

Neutron stars' hidden nuclear pasta

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The novel, amorphous state of matter that exists in the crust of neutron stars leaves a trace in the spins of magnetized, rapidly rotating pulsars.

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Within just a few years of the neutron's discovery in 1932, the idea of a neutron star had been articulated. Specifically, many physicists suggested that the supernova explosion of a star of 10 or so solar masses might signal a transition from a normal star to a compact, highly magnetic, rapidly rotating star composed mainly of neutrons. It took some 30 years to confirm the notion, but in 1967 Jocelyn Bell and Antony Hewish discovered the first neutron star by spotting its beamed radio emission. That phenomenon arises because particles radiate along the star's magnetic axis as they rapidly accelerate in its magnetic field; as the star rotates, it carries the radiation beam along, creating a lighthouse effect commonly called pulsar emission.

Neutron stars are extraordinary objects (see the article by Lars Bildsten and Tod Strohmayer, *PHYSICS TODAY*, February 1999, page 40). A typical one might have a radius of 12 km, a density exceeding that of nuclear matter, a magnetic field of 10^{12} gauss—two trillion times Earth's field—and a rotation period of 0.1 s. Astrophysicists have spotted almost 2500 neutron stars and have learned that they come in many different types, that their magnetic fields collectively span eight orders of magnitude, and that their spin periods span about six orders.

Despite decades of theoretical and observational efforts, however, we still have a great deal to learn about neutron stars. We don't know, for example, the equation of state that relates the pressure and density in their interior; intuitively, that equation tells how squeezable a neutron star is. Nor do we know just what makes up such objects. In particular, we don't know what anomalous forms of matter exist at the high densities and strong magnetic fields of neutron stars. The question of neutron-star composition has inspired research by physicists in many subdisciplines, including astrophysics, nuclear physics, and particle physics.

More than just neutrons

Given their name, you might think that neutron stars are giant balls packed with neutrons. In fact, they are much more complicated. Outside the star is a large region—the magnetosphere—dominated by the star's magnetic field. The magnetic field lines permeating the region are anchored in a stiff crust, and they determine the motion of the charged particles that fill the magnetosphere. Neutron stars might even have an atmosphere, just a few centimeters thick, of hydrogen, helium, carbon, and possibly heavier elements.

Panel a of the figure shows the interior of a neutron star. The outer crust of the star comprises rapidly moving electrons and mainly stationary nuclei—for example, iron-56—arranged in a Coulomb lattice of essentially point-like,

charged particles. The currents generated by the electrons partially dissipate the star's magnetic field and heat the crust.

The density of the outer crust spans about three orders, from 10^9 g/cm³ to 10^{11} g/cm³. As the density increases, electron-capture reactions become more favorable; the resulting Coulomb lattice is thus made from progressively more exotic and neutron-rich nuclei. At the so-called neutron drip point, where the density hits about 4×10^{11} g/cm³, nuclei are unable to hold more neutrons. Beyond that critical density, neutrons start to behave as a superfluid.

As the density of the inner crust increases beyond that of the drip point, the neutron-rich nuclei at first remain in a Coulomb lattice, but one that is now embedded in a fluid of electrons and neutrons. However, at a density of something like 8×10^{13} g/cm³, astrophysicists expect the spherical nuclei to begin to reorganize into exotic and complex pasta-like shapes as they try to balance short-range nuclear attraction and long-range Coulomb repulsion. About 300 m deeper into the neutron star lies the boundary of the neutron-star core; the density has increased to 1.8×10^{14} g/cm³ and superconductivity starts to become important.

