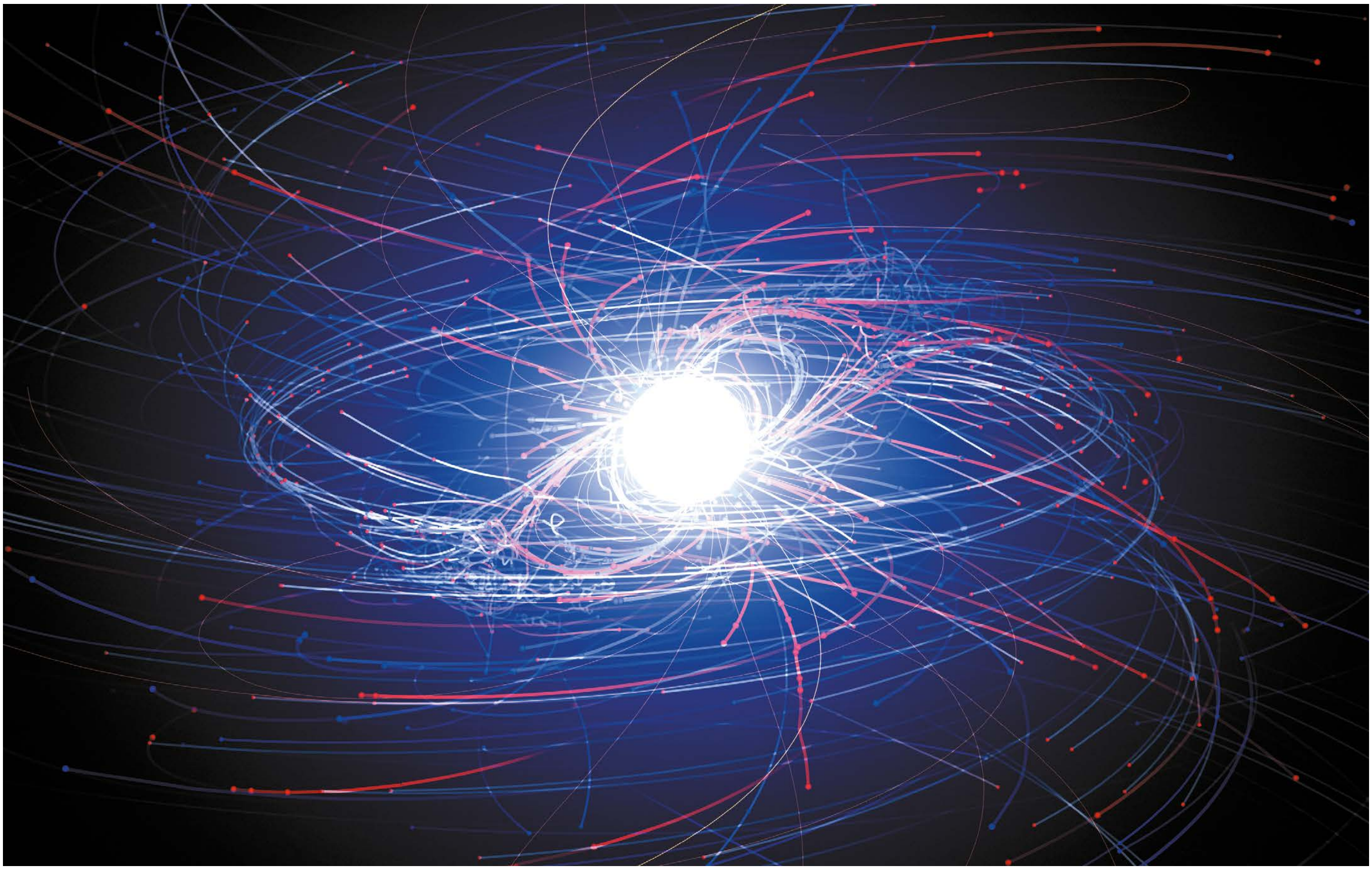


NASA'S GODDARD SPACE FLIGHT CENTER

Powerful magnetic and electric fields whip charged particles around, in a computer simulation of a spinning neutron star.

