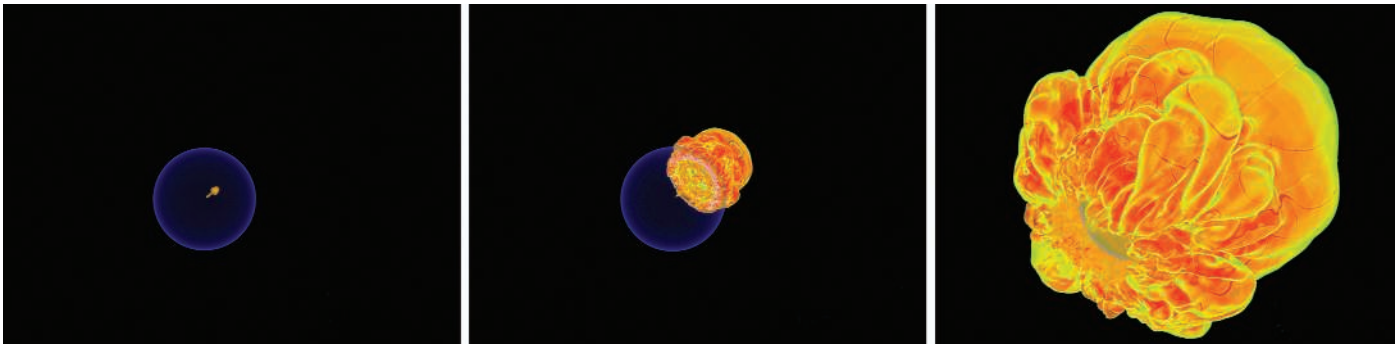

ASTRONOMY

Surveys of Exploding Stars Show One Size Does Not Fit All

Type Ia supernovae are regular enough that astronomers can use them to measure the universe. But some of the "standard candles" are breaking the theoretical mold

SANTA BARBARA, CALIFORNIA—When astronomers wish upon a star, they wish they knew more about how stars explode. In particular, experts on the stellar explosions known as supernovae wonder whether textbook accounts tell the true story—especially for a popular probe of the universe's history, the supernovae designated as type Ia.

In fact, new observational surveys suggest that cosmic evidence based on type Ia supernovae rests on a less-than-secure theoretical foundation. "We put the theory in the textbooks because it sounds right. But we don't really know it's right, and I think people are beginning to worry," says Robert Kirshner, a supernova researcher at the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. "We keep saying the same thing, but the evidence for it doesn't get better, and that's a bad sign."

Kirshner was among more than 100 experts on stars and their explosions who gathered to discuss their worries last month at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.* General agreement emerged that the textbook story "is a little bit of 'the emperor has no clothes,'" as Lars Bildsten, an astrophysicist at the Kavli Institute, put it. "There's a lot of holes in the story."

Understanding type Ia supernovae has become an urgent issue in cosmology, as they provide the most compelling evidence that the universe is expanding at an accelerating rate. That acceleration, most cosmologists conclude, implies the existence of a cosmic fluid called "dark energy" that exerts a repulsive force countering gravity.

In the textbook story, type Ia explosions occur in binary systems where a worn-out star known as a white dwarf siphons matter from a nearby companion. When the planet-sized dwarf accumulates enough mass to exceed the Chandrasekhar limit—about 1.4 times the mass of the sun—its density becomes great enough to ignite thermonuclear fusion, blowing itself to smithereens.

Because all white dwarfs presumably blow up the same amount of mass, they should all be equally bright at any given distance, and so their apparent brightness should diminish with distance in a predictable way. Faraway type Ia supernovae are dimmer than expected, however, suggesting that the universe's expansion rate has been speeding up.

But figuring out exactly what dark energy is will require a precise gauge of its effect on the expansion history of the universe. And type Ia supernovae are not yet well enough understood for analysis of their brightness to provide the needed precision, experts say. "We do not know the details," says Alex Filippenko of the University of California, Berkeley. "There is still a lot of controversy about what exactly is going on in a Ia."

