Thermonuclear flames: Astrophysicists use supercomputer to explore exotic stellar phenomena

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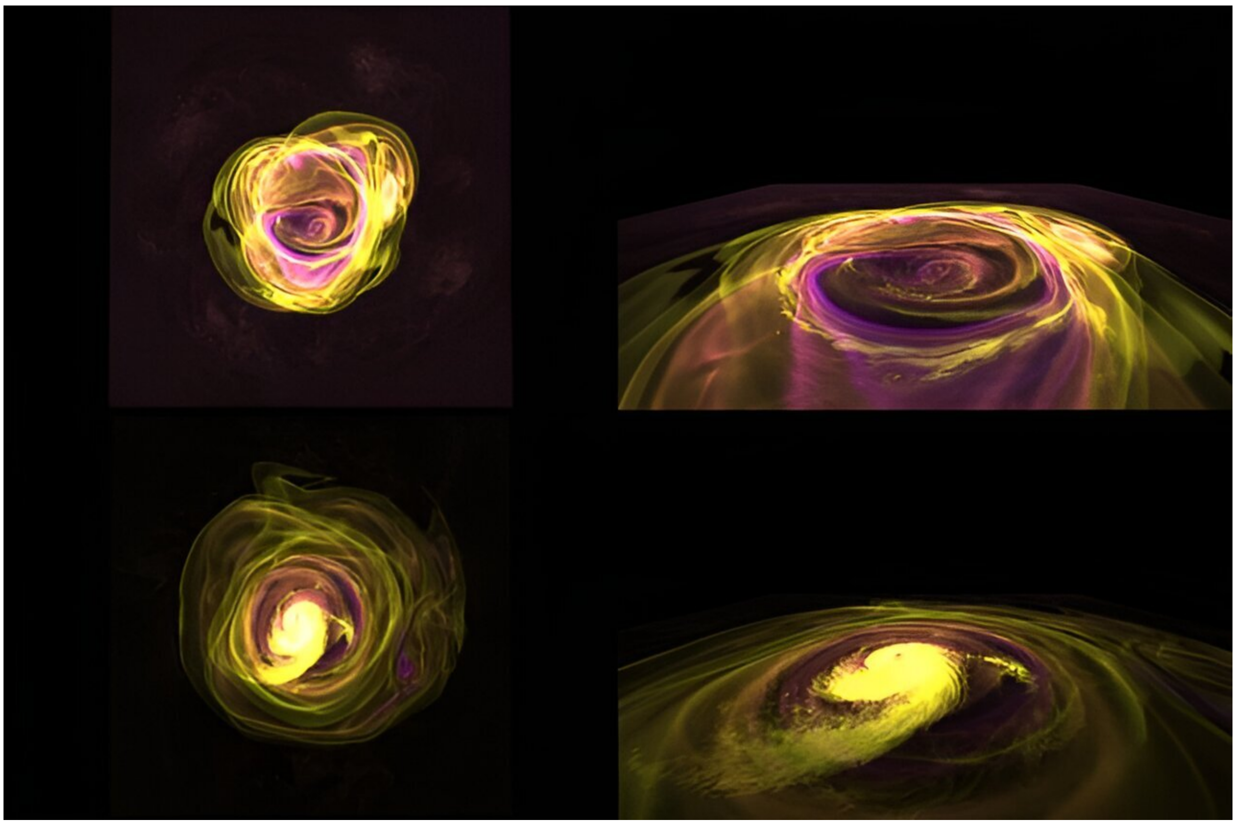

Astrophysicists at the State University of New York, Stony Brook, and University of California, Berkeley created 3D simulations of X-ray bursts on the surfaces of neutron stars. Two views of these X-ray bursts are shown: the left column is viewed from above while the right column shows it from a shallow angle above the surface. The panels (from top to bottom) show the X-ray burst structure at 10, 20 and 40 milliseconds of simulation time. Credit: Michael

Zingale, Department of Physics and Astronomy at SUNY Stony Brook

Understanding how a thermonuclear flame spreads across the surface of a neutron star—and what that spreading can tell us about the relationship between the neutron star's mass and its radius—can also reveal a lot about the star's composition.

