# NASA's NICER delivers best-ever pulsar measurements, first surface map

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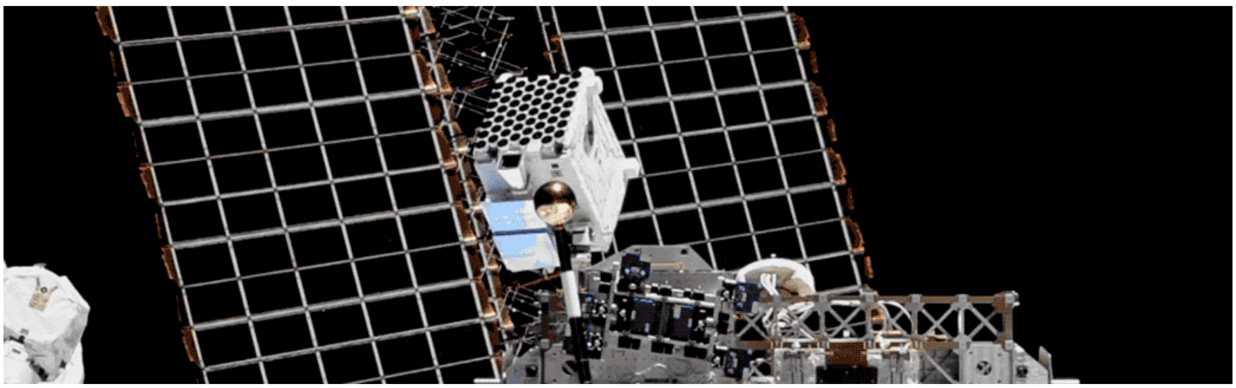


Credit: NASA's Goddard Space Flight Center

Astrophysicists are redrawing the textbook image of pulsars, the dense, whirling remains of exploded stars, thanks to NASA's Neutron star Interior Composition Explorer (NICER), an X-ray telescope aboard the International Space Station. Using NICER data, scientists have obtained the first precise and dependable measurements of both a pulsar's size and its mass, as well as the first-ever map of hot spots on its surface.

The pulsar in question, J0030+0451 (J0030 for short), lies in an isolated region of space 1,100 light-years away in the constellation Pisces. While measuring the pulsar's heft and proportions, NICER revealed that the shapes and locations of million-degree "hot spots" on the pulsar's surface are much stranger than generally thought.

"From its perch on the space station, NICER is revolutionizing our understanding of pulsars," said Paul Hertz, astrophysics division director at NASA Headquarters in Washington. "Pulsars were discovered more than 50 years ago as beacons of stars that have collapsed into dense cores, behaving unlike anything we see on Earth. With NICER we can probe the nature of these dense remnants in ways that seemed impossible until now."

A series of papers analyzing NICER's observations of J0030 appears in a focus issue of *The Astrophysical Journal Letters* and is now available online.

When a massive star dies, it runs out of fuel, collapses under its own weight and explodes as a supernova. These stellar deaths can leave behind neutron stars, which pack more mass than our Sun into a sphere roughly as wide as the island of Manhattan is long. Pulsars, which are one class of neutron star, spin up to hundreds of times each second and sweep beams of energy toward us with every rotation. J0030 revolves 205 times per second.

For decades, scientists have been trying to figure out exactly how pulsars work. In the simplest model, a pulsar has a powerful magnetic field shaped much like a household bar magnet. The field is so strong it rips particles from the pulsar's surface and accelerates them. Some particles follow the magnetic field and strike the opposite side, heating the surface and creating hot spots at the magnetic poles. The whole pulsar glows faintly in X-rays, but the hot spots are brighter. As the object spins, these spots sweep in and out of view like the beams of a lighthouse, producing extremely regular variations in the object's X-ray brightness. But the new NICER studies of J0030 show pulsars aren't so simple.

Using NICER observations from July 2017 to December 2018, two groups of scientists mapped J0030's hot spots using independent methods and converged on similar results for its mass and size. A team led by Thomas Riley, a doctoral student in computational astrophysics, and his supervisor Anna Watts, a professor of astrophysics at the University of Amsterdam, determined the pulsar is around 1.3 times the Sun's mass and 15.8 miles (25.4 kilometers) across. Cole Miller, an astronomy professor at the University of Maryland (UMD) who led the second team, found J0030 is about 1.4 times the Sun's mass and slightly larger, about 16.2 miles (26 kilometers) wide.

