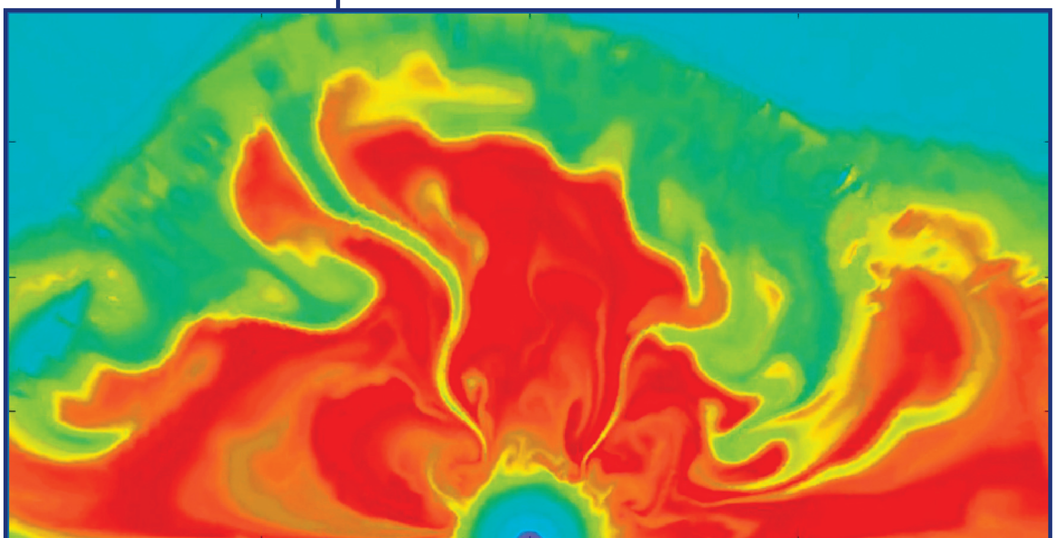
Astrophysicists Close in on Exploding Stars

A research group led by Anthony Mezzacappa of Oak Ridge National Laboratory (ORNL) is using the National Center for Computational Sciences' (NCCS's) Cray XT4 Jaguar supercomputer to solve one of the universe's enduring mysteries.



This image shows entropy in the late stages of a core-collapse supernova as simulated on the NCCS Jaguar supercomputer. The red, high-entropy plumes push the shock outward. The nascent neutron star, which is all that will be left after the supernova, is shown at bottom center in blue. This simulation was of a star 11 times the mass of the sun.

The group is homing in on details of the core-collapse supernova, the explosion of a star at least 10 times as massive as the sun. In doing so, it is helping to explain an indispensable source of elements in the universe and in our own world.

The death of a massive star is determined by the details of its evolution. Over millions of years, the star burns through its nuclear fuel, fusing atoms to create increasingly heavy elements. These elements form into layers—from hydrogen at the surface through helium, carbon, oxygen, silicon, and iron at the core. The process hits a roadblock at iron, which does not create energy when atoms fuse. Eventually, the iron core becomes so heavy that it collapses under its own weight and becomes a mass of neutrons.

The shock wave created when the core reaches the limit of its collapse eventually blows most of the star out into space, but that shock wave stalls as material from the star rains onto the collapsed core. The key mystery of the core-collapse supernova is how the shock wave gets revived to blow the star apart.

While researchers had assumed that the shock wave is revived while it is still within the iron layer, Mezzacappa's research suggests that it is not actually reinvigorated until the infalling oxygen layer reaches it.

"What we have discovered is that at late enough times, the infalling matter will move the shock into the oxygen layer, and that's where the shock wave revives," Mezzacappa explained.

This explanation would add two elements to help explain how the shock wave revives. The first is that the oxygen layer is less dense and falling more slowly than the layers preceding it, meaning the shock wave has less work to do as it pushes toward the surface. The second is that silicon and oxygen falling behind the shock wave undergo nuclear fusion, and the energy they create pushes the shock wave from behind.

The process happens in a fraction of a second, which is auspicious for researchers simulating a process that ranges in scale from the size of the earth's orbit around the sun to the interaction of subatomic particles. Mezzacappa's team, which includes Stephen Bruenn of Florida Atlantic University, John Blondin of North Carolina State University, NCCS scientific liaison Bronson Messer, and Raphael Hix of ORNL, was able to reach its conclusion by simulating the star for about 0.8 second after the bounce, which is about twice the time previously simulated by his team and others.

"If you look at the dynamics up to that point (0.3–0.4 second), not a lot is going on." Mezzacappa explained. "What we're finding is you just have to run it long enough. Once the shock gets into the oxygen layer, things develop and change."

The team has so far used the 119 teraflops Jaguar system to verify this new explanation in two dimensions using a star 11 times the mass of the sun (i.e., 11 solar masses). The team plans to continue its two-dimensional simulations with 15- and 20-solar-mass stars before repeating the process in three dimensions.

Mezzacappa stressed that the results are preliminary. Nevertheless, he believes they will be important.

"The story that's unfolding is new and exciting," he said. "We don't expect this story to go away in 3-D."

Mezzacappa noted that this research would be impossible without modern supercomputers. Jaguar is the world's most powerful system for open scientific research, and yet the team's simulations took the equivalent of two solid weeks.

"The first issue is, can you run these simulations?" he said. "There are people who don't have these resources, where it would take months or years to run."

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