THE STRANGE HEARTS OF NEUTRON STARS

Space observations are poised to reveal more about the centre of one of the Universe's most enigmatic objects. **By Adam Mann**

When a massive star dies in a supernova, the explosion is only the beginning of the end. Most of the stellar matter is thrown far and wide, but the star's iron-filled heart remains behind. This core packs as much mass as two Suns and quickly shrinks to a sphere that would span the length of Manhattan. Crushing internal pressure – enough to squeeze Mount Everest to the size of a sugar cube – fuses subatomic protons and electrons into neutrons.

Astronomers know that much about how neutron stars are born. Yet exactly what happens afterwards, inside these ultra-dense cores, remains a mystery. Some researchers theorize that neutrons might dominate all the way down to the centre. Others hypothesize that the incredible pressure compacts the material into more exotic particles or states that squish and deform in unusual ways.

Now, after decades of speculation, researchers are getting closer to solving the enigma, in part thanks to an instrument on the International Space Station called the Neutron Star Interior Composition Explorer (NICER).

Last December, this NASA space observatory provided astronomers with some of the most precise measurements ever made of a neutron star's mass and radius[1,2], as well as unexpected findings about its magnetic field[1,3]. The NICER team plans to release results about more stars in the next few months. Other data are coming in from gravitational-wave observatories, which can watch neutron stars contort as they crash together. With these combined observations, researchers are poised to zero in on what fills the innards of a neutron star.

For many in the field, these results mark a turning point in the study of some of the Universe's most bewildering objects. "This is beginning to be a golden age of neutron-star physics," says Jürgen Schaffner-Bielich, a theoretical physicist at Goethe University in Frankfurt, Germany.

Launched in 2017 aboard a SpaceX Falcon 9 rocket, the US$62-million NICER telescope sits outside the space station and collects X-rays coming from pulsars — spinning neutron stars that radiate charged particles and energy in enormous columns that sweep around like beams from a lighthouse. The X-rays originate from million-degree hotspots on a pulsar's surface, where a powerful magnetic field rips charged particles off the exterior and slams them back down at the opposing magnetic pole.

NICER detects these X-rays using 56 gold-coated telescopes, and time-stamps their arrival to within 100 nanoseconds. With this capability, researchers can precisely track hotspots as a neutron star whips around at up to 1,000 times per second. Hotspots are visible as they swing across the object. But neutron stars warp space-time so strongly that NICER also detects light from hotspots facing away from Earth. Einstein's general theory of relativity provides a way to calculate a star's mass-to-radius ratio through the amount of light-bending. That and other observations allow astrophysicists to pin down the masses and radii of the deceased stars. Those two properties could help in determining what is happening down in the cores.

Deep, dark mystery

Neutron stars get more complicated the deeper one goes. Beneath a thin atmosphere made mostly of hydrogen and helium, the stellar remnants are thought to boast an outer crust just a centimetre or two thick that contains atomic nuclei and free-roaming electrons. Researchers think that the ionized elements become packed together in the next layer, creating a lattice in the inner crust. Even further down, the pressure is so intense that almost all the protons combine with electrons to turn into neutrons, but what occurs beyond that is murky at best (see 'Dense matter').

"It's one thing to know the ingredients," says Jocelyn Read, an astrophysicist at California State University, Fullerton. "It's another to understand the recipe, and how those ingredients are going to interact with each other."

Physicists have some idea of what happens, thanks to particle accelerators on Earth. At facilities such as Brookhaven National Laboratory in Upton, New York, and CERN's Large Hadron Collider near Geneva, Switzerland, researchers have smashed together heavy ions, such as those of lead and gold, to create brief collections of monumentally dense material. But these kinetic experiments generate billion- or even trillion-degree flashes, in which protons and neutrons dissolve into a soup of their constituent quarks and gluons. Terrestrial instruments have a hard time probing the relatively mild millions-of-degrees conditions inside neutron stars.

