Physicists look to a new telescope to understand neutron stars and matter at the extremes

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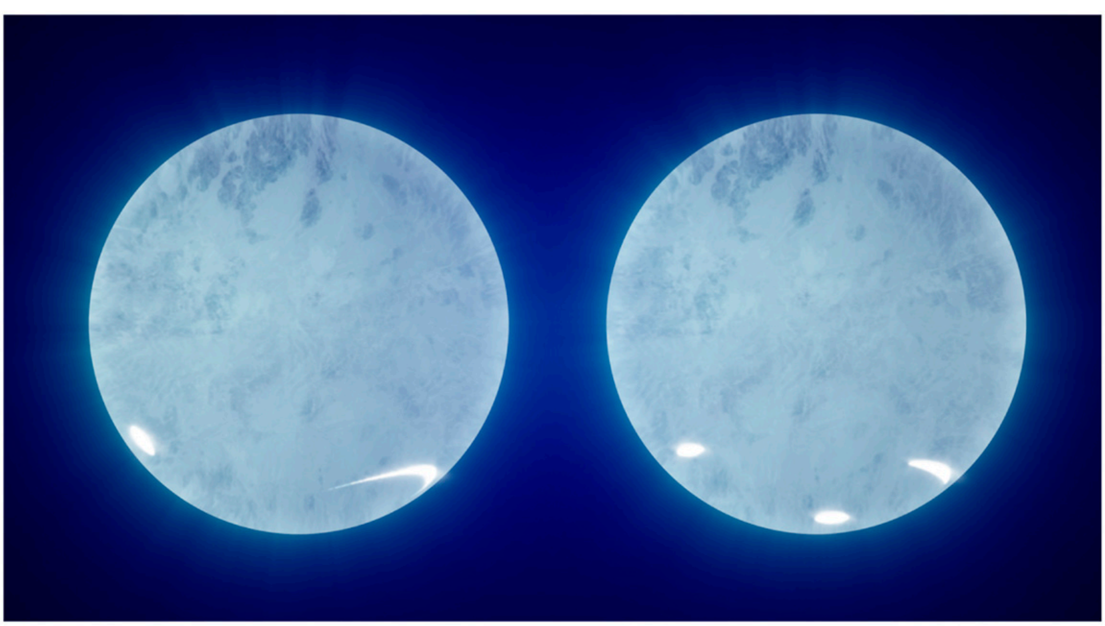
Astronomers ostensibly know plenty about neutron stars: the hot, collapsed remnants of massive stars that have exploded as supernovae. These objects can spin up to hundreds of times a second, generate intense magnetic fields, and send out jets of radiation that sweep the sky like beams from a lighthouse. When two neutron stars collide, the ripples in spacetime can be detected by gravitational wave observatories on Earth. Packing more than the mass of the Sun into a ball about 20–25 kilometers across, neutron stars pack in matter at the highest possible density before collapse. "They really are the last gasp of matter, before the event horizon and the nothingness of the black hole," says physicist Zaven Arzoumanian at the NASA Goddard Space Flight Center in Baltimore, MD.

And yet, what's deep inside a neutron star remains an open question. "Understanding what happens to matter at such high densities has long been a puzzle," says Arzoumanian. Now a small, boxy X-ray telescope mounted on the International Space Station is spilling the inner secrets of these stars. Called the Neutron Star Interior Composition Explorer, or NICER, it can measure the size and mass of neutron stars, revealing their true density.

Arzoumanian presented NICER data at the April 2020 meeting of the American Physical Society, which was held online. The early results are promising, showing that the instrument has the potential to capture ultraprecise measurements of these dead stars, which could tell us how the densest form of matter behaves. NICER's data also revealed a magnetic surprise which upends longstanding theories about magnetic fields and might provide clues about how neutron stars can power interstellar particle accelerators.



The powerful, spinning magnetic fields of pulsars accelerate charged particles that collide with the surface at hotspots, generating the X-rays that stream out into space. Thanks to NASA's Neutron star Interior Composition Explorer, Pulsar J0030+0451, visualized here based on data collected, has the most precise measurements of a pulsar's mass and size. Newly elucidated hotspot shape and location data have challenged conventional views. Image credit: NASA's Goddard Space Flight Center.

