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Supercomputer simulation provides missing link between turbulence, hypernovae and gamma-ray bursts

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Berkeley — A supercomputer simulation of a mere 10 milliseconds in the collapse of a massive star into a neutron star proves that these catastrophic events, often called hypernovae, can generate the enormous magnetic fields needed to explode the star and fire off bursts of gamma rays visible halfway across the universe.

The results of the simulation, published online Nov. 30 in advance of publication in the journal *Nature*, demonstrate that as a rotating star collapses, the star and its attached magnetic field spin faster and faster, forming a dynamo that revs the magnetic field to a million billion times the magnetic field of Earth.

A field this strong is sufficient to focus and accelerate gas along the rotation axis of the star, creating two jets that ultimately can produce oppositely directed blasts of highly energetic gamma rays.

The first electrical generators were dynamos, generating current as wires rotated through a magnetic field. Stellar dynamos generate electrical currents as magnetic fields move through space, while the currents in turn boost the magnetic field, resulting in a feedback loop that produces monster magnetic fields.

“A dynamo is a way of taking the small-scale magnetic structures inside a massive star and converting them into larger and larger magnetic structures needed to produce hypernovae and long gamma-ray bursts,” said Philipp Mösta, a UC Berkeley postdoctoral fellow and first author of the paper. “That kicks off the process.”

“People had believed this process could work out,” he said. “Now we actually show it.”

Key to this success was a computer simulation at finer detail than ever before, though one that required 130,000 computer cores operating in parallel over a span of two weeks on Blue Waters, one of the most powerful supercomputers in the world. It is located at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

Hypernovae produce heavy elements

Astrophysicists like Mösta are trying to improve their models of what stars do when they reach the ends of their lives, hoping to explain strange cosmic phenomena – like gamma-ray bursts and hypernovae that flash 10 times brighter than the average supernova – and understand how some of the very heavy elements found in nature are made.

“Now we have the first prototype model that allows us to ask the question, How are heavy elements made in these powerful supernova explosions?” said Eliot Quataert, a UC Berkeley professor of astronomy who was not involved with the study.

“The breakthrough here is that Philipp’s team starts from a relatively weak magnetic field and shows it building up to be a very strong and large-scale coherent magnetic field of the kind that is usually assumed to be there when people make models of gamma-ray bursts,” Quataert said.

Brightest events in universe

Gamma-ray bursts are so brief and energetic – long bursts last about 100 seconds, with wavelengths far outside the visible or ultraviolet bands – that they were not observed until 1967 by satellites looking for evidence of nuclear bomb tests. Most are billions of light years away in distant galaxies, so the fact we can see them at all means they are among the brightest events in the universe.

Observations over the last 50 years have led astronomers to propose that the bursts are produced during the extremely rare explosions of massive stars – stars 25 times the mass of the sun or larger – but the details of how such a hypernova generates focused beams of gamma rays are still being worked out. These stellar explosions are typically classified as Type Ic broadline supernovae.

‘It is thought that jets held together by ultra-strong magnetic fields are required to power these explosions, Mösta said, but one of the missing links was how a star with a normal magnetic field, like that of the sun, could amplify it a quadrillion (10^{15}) times. One possibility is that energy stored in the rotation of the collapsed star could be transformed into magnetic energy. These strong magnetic fields may also be critical to help accelerate charged particles to a speed and energy able to generate a gamma ray.

“We expect only a small fraction of stars to be spinning rapidly enough before collapse to explain pulsar spin periods of milliseconds,” said co-author Christian Ott, a professor of theoretical astrophysics at the California Institute of Technology. “But if a star is spinning this fast, then there is a lot of energy in the rotation. The problem has been how to extract that and dump it into the explosion.”

Creating ultra-strong magnetic fields

A core-collapse supernova occurs when hydrogen fusion in the core – which powers stars during most of their lifetime – stops after all the hydrogen is used up and the star begins to fuse helium and then carbon and oxygen. When the star finally fuses all these elements into iron, fusion stops entirely and the pressure at the core of the star can no longer support the gravitational weight of the surrounding material.

Within one second, the inner star out to a radius of about 1,500 kilometers collapses to a neutron star about 10 to 15 kilometers across, containing the mass of about 1.4 suns. This creates an outward-moving shock wave that plows into the outer layers of the star. As the inner star collapses to a neutron star, it increases its spin just as pirouetting ice skaters spin faster as they draw in their arms.

Theorists have attempted to explain how massive, rotating stars generate strong magnetic fields after they have collapsed by a process called magnetorotational instability: Layers of the star rotate at different speeds, creating turbulence that molds the embedded magnetic fields into kilometer-wide magnetic flux tubes much like magnetic flares on the sun. But can this process generate the much larger-scale magnetic fields needed to drive an explosion?

“What we have done are the first global extremely high-resolution simulations of this that actually show that you create this large global field from a purely turbulent one,” Mösta said. “The simulations also demonstrate a mechanism to form magnetars, neutron stars with an extremely strong magnetic field, which may be driving a particular class of very bright supernovae.”

Quataert compares the process to how small-scale turbulence in Earth’s atmosphere coalesces into large-scale hurricanes.

Mösta and his colleagues found that the key to this process in a rapidly rotating neutron star is a shear zone about 15 to 35 kilometers from the star where the different layers are rotating at very different

speeds, causing turbulence large enough to create a dynamo.

Mösta is working on simulations that encompass more than 10 milliseconds of the star's evolution after collapse, or "post-bounce," to better understand how the collapsing matter and outflowing material interact with the swirling magnetic fields.

Other co-authors with Mösta and Ott are David Radice and Luke Roberts of Caltech in Pasadena, Erik Schnetter of the Perimeter Institute and the University of Guelph in Ontario, Canada, and Roland Haas of the Max Planck Institute for Gravitational Physics in Potsdam-Golm, Germany.

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RELATED INFORMATION

- [A large scale dynamo and magnetoturbulence in rapidly rotating core-collapse supernovae](#) (*Nature*)
- [Philipp Mösta's website](#)

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