Exploring the magnetic personalities of stars

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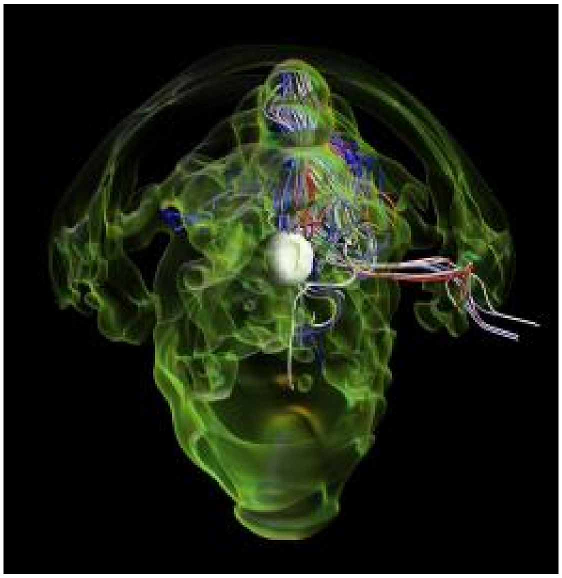

Volume rendering of fluid flows below the supernova shock wave during the operation of the SASI. The fluid velocity streamlines trace out complex flow patterns in the simulation.

(PhysOrg.com) -- Massive stars are inherently violent creatures-they burn, they churn, they turn, all the while creating and held hostage by constantly changing magnetic fields of almost unfathomable strength.

And, eventually, they explode, littering the universe with the elements of life as we know it: hydrogen, oxygen, carbon, etc. Everything including ourselves is the result of some star's violent demise. "We are stardust, we are golden, we are billion-year-old carbon" goes the song "Woodstock" by Crosby, Stills, Nash and Young. Even the hippies know it. And no stars do it better than those that will one day become core-collapse supernovas, or stars greater than eight solar masses. But the evolution and nature of these elemental fountains is still a mystery, one of the greatest unsolved problems in astrophysics. But perhaps not unsolved for long. A team led by Oak Ridge National Laboratory's Tony Mezzacappa is getting closer to explaining the origins of CCSN explosions with the help of Jaguar, a Cray XT5 supercomputer located at the Oak Ridge Leadership Computing Facility that likewise calls ORNL home.

Essentially, said Eirik Endeve, lead author of the team's latest paper, researchers want to know how these magnetic fields are created and how they impact the explosions of these massive stars. A recent suite of simulations allowed the team to address some of the most fundamental questions surrounding the magnetic fields of CCSNs. Its findings were published in *The* Astrophysical Journal. In untangling the mystery surrounding these stars' powerful magnetic fields, researchers could ultimately explain a great deal as to why these stellar giants evolve into elemental firecrackers.

In an effort to locate the source of the magnetic fields, the team simulated a supernova progenitor, or a star in its pre-supernova phase, using tens of millions of hours on Jaguar, the nation's fastest supercomputer. The process revealed that we still have much to learn when it comes to how these stellar marvels operate.

Rotation schmotation

Collapsed supernova remnants are commonly known as pulsars, and when it comes to magnetic fields, pulsars are the top players in the stellar community. These highly magnetized, rapidly rotating neutron stars get their name from the seemingly pulsing beam of light they emit, similar to the varying brightness produced by lighthouses as they rotate. This rotation is thought to be a big factor in determining the strength of a pulsar's magnetic field-the faster a star rotates the stronger its magnetic fields.

Supernova progenitors tend to be slower-rotating stars. Nevertheless, the simulations of these progenitors revealed a robust magnetic-field-generation mechanism, contradicting accepted theory that rotation could be a primary driver.

Interestingly, this finding builds on the team's previous work, which together with the latest simulations reveals that the culprit behind pulsar spins is likewise responsible for their magnetic fields. The earlier simulations, the results of which were published in "Pulsar spins from an instability in the accretion shock of supernovae" in the January 2007 edition of Nature, demonstrated that a phenomenon known as the spiral mode occurs when the shock wave expanding from a supernova's core stalls in a phase known as the standing accretion shock instability. As the expanding shockwave driving the supernova explosion comes to a halt, matter outside the shockwave boundary enters the interior, creating vortices that not only start the star spinning, but also yank and stretch its magnetic fields as well.

This new revelation means two things to astronomers: first, that any rotation that serves as a key driver behind a supernova's magnetism is created via the spiral mode, and second, that not only can the spiral mode drive rotation, but it can also determine the strength of a pulsar's magnetic fields.

Another major finding of the team's simulations is that shear flow from the SASI, or when counter-rotating layers of the star rub against one another during the SASI event, is highly susceptible to turbulence, which can also stretch and strengthen the progenitor's magnetic fields, similar to the expansion of a spring.

These two findings taken together show that CCSN magnetic fields can be efficiently generated by a somewhat unexpected source: shear flowinduced turbulence roiling the inner core of the star. "We found that starting with a magnetic field similar to what we think is in a supernova progenitor, this turbulent mechanism is capable of magnifying the magnetic field to pulsar strengths," Endeve said.

The GenASiS of magnetic fields

The team used the General Astrophysical Simulation System to study the evolution of the progenitor's magnetic fields. GenASiS, under development by Christian Cardall, Reuben Budiardia, Endeve and Mezzacappa at ORNL and Pedro Marronetti at Florida Atlantic University, features a novel approach to neutrino transport and gravity and makes fewer approximations than its earlier counterpart, which assumed CCSNs were perfectly spherical.

The simulations essentially solved a series of magnetohydrodynamic equations, or equations that describe the properties of electrically conductive fluids. After setting the initial conditions, the team ran several models at low and high resolutions, with the highest-resolution models taking more than a month to complete. Initially, Endeve said, they were run at lower resolutions, but very little significant activity occurred. However, as they ramped up the resolution, things got interesting.

The model starts at 4,000 cores, Endeve said, but as the star becomes more chaotic with turbulence and other factors, the simulations are scaled up to 64,000 cores, giving the team a more realistic picture of the magnetic activity in a CCSN. He added that the fact that the time to solution for these hugely varying job sizes is the same due to Jaguar's queue scheduling policy is a "great advantage." "The facilities here are excellent," said Endeve, adding that the center's high-performance storage system is very important to the team's research, as one model produces hundreds of terabytes of data. "We have also received a lot of

help from the visualization team, especially Ross Toedte, and the group's liaison to the OLCF, Bronson Messer."
The team will next incorporate sophisticated neutrino transport and relativistic gravity, which will give it an even more realistic picture of CCSNs. However, to make such a powerful code economical, said Endeve, it will need to employ an adaptive mesh. And it will no doubt require Jaguar's computing power.

This latest discovery is just one more step toward unraveling the mysteries of CCSNs. As GenASiS continues to evolve, the team will be able to investigate these important stellar cataclysms at unprecedented levels, bringing science one step closer to a fundamental understanding of our universe.

Provided by Oak Ridge National Laboratory

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