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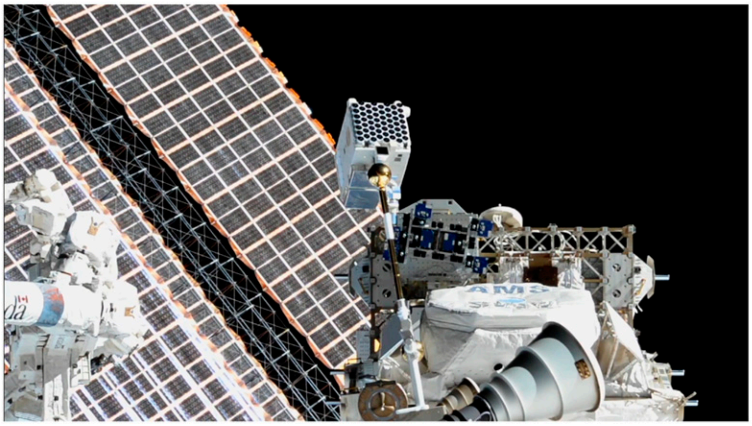

NASA's NICER, seen here in 2018, studies pulsars and other X-ray sources from its perch aboard the International Space Station. Image credit: NASA.

What's in a Star

Neutron stars were first predicted in 1934 by astronomers Walter Baade and Fritz Zwicky in a pair of remarkable articles, published in PNAS, which also introduced the term supernova and groundbreaking ideas about the sources of cosmic rays (1, 2). Baade and Zwicky proposed that in a core-collapse supernova, protons and electrons would smash together to form neutrons, joining the existing neutrons to form a dense, rapidly spinning core. This all remained theoretical until 1967, when astrophysicists including Jocelyn Bell, a postdoctoral researcher at Oxford University in the United Kingdom, found the first pulsar—a neutron star whose lighthouse beam sweeps across Earth.

"The biggest question is, what are neutron stars made of?" says nuclear physicist Chuck Horowitz at Indiana University, in Bloomington. Simulations show that neutron stars probably have a thin iron-rich crust, where atomic nuclei are squeezed close together to form a dense, hard material. In 2018, work by Horowitz and his colleagues suggested that the inner part of this crust may be the strongest stuff in the universe (3).

Beneath the crust, gravity crushes matter into something denser still. The usual assumption is that the main constituent of a neutron star is a fluid of neutrons, but at the very core it could be something much more exotic.

Quark Goo

The key to the heart of a neutron star is understanding what happens to particles under extreme pressure. Protons and neutrons are made of smaller particles called quarks. These are normally held tightly together by particles called gluons, which carry the strong nuclear force. But by colliding heavy ions at high energy in laboratory experiments, researchers have found that at high pressures and temperatures, quarks can be liberated, flowing freely in a quark-gluon plasma. A fleeting quark-gluon plasma created at the European Organization for Nuclear Research's (CERN's; Meyrin, Switzerland) Large Hadron Collider and reported in 2012 set the record for the hottest stuff ever made in a lab, at more than 5 trillion degrees (4).

The same quark goo may lie beneath the hard crust of neutron stars, where the pressure likely overwhelms the strong force holding the hadrons together. "They may be so dense that the neutrons all squeeze together, and the quarks inside are liberated," says Horowitz. Or it may be something else. Theorists have proposed, for example, that the pressure at the heart of a neutron star gives rise to a new type of multi-quark particle, called a hyperon.

To settle the issue, physicists have been trying to predict the dense matter's equations of state, which shows the relationships between pressure, temperature, and density of a material. Equations of state can be used to study phase transitions. An equation of state for water, for example, can be used to describe conditions under which ice becomes liquid or liquid becomes steam.

Water, we understand; neutron stars, not so much. Theorists have proposed various equations of state based on the few measurements of radius and mass that we have so far.

In one recent effort, Aleksi Vuorinen at the University of Helsinki in Finland and his team combined existing equations of state for ordinary nuclear matter with equations derived for neutron stars using QCD, or quantum chromodynamics. QCD is the theory that describes how quarks and gluons interact. However, QCD models typically simulate low-density situations, so Vuorinen's group had to constrain their equations according to what's known about the high-density cores of neutron stars. They generated a list of possible equations of state to fit these constraints, then tested them to see whether they would remain stable under extreme gravity or collapse into black holes. In June 2020, they reported that the majority of equations that made the cut showed the signature of a phase change, hinting at the presence of a quark-gluon plasma (5).

Coming from a different direction, physicists at Goethe University in Frankfurt, Germany, have simulated neutron star collisions. In April they reported that these smash-ups give rise to extreme conditions, in the aftermath of which neutrons break down into quarks and gluons, forming the core of the most massive neutron stars. The work suggests another way that neutron stars could form this exotic plasma. Signals of this phase transition could appear in observations of gravitational waves from neutron star mergers (6).