Several speakers during the Santa Barbara conference noted problems with the textbook view. For one, astronomers have long realized that not all type Ia's explode with the same brightness. Instead, the brightest are several times as luminous as the dimmest. Type Ia explosions in old, elliptical galaxies appear dimmer, on average, than explosions in younger galaxies. It may be that such differences reflect different pathways leading to explosion, hinting that type Ia supernovae come in two distinct flavors. "There is now very strong evidence that … there are very likely two populations of type Ia supernovae," said Bildsten.

Corrections for brightness differences can be made based on the color of the explosion's light and how rapidly it dims. Such fixes were good enough to establish accelerating expansion but not for pinning down dark energy's properties precisely. That will require answers to several nagging questions, including the nature of the white dwarf's companion and the mechanism of the explosion.

The good news from the conference is that several computer simulations seem to show that a 1.4-solar-mass white dwarf can indeed explode like a bomb, although various models differ in their details. In some models, a wave of fusion burns slowly through the star (a process known as deflagration), ultimately detonating the fast-burning explosion that mimics a hydrogen bomb. In the star, however, the elements fused are carbon and oxygen, the elements believed to make up the bulk of the white dwarf type Ia progenitors.

Immediate detonation of the entire star in a rapid shock-wave blast is unlikely because it would convert nearly all the material into an isotope of nickel (which eventually decays to form iron). Because intermediate-weight elements (such as silicon) are found in type Ia debris, some of the burning must be slower.

A deflagration model discussed at the conference by Wolfgang Hillebrandt of the Max Planck Institute for Astrophysics in Garching, Germany, seems able to produce an explosion, but only if deflagration begins at multiple points within the star. Another approach, presented by Don Lamb of the University of Chicago in Illinois, showed how a bubble of fusion beginning inside the star can burst out through its surface and then, confined by the star's gravity, wrap

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[*] "Paths to Exploding Stars: Accretion and Eruption," 19–23 March.

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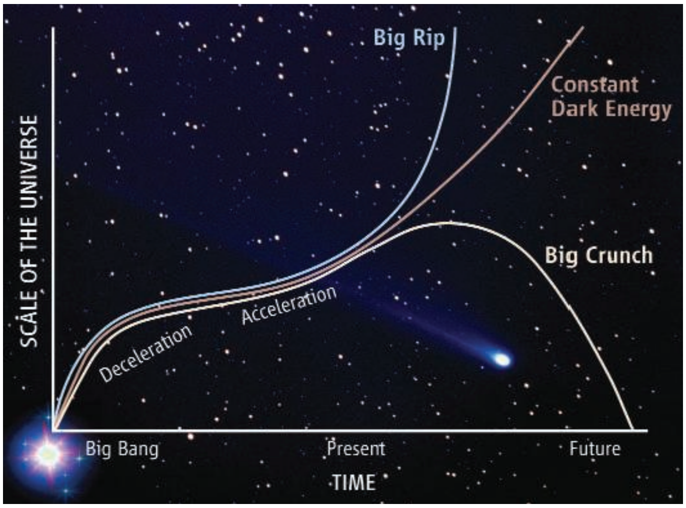
Kaboom! Computer models show ways stars might explode but not what primes them for the blast.

around the star in all directions, until encountering itself on the other side (see figure, p. 194). When the fusing material collides with itself, a jet of material fires back down into the star, detonating the full fusion explosion, a new three-dimensional computer simulation shows, confirming the basic picture seen in earlier two-dimensional models.

But, as Kirshner pointed out, simulating an explosion is one thing. It remains to be seen whether the models can replicate the energy and mix of elements actually seen in various type Ia explosions. And these models assume that a 1.4-solar-mass white dwarf is conveniently available and poised to explode, yet nobody knows exactly how white dwarfs reach that point, or whether there are enough of them to account for the observed rate of explosions. In fact, most observed white dwarfs are typically only a little heavier than half the mass of the sun, far below the explosion point.



What next? Uncertainties in supernova surveys could muddle efforts to determine the nature of dark energy—and thus the fate of the universe.

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In the standard story, white dwarfs reach the mass limit by accreting hydrogen from a companion star. But the accretion must occur at a "just right" rate—too fast, and it will be blown away by smaller explosions before reaching the bomb mass.

