

Probing the mysteries of neutron stars with a surprising earthly analog

Enlarge / Spectral analysis indicates that silica is present in this supernova remnant, Cassiopeia A.

NASA/JPL-Caltech/ O. Krause (Steward Observatory)

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Ever since neutron stars were discovered, researchers have been using their unusual properties to probe our universe. The superdense remnants of stellar explosions, neutron stars pack a mass greater than the Sun's into a ball about as wide as San Francisco. A single cup of this star matter would weigh about as much as Mount Everest.

These odd celestial bodies could alert us to distant disturbances in the fabric of spacetime, teach us about the formation of elements, and unlock the secrets of how gravity and particle physics work in some of the most extreme conditions in the universe.

"They're at the center of a lot of open questions in astronomy and astrophysics," says astrophysicist Vanessa Graber of the Institute of Space Sciences in Barcelona.

But to accurately interpret some of the neutron stars' signals, researchers must first understand what goes on inside them. They have their hunches, but experimenting directly on a neutron star is out of the question. So scientists need

another way to test their theories. The behavior of matter in such a superdense object is so complicated that even computer simulations aren't up to the task. But researchers think they may have found a solution: an earthly analog.

Though young neutron stars can have temperatures in the millions of degrees in their interior, by one important energetic measure neutrons are considered "cold." Physicists think that is a characteristic they can exploit to study the inner workings of neutron stars. Instead of looking to the sky, researchers are peering into clouds of ultracold atoms created in laboratories here on Earth. And that might help them finally answer some longstanding questions about these enigmatic objects.

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Space oddities

The existence of neutron stars was first proposed in 1934, two years after the discovery of the neutron itself, when astronomers Walter Baade and Fritz Zwicky wondered if a celestial body made entirely of neutrons might remain after a supernova explosion. Though they didn't get all the details right, their general idea is now widely accepted.

Stars power themselves by fusing the nuclei of lighter atoms into those of heavier atoms. But when stars run out of those lighter atoms, nuclear fusion stops and there is no longer an outward pressure to fight against the inward force of gravity. The core collapses and the star's outer layer races inward. When this layer hits the dense core, it bounces off and explodes outward, producing a supernova. The dense core that remains afterward is a neutron star.

Enlarge / The remains of a supernova witnessed in the year 1054, the Crab Nebula contains a rapidly spinning neutron star known as a pulsar.

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It wasn't until the 1960s that Zwicky and Baade's hypothetical neutron stars were finally detected. Radio astronomer Jocelyn Bell Burnell noticed a strange, regularly pulsed radio wave signal from space while working as a graduate student at the University of Cambridge. She was detecting something that had never been seen before: a special kind of neutron star called a pulsar, which flashes beams of radiation at regular intervals as it spins, like a lighthouse. (Her adviser, along with the director of the observatory—but not Bell Burnell—later received the Nobel Prize for the discovery.)

Since then, thousands of neutron stars have been detected. As some of the densest, highest-pressure objects in the universe, neutron stars might help us learn about what happens to matter at extremely high densities. Understanding their structure and the behavior of the neutron matter composing them is of paramount importance to physicists.

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Scientists already know that the neutrons, protons, and other subatomic particles that compose a neutron star arrange themselves differently depending on where in the star they are. In certain sections, they pack rigidly like water molecules in a block of ice. In others, they flow and swirl like a frictionless fluid. But exactly where the transition happens and how the different phases of matter behave, physicists aren't sure.

A superdense star born of a nuclear fireball seems, on its face, to have very little in common with a dilute cloud of ultracold particles. But they can share at least one useful characteristic: They are both below a threshold known as the Fermi temperature that depends on—and is calculated based on—the matter each system is made of. A system that is well above this temperature will largely behave according to the laws of classical physics; if it is well below, its behavior will be ruled by quantum mechanics. Certain ultracold gases and neutron star material can both be well below their Fermi temperatures and consequently can act in similar ways, says Christopher Pethick, a theoretical physicist at the Niels Bohr Institute in Copenhagen and coauthor of an early overview of neutron stars in the 1975 Annual Review of Nuclear Science.

[embedded content]

Matter that is below its Fermi temperature can obey remarkably universal laws. This universality means that, while we don't have easy access to several-million-degree neutron star matter, we could learn about some of its behavior by experimenting with ultracold gases that can be created and manipulated in laboratory vacuum chambers on Earth, says theoretical astrophysicist James Lattimer of Stony Brook University in New York, author of a summary of the science of nuclear matter in the 2012 Annual Review of Nuclear and Particle Science.

Of particular interest to Lattimer is a theoretical state called a unitary gas. A gas is unitary when each of its particles' sphere of influence becomes infinite, meaning that they would influence each other no matter how far apart they are. This is impossible to have in reality, but ultracold atom clouds can get close—and so can the matter inside of neutron stars. "It's similar to a unitary gas," Lattimer says, "but it's not a perfect unitary gas."

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