Neutron stars—the compact remnants of supernova explosions—are found throughout the universe. Because most stars are in binary systems, it is possible for a neutron star to have a stellar companion. X-ray bursts occur when matter accumulates on the surface of the neutron star from its companion and is compressed by the intense gravity of the neutron star, resulting in a thermonuclear explosion.

Astrophysicists at the State University of New York, Stony Brook, and University of California, Berkeley, used the Oak Ridge Leadership Computing Facility's Summit supercomputer to compare models of X-ray bursts in 2D and 3D. The OLCF is a Department of Energy Office of Science user facility located at DOE's Oak Ridge National Laboratory.

Summit's high-performance computing power, accelerated by its graphics processing units, or GPUs, was a critical factor in the team's ability to perform the 3D simulations. All the computational work was offloaded to the GPUs. This enabled the team to run the simulations more than an order of magnitude faster using all the GPUs on a Summit compute node compared to using all of the central processing unit, or CPU, cores on the node. (Summit has 4,608 nodes, each of which contains two IBM POWER9 CPUs and six NVIDIA Volta GPUs.)

"We can see these events happen in finer detail with a simulation. One of the things we want to do is understand the properties of the neutron star because we want to understand how matter behaves at the extreme densities you would find in a neutron star," said Michael Zingale, who led the project and is a professor in the Physics and Astronomy department at SUNY Stony Brook.

By comparing computer models of the thermonuclear flames with observed X-ray burst radiation, researchers can put constraints on the size of the source to calculate the neutron star's radius.

Neutron stars have around 1.4 to 2 times the mass of the sun despite averaging only 12 miles in diameter. Mass and radii are important factors in understanding neutron stars' interiors based on how matter behaves under extreme conditions. This behavior is determined by the star's "equation of state," which is a description of how the pressure and internal energy in a neutron star respond to changes in its density, temperature and composition.

The study generated a 3D simulation based on insights from a previous 2D simulation that the team had performed to model an X-ray burst flame moving across the neutron star's surface. The 2D study centered on the flame's propagation under different conditions such as surface temperature and rotation rate. The 2D simulation indicated that different physical conditions led to different flame spread rates.

Extending those results, the 3D simulation used the Castro code and its underlying exascale AMReX library on Summit. The AMReX library was developed by the Exascale Computing Project to help science applications run on DOE's exascale systems, including the OLCF's HPE Cray EX supercomputer, Frontier. The simulation results were published in *The Astrophysical Journal*.

"The big goal is always to connect the simulations of these events to what we've observed," Zingale said. "We're aiming to understand what the underlying star looks like, and exploring what these models can do across dimensions is vital."

The team's 3D simulation focused on the flame's early evolution and used a neutron star crust temperature several million times hotter than the sun, with a rotation rate of 1,000 hertz. The 3D flame does not stay perfectly circular as it propagates around the neutron star, so the team used the mass of the ash material produced by the flame to determine how rapidly the burning occurred compared with the burning of the 2D flame.

Although the burning was slightly faster in the 2D model, the growth trends in both simulations were similar. The agreement between the models indicated that 2D simulation remains a good tool for modeling the flame spreading on the neutron star's surface.

However, 3D simulations will be required to capture more complex interactions, such as the turbulence that the flame will encounter as it propagates, created by the star's convective burning in the accreted layer of matter. Turbulence is fundamentally different in 2D and 3D.

In addition, the team can apply the "savings" they realize from being able to follow much of the evolution in 2D by increasing the physical fidelity of the nuclear burning and expanding the region of the star they simulate, adding even more realism.

Other facilities are used to study these astrophysical systems but are tackling other parts of the problem. The Facility for Rare Isotope Beams, or FRIB, at Michigan State University has launched the world's most powerful heavy ion accelerator. FRIB will explore the proton-rich nuclei that are created by X-ray bursts, and Zingale's team will be able to use those data to improve its own simulations.

"We're close to modeling the flame spread across the whole star from pole to pole. It's exciting," Zingale said.

More information: Michael Zingale et al, Comparing Early Evolution of Flames in X-Ray Bursts in Two and Three Dimensions, *The Astrophysical Journal* (2023). DOI: 10.3847/1538-4357/ace04e

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