There are multiple ideas about what might occur. It could be that quarks and gluons roam freely. Or, the extreme energies could lead to the creation of particles called hyperons. Like neutrons, these particles contain three quarks. But whereas neutrons contain the most basic and lowest-energy quarks, known as up and down quarks, a hyperon has at least one of those replaced with an exotic 'strange' quark. Another possibility is that the centre of a neutron star is a Bose–Einstein condensate, a state of matter in which all subatomic particles act as a single quantum-mechanical entity. And theorists have dreamt up even more outlandish prospects, too.

"It's one thing to know the ingredients. It's another to understand the recipe."

Crucially, each possibility would push back in a characteristic way against a neutron star's colossal gravity. They would generate different internal pressures and therefore a larger or smaller radius for a given mass. A neutron star with a Bose–Einstein condensate centre, for instance, is likely to have a smaller radius than one made from ordinary material such as neutrons. One with a core made of pliable hyperon matter could have a smaller radius still.

"The types of particles and the forces between them affect how soft or squashy the material is," says Anna Watts, a NICER team member at the University of Amsterdam.

Differentiating between the models will require precise measurements of the size and mass of neutron stars, but researchers haven't yet been able to push their techniques to fine-enough levels to say which possibility is most likely. They typically estimate masses by observing neutron stars in binary pairs. As the objects orbit one another, they tug gravitationally on each other, and astronomers can use this to determine their masses. Roughly 35 stars have had their masses measured in this way, although the figures can contain error bars of up to one solar mass. A mere dozen or so have also had their radii calculated, but in many cases, the techniques can't determine this value to better than a few kilometres — as much as one-fifth of the size of a neutron star.

NICER's hotspot method has been used by the European Space Agency's XMM-Newton X-ray observatory, which launched in 1999 and is still in operation. NICER is four times more sensitive and has hundreds of times better time resolution than the XMM-Newton. Over the next two to three years, the team expects to be able to use NICER to work out the masses and radii of another half a dozen targets, pinning down their radii to within half a kilometre. With this precision, the group will be well placed to begin plotting out what is known as the neutron-star equation of state, which relates mass to radius or, equivalently, internal pressure to density.

If scientists are particularly lucky and nature happens to serve up especially good data, NICER might help eliminate certain versions of this equation. But most physicists think that, on its own, the observatory will probably narrow down rather than completely rule out models of what happens in the mysterious objects' cores.

"This would still be a huge advance on where we are now," says Watts.

Field lines

NICER's first target was J0030+0451, an isolated pulsar that spins roughly 200 times per second and is 337 parsecs (1,100 light years) from Earth, in the constellation Pisces.

Two groups — one based primarily at the University of Amsterdam[1] and another led by researchers at the University of Maryland in College Park[2] — separately sifted through 850 hours of observations, serving as checks on one another.