Although these studies suggest that neutron star cores may hold exotic matter similar to the quark-gluon plasma seen in labs on Earth, they don't offer proof. For that, Vuorinen says, researchers need more accurate measurements of the neutron star's size and heft. Each candidate for the core of a neutron star only fits certain ranges of pressures and densities, which is why precisely knowing the diameter is tied so critically to understanding the interior. A quark-gluon plasma would be denser than a fluid of individual neutrons, which means the neutron stars would be more compact.

A NICER View

Astrophysicists can estimate the mass of neutron stars by watching the dynamics of pairs that orbit around each other; about three dozen have been studied this way. NICER offers a way to obtain more precise measurements, and on individual neutron stars as well.

NICER perches above the International Space Station's solar panels. It's about the size of a small-refrigerator and can nimbly swivel from target to target, guided by a star tracker. Its 56 eyes focus incoming X-ray photons onto sensitive detectors that measure the photons' energy, direction, and time of arrival.

The powerful, spinning magnetic fields of pulsars accelerate charged particles to high energies, and these particles generate the X-rays that stream out into space. But the gravitational tug around a neutron star is so strong—hundreds of billions of times that of Earth—that it bends the trajectories of outbound X-rays, distorting the rise and fall of X-ray intensity that NICER sees. It also shifts the spectrum of X-ray energies. Physicists fit NICER's data to computer simulations, to find combinations of mass and radius that produce the X-ray signature.

Between July 2017 and December 2018, NICER focused its gaze on J0030, a pulsar rotating more than 200 times per second in the Pisces constellation, about 1,100 light-years away. Two groups—one in the United States and one in The Netherlands—independently analyzed the data and published their results at the end of 2019. The US group estimated the mass at 1.4 solar masses and the diameter at 26 kilometers; the group in The Netherlands reported 1.3 solar masses and 25.4 kilometers. The closeness of these estimates, as well as their agreement with past measurements of the size and mass of other neutron stars, bolstered researchers' confidence in NICER's accuracy. And crucially, these numbers have smaller uncertainties—around 5%—than previous estimates.

Preliminary analyses of the data suggest that J0030's interior pressure exceeds the limit for nuclear matter, suggesting that the core is not merely neutrons. Alone, this first measurement doesn't settle the issue. But NICER observations of other neutron stars could confirm this suggestion of exotic matter—or perhaps reveal that they have a range of different interior compositions.

Poles Together

A real surprise emerged when physicists studied the jets of J0030, which stream out from the star's magnetic poles. A bar magnet has two poles, north and south. So does the Earth, and the Sun, and Mercury, and most other known celestial objects with a strong magnetic field. Earth's magnetic poles are found in opposite hemispheres. Not so for the neutron star: NICER's data revealed no magnetic pole in the northern hemisphere and at least two in the southern. (Physicists label the hemispheres "northern" and "southern" according to the observed axis of rotation, which differs from—and doesn't align with—the magnetic field.)

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High-energy charged particles such as electrons and positrons are funneled by the magnetic field, and where they hit the star's surface they generate intensely powerful X-rays, so a magnetic pole creates an X-ray hotspot. As a neutron star rotates, such a hotspot will send out signals that strengthen and weaken, as measured from Earth, in a way that reveals its latitude on the star—which is how NICER data revealed the lopsided poles of J0030.

Analyses by the other two teams, in the United States and The Netherlands, found similar signals. The two groups differed on the sizes and shapes of these poles—one reported finding a crescent-shaped hotspot, for example—but the overall picture was the same (7, 8). The hotspots were all in the southern hemisphere.

The challenge now is to understand how the quark-gluon plasma—or whatever's at the heart of the dead stars—can create such strange magnetic patterns. It's probably tied in with rapid rotation of the plasma. In quark-gluon simulations and experiments on Earth, physicists have reported unusual magnetic behavior. We can explore these phenomena with more measurements from NICER, Arzoumanian says.

NICER's initial observations of neutron stars have already changed the way researchers look at these dead cores. Arzoumanian's group is now studying data on at least five pulsars, as well as a fast-spinning neutron star with a white dwarf companion, to refine their size measurements even further and delve into the inner mysteries of neutron stars.

And solving that mystery isn't only a boon for astrophysicists. It can also push particle physics forward. "Measuring the density of a neutron star has been a sort of holy grail for decades in the nuclear physics community," says Arzoumanian. A better understanding of matter at its most extreme improves not only our knowledge about far-flung, exotic cosmic objects but also quantum phenomena at the smallest scales and even the stuff that holds atoms together.

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