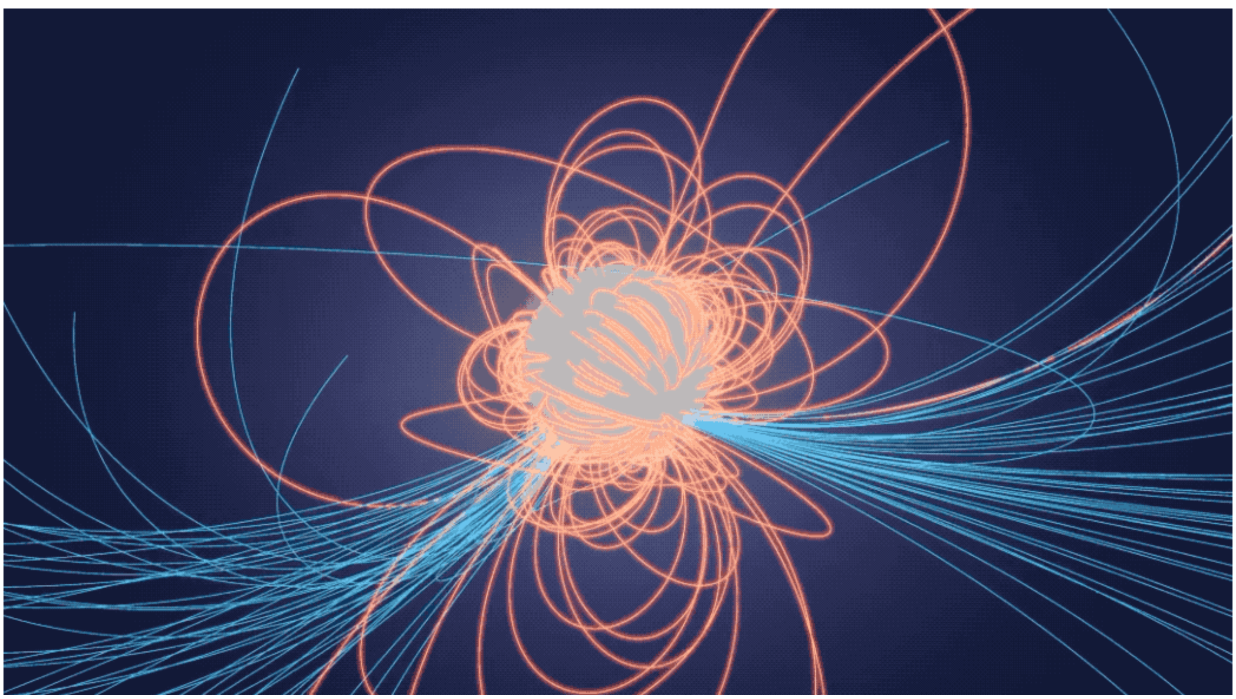
"When we first started working on J0030, our understanding of how to simulate pulsars was incomplete, and it still is," Riley said. "But thanks to NICER's detailed data, open-source tools, high-performance computers and great teamwork, we now have a framework for developing more realistic models of these objects."

A pulsar is so dense its gravity warps nearby space-time—the "fabric" of the universe as described by Einstein's general theory of relativity—in much the same way as a bowling ball on a trampoline stretches the surface. Space-time is so distorted that light from the side of the pulsar facing away from us is "bent" and redirected into our view. This makes the star look bigger than it is. The effect also means the hot spots may never completely disappear as they rotate to the far side of the star. NICER measures the arrival of each X-ray from a pulsar to better than a hundred nanoseconds, a precision about 20 times greater than previously available, so scientists can take advantage of this effect for the first time.

"NICER's unparalleled X-ray measurements allowed us to make the most precise and reliable calculations of a pulsar's size to date, with an uncertainty of less than 10%," Miller said. "The whole NICER team has made an important contribution to fundamental physics that is impossible to probe in terrestrial laboratories."

Our view from Earth looks onto J0030's northern hemisphere. When the teams mapped the shapes and locations of J0030's spots, they expected to find one there based on the textbook image of pulsars, but didn't. Instead, the researchers identified up to three hot "spots," all in the southern hemisphere.

Riley and his colleagues ran rounds of simulations using overlapping circles of different sizes and temperatures to recreate the X-ray signals. Performing their analysis on the Dutch national supercomputer Cartesius took less than a month—but would have required around 10 years on a modern desktop computer. Their solution identifies two hot spots, one small and circular and the other long and crescent-shaped.



Simulation of a possible quadripole magnetic field configuration for a pulsar with hot spots in only the southern hemisphere. Credit: NASA's Goddard Space Flight Center

Miller's group performed similar simulations, but with ovals of different sizes and temperatures, on UMD's Deepthought2 supercomputer. They found two possible and equally likely spot configurations. One has two ovals that closely match the pattern found by Riley's team. The second solution adds a third, cooler spot slightly askew of the pulsar's south rotational pole.

Previous theoretical predictions suggested that hot spot locations and shapes could vary, but the J0030 studies are the first to map these surface features. Scientists are still trying to determine why J0030's spots are arranged and shaped as they are, but for now it's clear that pulsar magnetic fields are more complicated than the traditional two-pole model.

NICER's main science goal is to precisely determine the masses and sizes of several pulsars. With this information scientists will finally be able to decipher the state of matter in the cores of neutron stars, matter crushed by tremendous pressures and densities that cannot be replicated on Earth.

"It's remarkable, and also very reassuring, that the two teams achieved such similar sizes, masses and hot spot patterns for J0030 using different modeling approaches," said Zaven Arzoumanian, NICER science lead at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "It tells us NICER is on the right path to help us answer an enduring question in astrophysics: What form does matter take in the ultra-dense cores of neutron stars?"

NICER is an Astrophysics Mission of Opportunity within NASA's Explorers program, which provides frequent flight opportunities for world-class scientific investigations from space utilizing innovative, streamlined and efficient management approaches within the heliophysics and astrophysics science areas. NASA's Space Technology

Mission Directorate supports the SEXTANT component of the mission, demonstrating pulsar-based spacecraft navigation.

**More information:** Zaven Arzoumanian & Keith C. Gendreau. Focus on NICER Constraints on the Dense Matter Equation of State. The *Astrophysical Journal Letters* iopscience.iop.org/journal/204 … er_Equation_of_State

Provided by NASA's Goddard Space Flight Center