BEHIND THE BIG FLASH

CALCULATIONS REVEAL NEW EXPLANATION OF SUPERNOVA EXPLOSIONS

Type Ia supernovae are stars in more than one sense — they are playing a leading role in revealing the history of the Universe, and they are attracting the devoted attention of a multitude of researchers.

As cosmic distance markers, Type Ia supernovae, combined with other observations, led to the discovery of the mysterious dark energy that is accelerating the expansion of the Universe. These supernovae also play an important role in the chemical evolution of the Universe, fusing carbon and oxygen atoms into heavier elements such as magnesium, silicon, sulfur, iron, and nickel.

Understanding Type Ia supernovae in more detail will provide answers to many cosmological questions. But one of the most basic questions about the supernovae themselves remains unanswered: How do they explode?

Although the origins of Type Ia supernovae have not been demonstrated conclusively, they are generally believed to originate in binary systems in which a dense, compact star (possibly a white dwarf) accretes mass from a companion star (Figure 1). When the compact star's mass approaches the Chandrasekhar limit (about 1.4 times the mass of the Sun), a thermonuclear explosion takes place, consuming the entire star and creating a brilliant flash that traverses the expanse of the Universe. But the triggering mechanism of that explosion, and the details of its evolution, have remained mysteries.

A star can burn in two ways: like a flame, which is called deflagration, or like an explosion, called detonation. Neither deflagration nor detonation by itself can explain everything astronomers see in Type Ia supernovae. So in the past decade, theorists have proposed several "delayed detonation" models, in which a deflagration phase is followed by detonation. These models produce plausible results, but they do not explain why or when the star detonates.

More details on how the explosion might be initiated have emerged from the unprecedented full-star simulations created by one of the 2004 INCITE projects

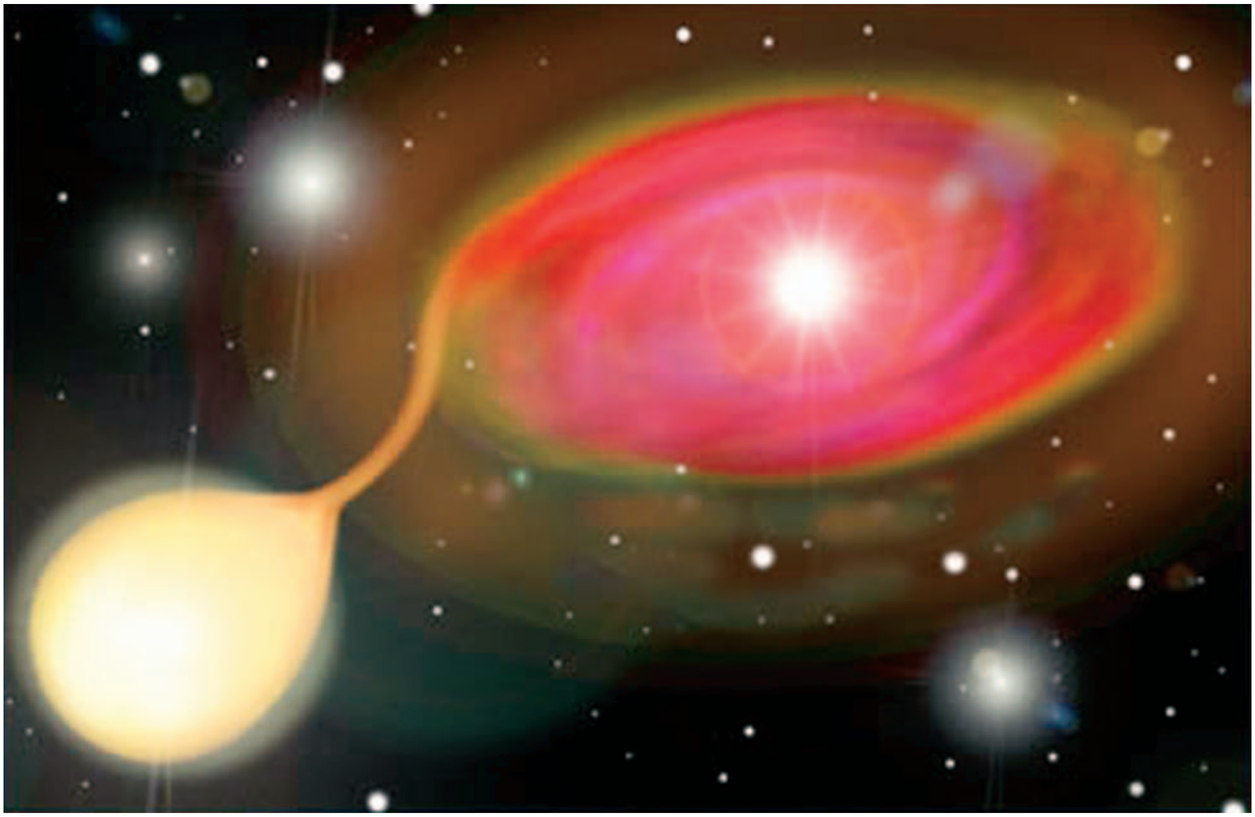

FIGURE 1 Artist's rendition of a white dwarf accreting mass from its companion star.

