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Quantum Matter Shapes the Strongest Magnetic Fields in the Universe

New models show how superconductivity can launch giant magnetic waves in neutron stars, and how those waves can break the solid crust.

CHICAGO— Neutron stars are the super-dense and ultra-magnetized remnants of massive stars following supernova and gravitational collapse. They squeeze more mass than the Sun into a sphere about the size of a city. Their magnetic fields reach up to a thousand trillion times Earth's. Inside them, matter is compressed beyond the density of an atomic nucleus, forming exotic plasmas (gases of charged particles) found nowhere else in the universe.

At the 68th Annual Meeting of the APS Division of Plasma Physics, Ashley Bransgrove of the Princeton Center for Theoretical Science will present new theory and simulations showing how these plasmas drive powerful magnetic waves and break the star's dense, solid crust. This may help explain the activity of special types of neutron stars called pulsars and magnetars. Pulsars are neutron stars that emit electromagnetic radiation at extremely regular intervals, while magnetars are neutron stars with exceptionally strong magnetic fields that emit high-energy radiation in the form of X-ray and gamma-ray flares and bursts.

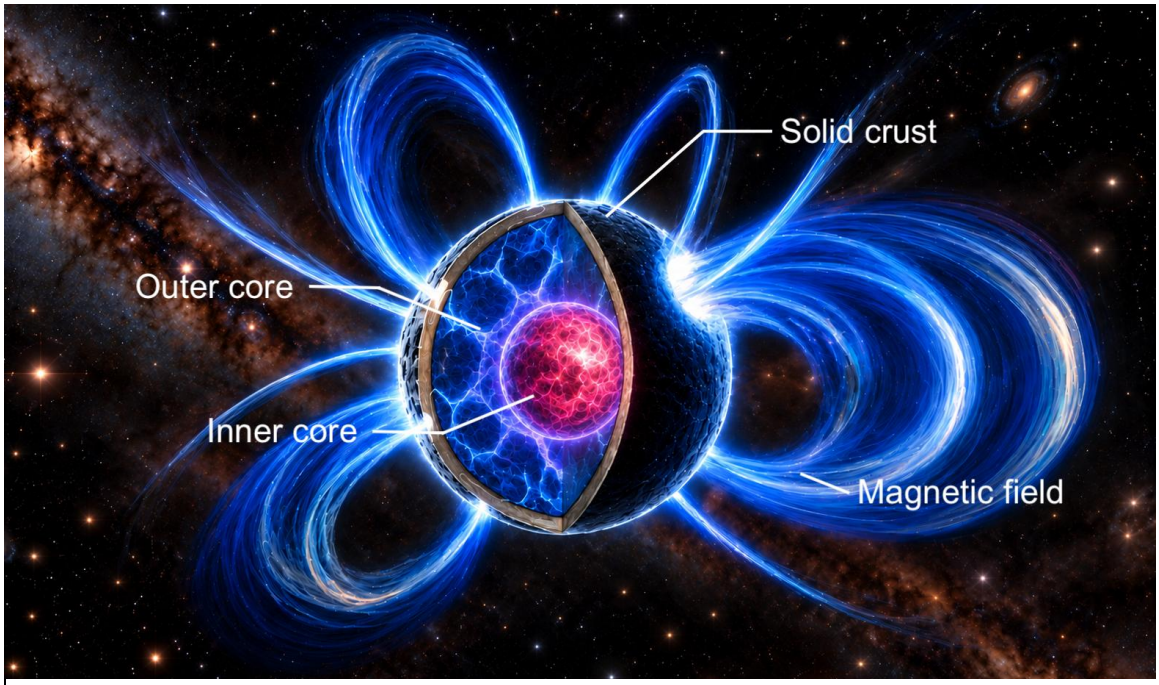


Figure 1: Structure of a neutron star. Credit: A. Bransgrove.

From the surface inward, a neutron star contains a sequence of superdense plasmas, each stranger than the last (Figure 1). The outer layer is a solid crust — a frozen plasma in which atomic nuclei are locked into a crystal lattice (the strongest known material in the universe) while electrons flow freely through it. In the core, protons and electrons coexist with a frictionless neutron superfluid, and the protons become superconducting, confining the magnetic field into microscopic magnetic tubes. The deepest regions may contain quark matter, in which neutrons and protons dissolve into their constituent sub-atomic particles called quarks. Each layer responds differently to magnetic fields, so modeling the star requires plasma physics, nuclear physics, and solid mechanics.

"Neutron stars contain the most extreme plasmas in nature," says Bransgrove. "To understand what the magnetic field is doing, we have to follow it layer by layer, from the core to the surface."

Shortly after a pulsar's birth, the protons in its core undergo a quantum phase transition and become superconducting. Bransgrove and collaborators showed that this transition enhances the stress of the core magnetic field a thousandfold and launches giant magnetic waves into the crust (Figure 2). These magnetic waves are carried by the flow of electrons through the frozen lattice and are close relatives of a plasma wave studied in the magnetic field surrounding Earth, called the magnetosphere, and in laboratory plasmas. Over hundreds of thousands of years, they travel toward the surface, where they reshape the magnetic field outside the star, altering how the pulsar spins down, and the waves may even break the crust.