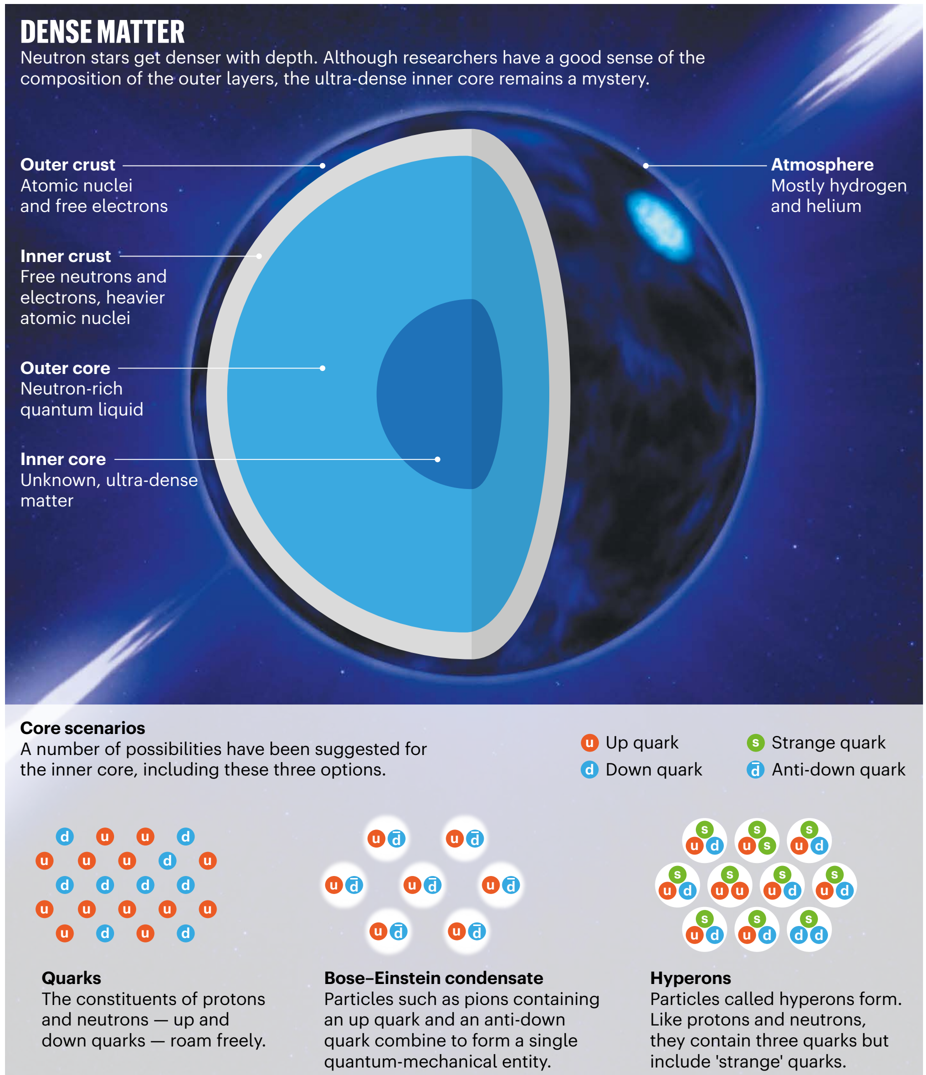
Because the hotspot light curves are so complex, the groups needed supercomputers to model various configurations and work out which ones best fit the data. But both came up with similar results, finding that J0030 has a mass that is 1.3 or 1.4 times that of the Sun, and a radius of roughly 13 kilometres.

Those results are not definitive: they could be used to support either the mundane or the otherworldly predictions for what's inside the guts of neutron stars. "There's no requirement for anything funky or crazy or exotic yet," says Andrew Steiner, a nuclear astrophysicist at the University of Tennessee, Knoxville.

Researchers got a bigger surprise with findings about the shape and position of the hotspots. The canonical view of neutron stars has their magnetic field lines looking like those surrounding a bar magnet, with north and south sides emerging from circular spots at opposing ends of the star. By contrast, the Dutch supercomputer simulations implied that both of J0030's hotspots are in its southern hemisphere, and that one of them is long and crescent-shaped[1]. The Maryland team also came up with the possibility of a three-hotspot solution: two southerly oval-shaped ones and a final circle near the rotational south pole[3].

"It looks like they might have made the first real detection of a pulsar where the beams are not 180 degrees separated," says Natalie Webb, an astrophysicist at the Institute for Research in Astrophysics and Planetology in Toulouse, France, who has modelled such possibilities. "That's fantastic if true."

