\odot$ of that being Ni and 0.4 $M_\odot$ being the C–O envelope.

The ejecta for SN 2007if are not only relatively slow, but their velocity exhibits a plateau in time, in agreement with the envelope model. But SN 2009dc's ejecta velocity appears to have declined more smoothly. "I like Scalzo's interpretation," says Jeffrey Silverman, lead author of the Berkeley group's paper, "but I'm not completely convinced that it's valid for all super-Chandrasekhar supernovae."

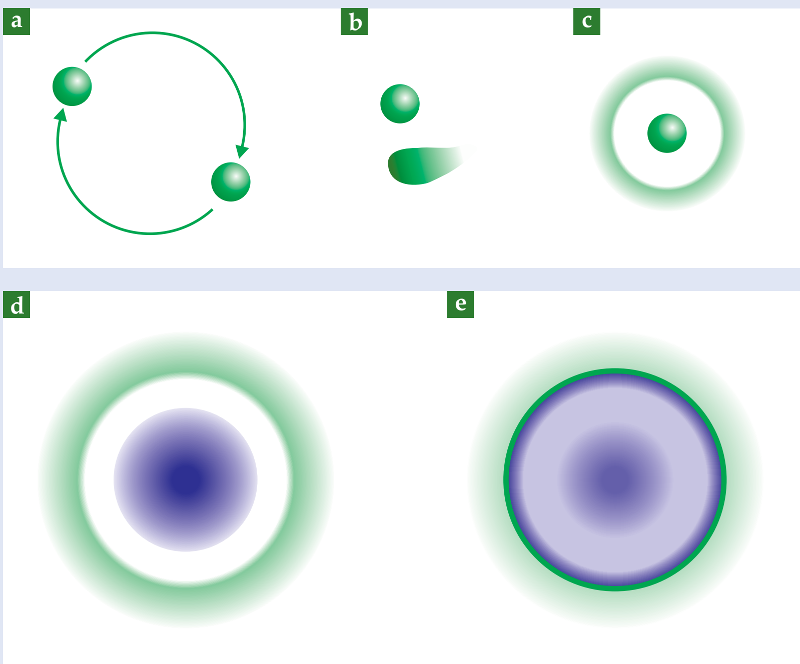

Figure 2. A supernova from two merging white dwarfs shown schematically. Carbon and oxygen are shown in green; fusion products are shown in purple. **(a)** White dwarfs orbit each other in a binary system. **(b)** The more massive dwarf tidally disrupts the less massive one. **(c)** Some of the disrupted white dwarf's mass forms a diffuse disk or envelope. **(d)** The central dwarf explodes, but the envelope remains intact. **(e)** Ejecta from the explosion collide with the envelope, initiating a shock wave that slows down the ejecta.

Different approaches

Other recent work also supports the idea that at least some type Ia supernovae are formed by merging white dwarfs rather than accreting ones. Rosanne Di Stefano at the Harvard–Smithsonian Center for Astrophysics, and Marat Gilfanov and Ákos Bogdán at the Max Planck Institute for Astrophysics, argue separately that there aren't enough accreting white dwarfs to produce all the observed type Ia supernovae, at least in some galaxies.[5] Accreting white dwarfs give off an x-ray signal as they burn their newly acquired H-rich material into carbon and oxygen. Since accretion is a slow process, many white dwarfs must be emitting x rays for each one that explodes. But observers don't detect that many x rays.

Wolfgang Hillebrandt and colleagues, also at the Max Planck Institute for Astrophysics, have for the first time simulated how two white dwarfs can merge and then explode.[6] The simulated explosion turned out to be underluminous, not overluminous, and the only way they could keep the one dwarf from entirely shredding the other was to start with two dwarfs of exactly equal mass, which isn't realistic. But simulating merging white dwarfs is a computationally demanding task, and the necessary simplifications may work to forestall explosions that would actually take place.