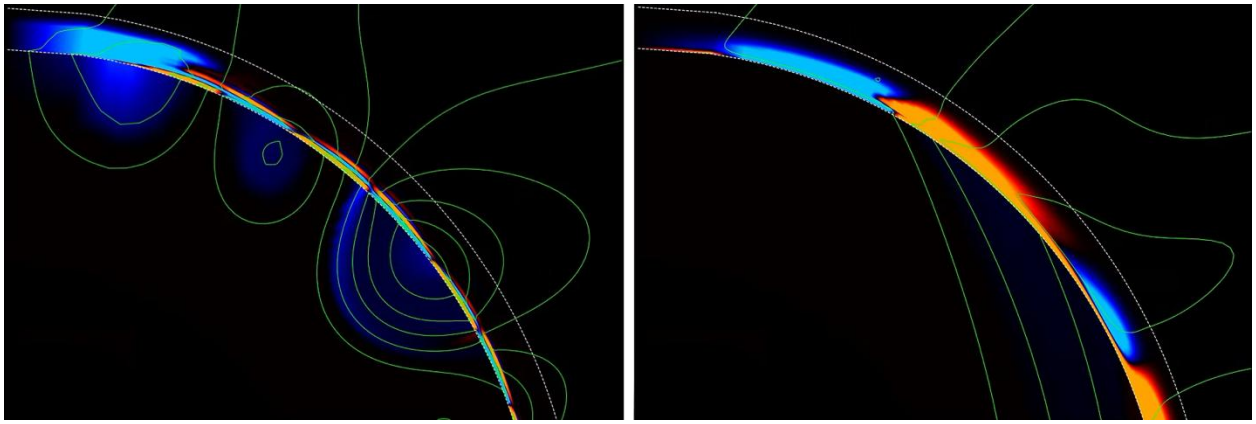


Figure 2: Magnetic field evolution in a young neutron star, 10,000 years (left) and 200,000 years (right) after its protons become superconducting. Green curves are magnetic field lines; color shows the out-of-plane magnetic field. Credit: A. Bransgrove.

"The superconducting transition acts like a switch deep inside the star," Bransgrove says. "It sends enormous magnetic stresses up into the crust, and the crust has to respond."

New simulations led by Matt Caplan of Illinois State University, with Bransgrove and collaborators, show how the crust responds. The frozen plasma can fail in two ways: it can break suddenly, releasing its stored elastic energy like an earthquake (Figure 3), or

flow plastically, slowly deforming like metal under load. Either way, the neutron star's magnetosphere feels it. A sudden break shakes the field lines anchored in the crust and launches waves into the magnetosphere, while slow plastic flow gradually twists the external field. In magnetars, this may power the observed X-ray bursts and persistent emission; in pulsars, it may disrupt the usually steady radio pulses.

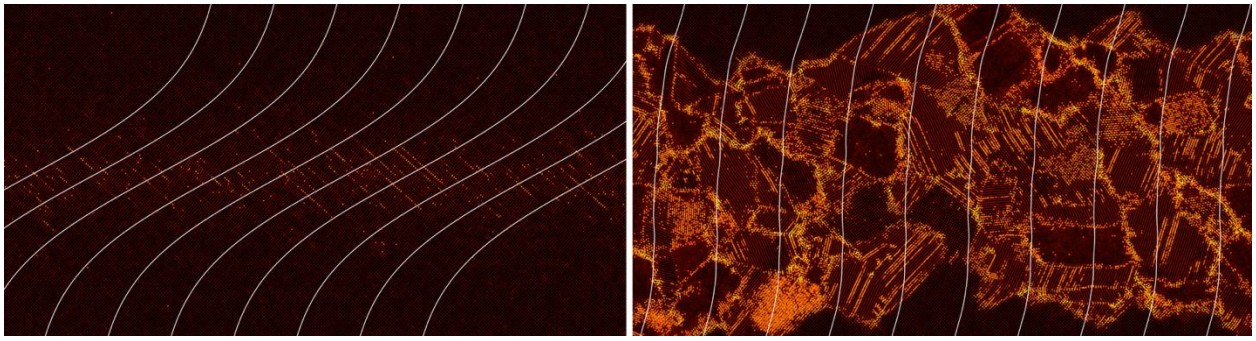


Figure 3: Simulation of a neutron star's crust breaking under magnetic stress. Before the break (left), the magnetic field lines (white) are sharply bent; afterward (right), the crystal has shattered into grains, and the field lines have straightened. Color marks where the lattice is disrupted. Credit: N. Smith.

In magnetars, the field also evolves in the core because charged plasma drifts relative to the neutron fluid — a process called ambipolar diffusion that also shapes magnetic fields in partially ionized gas of star-forming clouds. Related work by Bransgrove and collaborators suggests that this process can trigger magnetic eruptions in young magnetars and may drive giant gamma-ray flares.

These studies are part of a broader effort to model magnetic fields in the extreme matter inside neutron stars. Because the magnetic field links the interior to what astronomers observe, pulsars and magnetars can test dense-matter physics that no laboratory on Earth can reproduce. How magnetic fields behave in superconducting quark matter, possibly present at the center of neutron stars, remains an open frontier.

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Abstract

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Session CTI01: Astrophysical Compact Objects and Relativistic Plasmas
2:00 PM–5:00 PM, Monday, November 2, 2026
Room: Hilton Chicago, International North, Second Floor