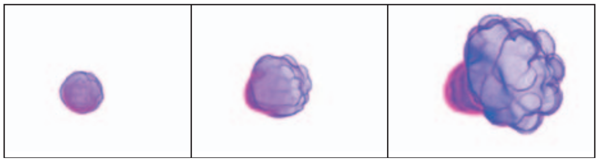

FIGURE 2 A three-billion-degree bubble of thermonuclear flame mushrooms out of a compact star just seconds before a supernova explosion. Pulled by the star's gravity, the flame will sweep around the star's surface and collide with itself, detonating the explosion.

at NERSC, "Thermonuclear Supernovae: Stellar Explosions in Three Dimensions," led by Tomasz Plewa of the Center for Astrophysical Thermonuclear Flashes at the University of Chicago and the Nicolaus Copernicus Astronomical Center in Warsaw.

The simulations that Plewa and his colleague Timur Linde ran on Seaborg — using 3.2 million processor hours over the course of the year — investigated the birth of the thermonuclear flame, an essential part of an unexpected scenario that the researchers call "gravitationally confined detonation" or GCD.[1] In this scenario, the explosion begins with the ignition of deflagration slightly off-center in the core of the star, which results in the formation of a buoyancy-driven bubble of hot material. This bubble rushes outward at transonic speeds and breaks through the stellar surface (Figure 2). Confined by the star's gravity, the burning shock wave races around the surface of the

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[1] T. Plewa, A. C. Calder, and D. Q. Lamb, "Type Ia supernova explosion: Gravitationally confined detonation," Astrophys. J. **612,** L37 (2004).

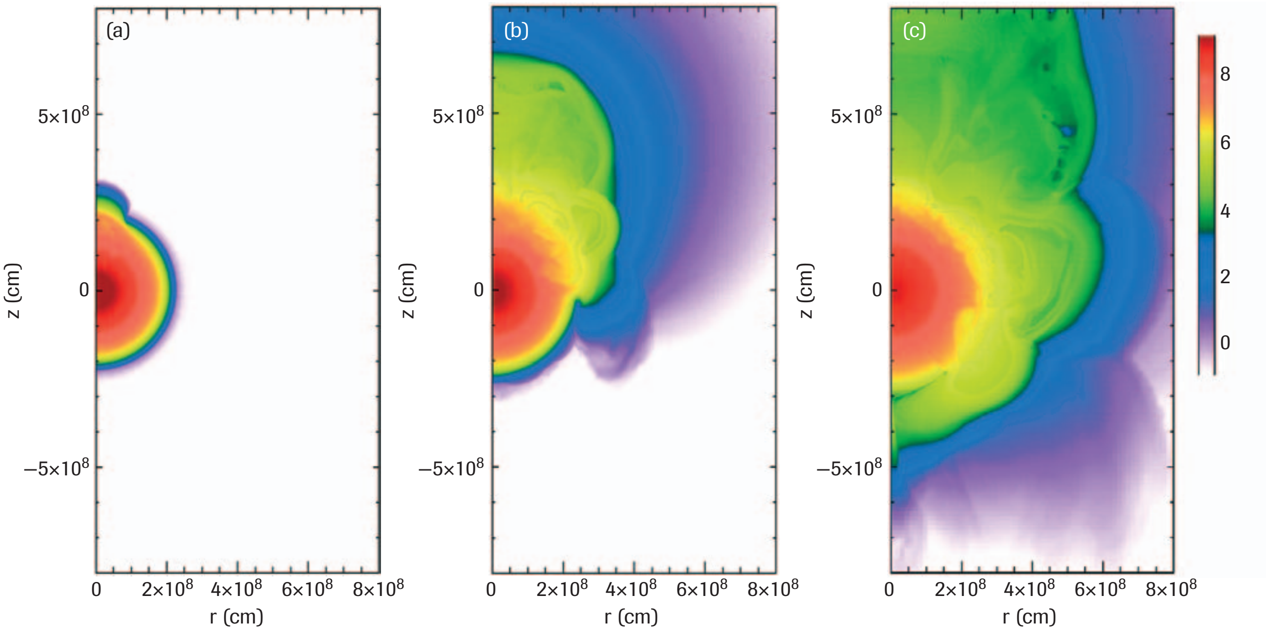

FIGURE 3 This half cross section of the star shows the density evolution of the deflagration phase, from the point of bubble breakout (top of image) at 0.9 seconds after ignition (a), 1.4 seconds (b), and 1.9 seconds (c). Note that most of the material in the outer layers of the star is closely confined as it rushes around the surface and engulfs the star.

star, pushing the fuel-rich outer layers ahead of it like a thermonuclear tsunami (Figure 3).