Furthermore, if white dwarfs really explode by accreting hydrogen from a companion, leftover hydrogen should be visible in the supernova remnant. But sensitive observational searches have failed to find the hydrogen. "I think this lack of hydrogen is a very, very serious issue," said Filippenko.

The missing hydrogen leads some experts to speculate that the companion star is not an ordinary hydrogen-rich star but something else—perhaps even another white dwarf. But searches find few double-dwarf systems likely to become supernovae. The Supernova Ia Progenitor Survey at the European Southern Observatory in Chile has observed more than 1000 white dwarfs and has found only two double-dwarf systems, Ralf Napiwotzki of the University of Hertfordshire, U.K., said at the conference.

In one, the total mass of both dwarfs didn't reach the explosion threshold, and they wouldn't merge for 25 billion years, anyway. The other double dwarf falls just short of bomb mass. "At the moment, we can't say we have a clear-cut supernova Ia progenitor," Napiwotzki said. But deeper searches may find more candidates, he added.

If double dwarfs do merge and explode, their combined mass could exceed the Chandrasekhar limit, producing an unusually bright explosion. And in fact, one such unusual explosion was spotted in 2003 and reported in *Nature* last year by the Supernova Legacy Survey, an international project using the Canada-France-Hawaii telescope on Mauna Kea.

Supernova 2003fg looks like a type Ia, said Andrew Howell of the University of Toronto, Canada, but glows with more than double the median Ia brightness. Its brightness and energy output suggest a combined mass of more than two solar masses, implying (among other possibilities) a double-dwarf explosion or the growth of a single white dwarf to larger than the expected maximum mass. Many experts find it hard to envision a single dwarf growing that fat, but neither has current theory established that the merger of two dwarfs would produce the observed features of a type Ia explosion.

In any case, freak explosions such as 2003fg are just the sort that could contaminate supernova data needed to determine whether dark energy is the residual energy of empty space incorporated by Einstein into his theory of relativity as a "cosmological constant." If it is, the ratio of the dark energy's pressure to its density would be exactly –1, at all times and places throughout the universe. (That ratio, known as the equation of state, is negative because the pressure is negative, conferring the dark energy's repulsive effect.)

If the ratio is greater than –1, dark energy could be a new sort of field, sometimes called quintessence, that changes its strength over time. A ratio less than –1 suggests an entirely weird "phantom" energy that would someday rip the universe to shreds (See figure below and *Science*, 20 June 2003, p. 1896).

Current efforts to gauge the equation of state using supernovae are all consistent with –1 but not sensitive enough to detect small deviations. At the conference, Mark Sullivan of the University of Toronto reported a Supernova Legacy Survey analysis of 250 supernovae giving a value of –1.02, but with an error range including –1. Michael Wood-Vasey of CfA, presenting for another supernova survey known as ESSENCE, reported –1.05, based on more than 170 supernovae, but again with uncertainties large enough to include –1.

Reducing such uncertainties further is a prime goal of several supernova-search satellite missions to probe dark energy that will be competing for funding, as described in last year's Dark Energy Task Force report prepared for NASA, the National Science Foundation, and the Department of Energy (www.science.doe.gov/hep/DETF-FinalRptJune30,2006.pdf). But some experts doubt that supernova theory will ever be good enough to identify small deviations from –1, even with thousands of supernovae observed from a dark-energy satellite. (Some of the proposed missions, however, would measure both supernovae and other features, such as gravitational-lensing effects, that could help narrow the uncertainties.)

In any event, better supernova data could still be useful to cosmologists, Bildsten pointed out. "If there's really two populations, you might decide that one of those populations isn't so good, and if it's in this type of galaxy or that, you don't use it for your cosmology," he said. "Maybe that's helpful information."

But whatever help supernovae can provide will still depend on plugging the worrisome gaps in current textbooks accounts, Kirshner said, and answers to many critical questions remain elusive. "I wouldn't say it's a crisis," he said. "But if you ask, 'Are the pieces falling into place?' I'd say the answer is no."

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