Computer code gives astrophysicists first full simulation of star's final hours

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The precise conditions inside a white dwarf star in the hours leading up to its explosive end as a Type Ia supernova are one of the mysteries confronting astrophysicists studying these massive stellar explosions. But now, a team of researchers, composed of three applied mathematicians at the U.S. Department of Energy's (DOE) Lawrence Berkeley National Laboratory and two astrophysicists, has created the first full-star simulation of the hours preceding the largest thermonuclear explosions in the universe.

In a paper to be published in the October issue of *Astrophysical Journal*, Ann Almgren, John Bell and Andy Nonaka of Berkeley Lab's Computational Research Division, with Mike Zingale of Stony Brook University and Stan Woosley of University of California, Santa Cruz, describe the first-ever three-dimensional, full-star simulations of convection in a white dwarf leading up to ignition of a Type Ia supernova. The project was funded by the DOE Office of Science.

Type Ia supernovae are of particular interest to astrophysicists as they are all believed to be surprisingly similar to each other, leading to their use as "standard candles" which scientists use to measure the expansion of the universe. Based on observations of these massive stellar explosions—a single supernova is as bright as an entire galaxy—scientists believe our universe is expanding at an accelerating rate. But what if Type Ia supernovae have not always exploded in the same way? What if they aren't standard?

"We're trying to understand something very fundamental, which is how these stars blow up, but it has implications for the fate of the universe," Almgren said.

The problem is that astrophysicists still don't know exactly how a star of this type explodes. Over the years, several simulations have tried to answer the problem, but the traditional methods and available supercomputing power haven't been up to the task.

"Few have tackled this problem before because it was considered intractable," said Almgren. "We needed to simulate the conditions for hours, not just a few seconds. We are now doing calculations that weren't possible before."

For the past three years, Almgren, Bell and Nonaka, along with their collaborators, have been developing a simulation code known as MAESTRO. The code simulates the flow of mass and heat throughout the star over time, and requires supercomputers to model the entire star. It's unique in that it is intended for processes that occur at speeds much lower than the speed of sound, which allows the simulation to produce detailed results using much less supercomputing time than traditional codes. What makes MAESTRO's approach different from the traditional methods is that the sound waves have been stripped out, which allows the code to run much more efficiently.

The team ran their simulations on Jaguar, a Cray XT4 supercomputer at the Oak Ridge Leadership Computing Facility in Tennessee, using an allocation under DOE's Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program.

"The INCITE allocation on Jaguar was crucial in enabling the successful runs leading to these groundbreaking results," said Woosley, leader of the SciDAC supernova project, which has fostered successful collaborations like this one between applied mathematicians and astrophysicists. "And the continuing support of the Department of Energy Office of Science is critical to advancing our research."

The simulation provided a valuable glimpse into the end of a process that started several billion years ago. A Type Ia supernova begins as a white dwarf, the compact remnant of a low-mass star that never got hot enough to fuse its carbon and oxygen. But if another star is near enough, the white dwarf may start taking on mass ("accreting") from its neighbor until it reaches a critical limit, known as the Chandrasekhar mass. Eventually, enough heat and pressure build up and the star begins to simmer, a process that lasts several centuries. During this simmering phase, fluid near the center of the star becomes hotter and more buoyant, and the buoyancy-driven convection "floats" the heat away from the center. During the final few hours, the convection can't move the heat away from the center fast enough, and the star gets hotter, faster. The fluid flow becomes stronger and more turbulent, but even so, at some point or points in the star, the temperature finally reaches about 1,000,000,000 degrees Kelvin (about 1.8 million degrees F), and ignites. A burning front then moves through the star, slowly at first, but gaining speed as it goes. From ignition to explosion is only a matter of seconds.

The team's simulations show that at the early stages, the motion of the fluid appears as random swirls. But as the heating in the center of the star increases, the convective flow clearly moves into the star's core on one side and out the other, a pattern known as a dipole. But the flow also becomes increasingly turbulent, with the orientation of the dipole bouncing around inside the star. While others have also seen this dipole pattern, the simulations using MAESTRO are the first to have captured the full star in three dimensions.

This, according to the paper written by the team, could be a critical piece in our understanding of how the final explosion happens. "As calculations have become more sophisticated, it has only become more clear that the outcome of the explosion is extremely sensitive to exactly how the burning fronts are initiated."

"As seen from the wide range of explosion outcomes in the literature, realistic initial conditions are a critical part of SNe Ia modeling. Only simulations of this convective phase can yield the number, size, and distribution of the initial hot spots that seed the flame," the team wrote in their paper. "Additionally, the initial turbulent velocities in the star are at least as large as the flame speed, so accurately representing this initial flow may be an important component to explosion models."

Almgren and Nonaka caution against reading too much into results from a single calculation. While the work described in this paper—their fourth in the Astrophysical Journal about MAESTRO—is an important step towards understanding this problem, more work is needed to be confident in the results. "We need to explore the effects of rotation, of resolution, and of different initial compositions of the star," says Zingale. "But with MAESTRO now up and running on today's fastest supercomputers, we are well on our way."

More information: For more information about MAESTRO, go to: ccse.lbl.gov/Research/MAESTRO/

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