This flood of nuclear fuel converges at the point opposite the bubble breakout, forming a conical compressed region bounded by the shock (Figure 4). The crashing waves of matter carry enough mass and energy to trigger a detonation just above the stellar surface, resulting in a supernova explosion that incinerates the progenitor star.

Plewa and his team still need to fill in the details of gravitationally confined detonation. For example, although the simulations show the right conditions for detonation in two dimensions (assuming a simplified geometry of the problem), the researchers have not yet been able to simulate the inception of detonation in three dimensions. Such high-resolution simulations will push current supercomputers to the limits of their capabilities.

In addition, the GCD mechanism needs to be verified by comprehensive spectral and polarimetric studies and observations. The first such study was conducted by Daniel Kasen and Plewa, who used a part of the INCITE allocation to conduct Monte Carlo radiative transport calculations. They demonstrated that certain spectral features of some Type Ia supernovae that cannot be explained by other models can be interpreted as natural consequences of the deflagration phase in the GCD model.[2]

One strength of the GCD model is that it can account for a number of typical characteristics observed in thermonuclear supernovae:

[2] D. Kasen and T. Plewa, "Spectral signatures of gravitationally confined thermonuclear supernova explosions," Astrophys. J. Lett. (in press), astro-ph/0501453 (2005).

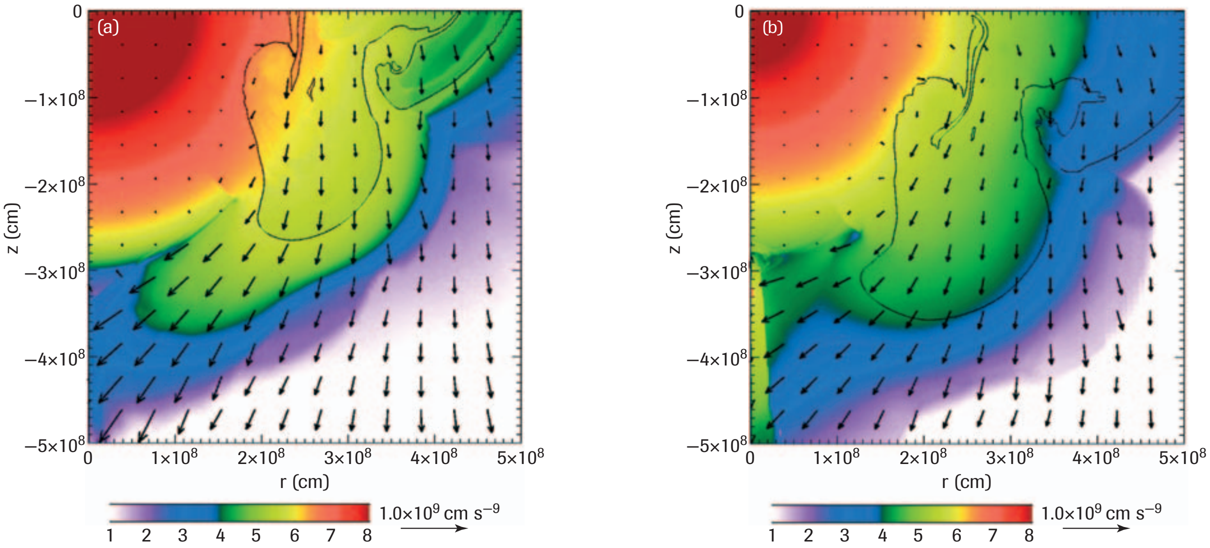

FIGURE 4 This quarter cross section shows the density evolution of the surface flood across the lower portion of the star at 1.85 seconds (a) and 2.005 seconds (b). The conical compressed region is the bright green strip in the lower left of (b); the high-pressure detonation point is the red spot just below -3×10^8.

- The stellar expansion following the deflagration redistributes mass in a way that ensures production of intermediate-mass and iron group elements.
- The ejected matter has a strongly layered structure, with lighter elements on the outside and heavier elements on the inside.
- The ejected matter is slightly asymmetrical, resulting from bubble breakout and detonation occurring on opposite sides of the star.
- This asymmetry, combined with the amount of stellar expansion determined by details of the evolution (principally the energetics of deflagration, timing of detonation, and original structure of the progenitor star), can be expected to create a family of Type Ia supernova explosions that are almost but not exactly alike — just as astronomers have observed.

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