The results would bolster previous observations and theories suggesting that neutron stars' magnetic fields, which are one trillion times stronger than the Sun's, can be more complex than generally assumed. After they first form, pulsars are thought to slow their



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rotation over millions of years. But if they have a companion star orbiting around them, they might steal material and angular momentum from this partner, boosting their spinning to superfast speeds. As the matter gets deposited on the star's exterior, some theorists suggest it could affect a fluid-like layer of subsurface neutrons, generating gigantic vortices that twist the neutron star's magnetic field into odd arrangements. The companion might ultimately be consumed or lose so much mass that it becomes gravitationally unbound and flies away, as could have been the case with the now-solitary J0030.

Work in progress

NICER is continuing to observe J0030 to further improve the precision of its radius measurements. At the same time, the team is beginning to analyse data from a second target, a slightly heavier pulsar with a white-dwarf companion. Other astronomers have used observations of this pair's orbital dance to determine the pulsar's mass, which means NICER researchers have an independent measurement that they can use to validate their findings.

Among NICER's targets, the team plans to include at least a couple of high-mass pulsars, including the current record-holder for most massive neutron star – a behemoth with a mass 2.14 times that of the Sun. That should allow the researchers to probe an upper limit: the point at which a neutron star collapses into a black hole. Even the 2.14-solar-mass object is challenging for theorists to explain. Several researchers have also suggested that NICER might be able to find two neutron stars with the same mass but different radii. That would suggest the presence of a transition point, at which slight differences create two distinct cores. One might contain mostly neutrons, for example, and the other might be composed of more-exotic material.

Although NICER is at the vanguard, it is not the only instrument plumbing pulsars' depths. In 2017, the US Laser Interferometer Gravitational-Wave Observatory (LIGO), along with the Virgo detector in Italy, picked up the signal from two neutron stars crashing and merging together[4]. As the objects rotated around one another before the crash, they emitted gravitational waves that contained information about the stars' size and structure. Each star's colossal gravitational influence tugged on and deformed its partner, contorting both from spheres into teardrop shapes. The amount of distortion in those final moments gives physicists clues about the malleability of the material inside the neutron stars.

LIGO's facility in Livingston, Louisiana, picked up a second neutron-star smash-up last April, and more events could be spotted at any time. So far, the two mergers have only hinted at the properties of neutron-star interiors, suggesting that they are not particularly deformable. But the current generation of facilities can't observe the crucial final moments, when the warping would be greatest and would display internal conditions most clearly.

The Kamioka Gravitational Wave Detector in Hida, Japan, is expected to come online later this year, and the Indian Initiative in Gravitational-wave Observations near Aundha Naganath, Marathwada, in 2024. In combination with LIGO and Virgo, they will improve sensitivity, potentially even capturing the details of the moments leading up to a crash.

Looking further into the future, several planned instruments could make observations that elude NICER and current gravitational-wave observatories. A Chinese–European satellite called the enhanced X-ray Timing and Polarimetry mission, or eXTP, is expected to launch in 2027 and study both isolated and binary neutron stars to help determine their equation of state. Researchers have also proposed a space-based mission that could fly in the 2030s called the Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays, or STROBE-X. It would use NICER's hotspot technique, pinning down the masses and radii of at least 20 more neutron stars with even more precision.

The hearts of neutron stars will probably always retain some secrets. But physicists now seem well placed to begin peeling back the layers. Read, who is a member of the LIGO team, says that she has collaborated on a project to imagine what scientific questions gravitational-wave detectors would be able to tackle in the 2030s and 2040s. In the process, she realized that the landscape for neutron-star research – in particular, the question of the equation of state – should look very different by then.

"It's been this long-standing puzzle that you figure will always be there," she says. "Now we're at a point where I can see the scientific community figuring out the neutron-star-structure puzzle within this decade."

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1. Riley, T. E. *et al. Astrophys. J. Lett.* **887**, L21 (2019).
2. Miller, M. C. *et al. Astrophys. J. Lett.* **887**, L24 (2019).
3. Bilous, A. V. *et al. Astrophys. J. Lett.* **887**, L23 (2019).
4. Abbott, B. P. *et al. Phys. Rev. Lett.* **119**, 161101 (2017).