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Advanced Scientific Computing Research

First 3D Simulation of the Spontaneous Detonation of a White Dwarf Star into a Supernova (2007)

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Scientists for years have attempted to blow up a white dwarf star by writing the laws of physics into computer software and then testing it in simulations. At first the detonations would only occur if inserted manually into the programs. But in January 2007, the Flash Center team for the first time naturally detonated a white dwarf in a realistic three-dimensional simulation. The simulation confirmed what the team already suspected from previous tests: that the stars detonate in a supersonic process resembling diesel-engine combustion, which they call gravitationally confined detonation.

University of Chicago scientists demonstrated how to incinerate a white dwarf star in unprecedented detail at the "Paths to Exploding Stars" conference on March 22, 2007, in Santa Barbara, Calif.

White dwarf stars pack one and a half times the mass of the sun into an object the size of Earth. When they burn out, the ensuing explosion produces a type of supernova that astrophysicists believe manufactures most of the iron in the universe. These type Ia supernovas, as they are called, may also help illuminate the mystery of dark energy, an unknown force that dominates the universe.

"That will only be possible if we can gain a much better understanding of the way in which these stars explode," said Don Lamb, Director of the University of Chicago's Center for Astrophysical Thermonuclear Flashes.

Scientists for years have attempted to blow up a white dwarf star by writing the laws of physics into computer software and then testing it in simulations. At first the detonations would only occur if inserted manually into the programs. Then the Flash team naturally detonated white dwarf stars in simplified, two-dimensional tests, but "there were claims made that it wouldn't work in 3D," Lamb said.

But in January 2007, the Flash Center team for the first time naturally detonated a white dwarf in a more realistic three-dimensional simulation. The simulation confirmed what the team already suspected from previous tests: that the stars detonate in a supersonic process resembling diesel-engine combustion, which they call *gravitationally confined detonation.*

Unlike a gasoline engine, in which a spark ignites the fuel, it is compression that triggers ignition in a diesel engine. "You don't want supersonic burning in a car engine, but the triggering is similar," said Dean Townsley, a Research Associate at the Joint Institute for Nuclear Astrophysics at Chicago.

The temperatures attained by a detonating white dwarf star makes the 10,000-degree surface of the sun seem like a cold winter day in Chicago by comparison. "In nuclear explosions, you deal with temperatures on the order of a billion degrees," said Flash Center Research Associate Cal Jordan.

The new 3D white dwarf simulation shows the formation of a flame bubble near the center of the star. The bubble, initially measuring approximately 10 miles in diameter, rises more than 1,200 miles to the surface of the star in one second. In another second, the flame crashes into itself on the opposite end of the star, triggering a detonation. "It seems that the dynamics of the collision is what creates a localized compression region where the detonation will manifest," Townsley said. Figure 1 shows stages of the flame erupting and enveloping the star.

This process plays out in no more than three seconds, but the simulations take considerably longer. The Flash Center team ran its massive simulation on two powerful supercomputers at Lawrence Livermore National Laboratory and at NERSC at Lawrence Berkeley National Laboratory. Just one of the jobs

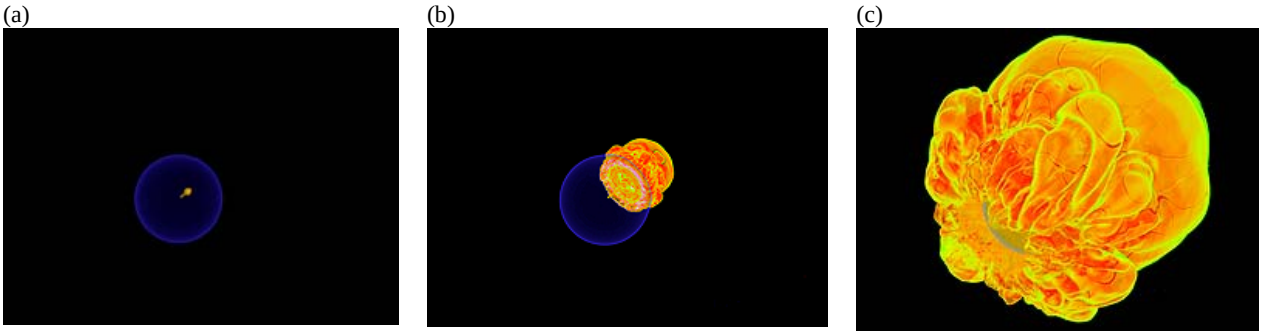

Figure 1. Three phases of the gravitationally confined detonation mechanism. The images show the flame surface (orange) and the star surface (blue) (a) at 0.5 s, soon after the bubble becomes unstable and develops into a mushroom shape, (b) at 1.0 s, as the bubble breaks through the surface of the star, and (c) at 1.7 s, shortly before the hot ash from the bubble collides at the opposite point on the surface of the star. These images are generated from volume-renderings of the flame surface and the density.

ran for 75 hours on 768 computer processors, for a total of 58,000 hours.

"I cannot say enough about the support we received from the high-performance computing teams at Lawrence Livermore and NERSC," Lamb said. "Without their help, we would never have been able to do the simulations."

Katie Antypas, an HPC consultant in NERSC's User Services Group, worked closely with Lamb to run the simulations. "With help and input from many people at NERSC, from setting up accounts, allocating terabytes of disk space, granting file sharing permissions to analyzing output from failed runs, we were able to get the Flash team's 512-processor job up and running on short notice to help them meet a hard deadline," Antypas said.

The simulations were so demanding—the Flash team calls it "extreme computing"—that they monopolized powerful computers of the U.S. Department of Energy during the allocated time. To ensure that these computers are used to their maximum potential, the Flash team stood on alert to rapidly correct any glitches that may arise.

"We had it set up so that if something went wrong, text messages were sent out instantaneously to everyone," said Flash Center Research Scientist Robert Fisher. "It's like being a doctor on call 24/7."

But the scientific payoff for logging these long, stressful hours is potentially huge. Astrophysicists value type Ia supernovas because they all seem to explode with approximately the same intensity. Calibrating these explosions according to their distance reveals how fast the universe has been expanding at various times during its long history.

In the late 1990s, supernova measurements revealed that the expansion of the universe is accelerating. Not knowing what force was working against gravity to cause this expansion, scientists began calling it "dark energy." The Flash Center simulations may help astrophysicists make better calibrations to adjust for the minor variation that they believe occurs from one supernova to the next.

"To make extremely precise statements about the nature of dark energy and cosmological expansion, you have to be able to understand the nature of that variation," Fisher said.

Telescopic images of the two supernovas closest to Earth seem match the Flash team's findings. The images of both supernovas show a sphere with a cap blown off the end.

"In our model, we have a rising bubble that pops out of the top. It's very suggestive," Jordan said.

Publications:

G. C. Jordan IV, R. T. Fisher, D. M. Townsley, A. C. Calder, C. Graziani, S. Asida, D. Q. Lamb, and J. W. Truran, "Three-Dimensional Simulations of the Deflagration Phase of the Gravitationally Confined Detonation Model of Type Ia Supernovae," Astrophysical Journal **681**, 1448–1457 (2008).

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