The too-bright supernovae are rare enough that they alone probably don't have much of an impact on cosmological measurements. But they're part of the mounting evidence that type Ia supernovae are more diverse than the simple picture of a white dwarf gaining mass up to the Chandrasekhar limit would suggest. Better understanding of their formation—how their explosion mechanisms relate to their observed properties and how to either weed out the exceptional ones or make them cosmologically useful—could make the cosmological measurements more precise.

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References

1. D. A. Howell et al., *Nature* **443**, 308 (2006).
2. R. A. Scalzo et al., *Astrophys. J.* **713**, 1073 (2010); J. M. Silverman et al., http://arxiv.org/abs/1003.2417; M. Yamanaka et al., *Astrophys. J. Lett.* **707**, L118 (2009).
3. M. Hicken et al., *Astrophys. J. Lett.* **669**, L17 (2007).
4. M. Tanaka et al., *Astrophys. J.* (in press).
5. R. Di Stefano, *Astrophys. J.* **712**, 728 (2010); M. Gilfanov, Á. Bogdán, *Nature* **463**, 924 (2010).
6. R. Pakmor et al., *Nature* **463**, 61 (2010).

A magnetic insulator transmits electrical signals via spin waves

The spin Hall effect, which converts the charge current to a spin current, and its inverse form the basis for a proof of principle.

Electrons carry both charge and spin as they flow in a material. For many applications, the spins are artificially polarized by magnetic fields or are naturally polarized in ferromagnets such as iron and nickel. The recent history of spintronics is rich with examples of heterostructures carefully engineered to send a current of spin-polarized electrons from a ferromagnet to metals, semiconductors, or superconductors (see the article by Jagadeesh Moodera, Guo-Xing Miao, and Tiffany Santos in PHYSICS TODAY, April 2010, page 46).

In fact, though, a spin current may appear wherever there is a charge current—no magnetism required. The spin polarization arises from the relativistic coupling of the electrons' spin and orbital angular momenta. As electrons scatter from atomic impurities, they feel an effective magnetic field that alters their paths: Spin-up electrons bend in one direction, spin-down electrons in the other, both transverse to the original direction of the charge current. The transverse spin current, known as the spin Hall effect, was predicted in 1971 to exist in semiconductors but was not detected experimentally until just five years ago (see PHYSICS TODAY, February 2005, page 17).

A year later Eiji Saitoh (now at Tohoku University) and his Japanese colleagues discovered the inverse of the effect—the conversion of a spin current into a transverse charge current—in platinum.[1] Because both a spin Hall

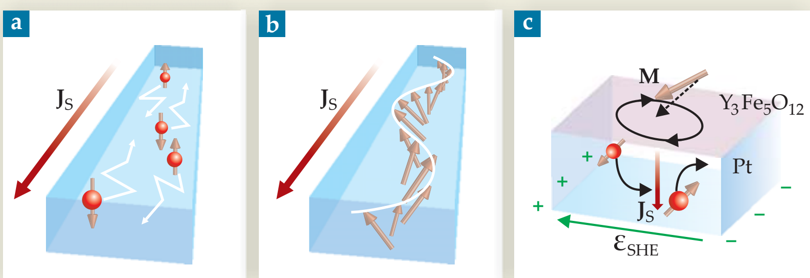

Figure 1. Spin currents in solids. Spin angular momentum $\mathbf{J}_S$ can be carried by **(a)** electron diffusion or by **(b)** spin waves, the collective precession of magnetic moments. **(c)** At the interface of an insulator such as yttrium iron garnet and a metal film such as platinum, angular momentum from the precession of the insulator's magnetization **M** can be pumped into the metal, where it appears as a conduction-electron spin current. By the inverse spin Hall effect, spin–orbit coupling deflects electrons of opposite spins in the same direction, whereby they accumulate on the same Pt edge. The charge imbalance sets up an electromotive force, $\mathcal{E}_{SHE}$, measurable as a voltage. (Adapted from ref. 2.)