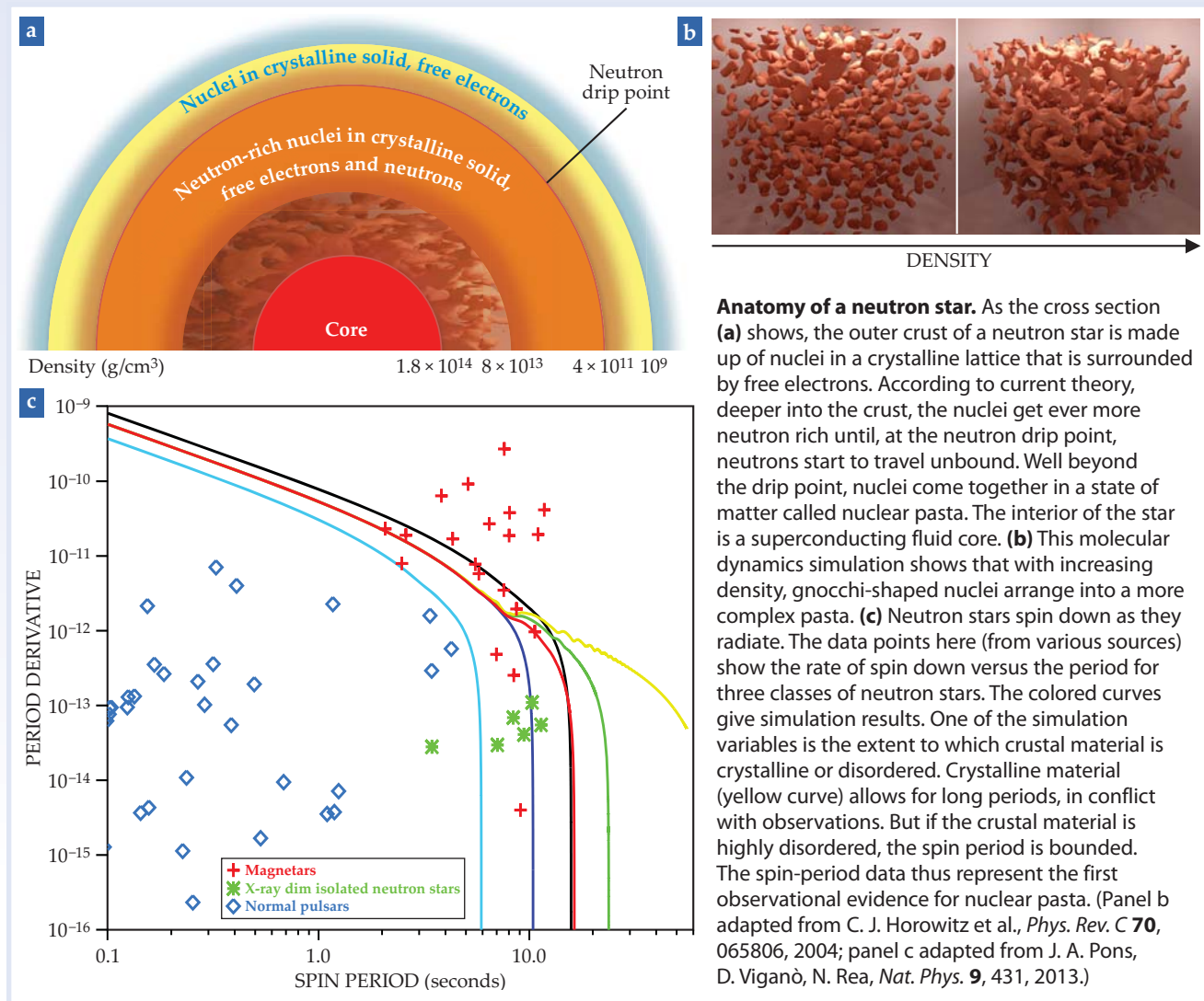
The 300-m-thick region terminating at the core, often called the mantle, separates the outer crust's uniform crystal lattice from the core's uniform liquid of nucleons, electrons, and possibly more exotic particles. It is where nuclear pasta is cooked and served. Several research groups have carried out molecular dynamics simulations to ascertain the shapes of pasta matter at different densities. The exact shapes and transitions vary from model to model, and the astrophysics community has yet to reach consensus on the details. The models do agree that the pasta shapes become more complex as the density increases deep within the neutron star. Panel b of the figure shows the results of a representative simulation, which finds gnocchi at relatively modest density and a complex, fresh strozzapreti kind of pasta at the base of the inner crust.

More than just pulsars

Presumably, all neutron stars are governed by the same equation of state. In light of that presumption, the neutron-star population has displayed a bewildering variety of physics—so much that astrophysicists have established several classes of neutron stars. About 2000 stars are radio pulsars. The radiation emitted by such pulsars ranges from radio to gamma-ray energies—the “radio” in their name notwithstanding—and it is powered by the pulsar's rotational energy.

Magnetars, the strongest magnets in the universe, are extremely bright x-ray pulsars with fields typically of about 10^{14} – 10^{15} G. They exhibit peculiar flaring that generally lasts for 0.01–100 s but sometimes endures for years. Current theory posits that magnetar emissions are powered by decay and instabilities of the star's magnetic field rather than by rotational energy.

X-ray dim isolated neutron stars (XDINSs) are x-ray pulsars, probably old magnetars, that are relatively nearby—within about 1000 light-years of Earth. They emit thermal



Anatomy of a neutron star. As the cross section (a) shows, the outer crust of a neutron star is made up of nuclei in a crystalline lattice that is surrounded by free electrons. According to current theory, deeper into the crust, the nuclei get ever more neutron rich until, at the neutron drip point, neutrons start to travel unbound. Well beyond the drip point, nuclei come together in a state of matter called nuclear pasta. The interior of the star is a superconducting fluid core. (b) This molecular dynamics simulation shows that with increasing density, gnocchi-shaped nuclei arrange into a more complex pasta. (c) Neutron stars spin down as they radiate. The data points here (from various sources) show the rate of spin down versus the period for three classes of neutron stars. The colored curves give simulation results. One of the simulation variables is the extent to which crustal material is crystalline or disordered. Crystalline material (yellow curve) allows for long periods, in conflict with observations. But if the crustal material is highly disordered, the spin period is bounded. The spin-period data thus represent the first observational evidence for nuclear pasta. (Panel b adapted from C. J. Horowitz et al., *Phys. Rev. C* **70**, 065806, 2004; panel c adapted from J. A. Pons, D. Viganò, N. Rea, *Nat. Phys.* **9**, 431, 2013.)

photons from their hot surfaces and have magnetic fields of 10^{13} G—greater than the 10^{12} G of a typical radio pulsar but less than the 10^{15} G of younger magnetars.

Compact central objects (CCOs) are x-ray-emitting neutron stars that were discovered in the centers of bright supernova remnants. Like XDINSs, they emit thermally from their hot surfaces. But they are younger than XDINSs and have smaller magnetic fields of 10^{10} – 10^{11} G. Indeed, such fields, though very high by terrestrial standards, are actually rather low for a young, hot x-ray pulsar. Astrophysicists are trying to learn if the CCOs are born with low fields, or if high fields initially present at birth get buried inside the crust as material from the supernova explosion falls onto the CCO.

Evidence for pasta

Until just a couple of years ago, the diversity of the neutron-star population was a puzzle for astrophysicists. But in 2013 I joined Daniele Viganò and colleagues to analyze the magnetic and thermal history of neutron stars in a numerical simulation of neutron-star evolution. Our study, which traced the stars' evolution from birth to an age of a few million years, showed that the various types of neutron star fit into a uniform classification scheme based on age, magnetic field strength, and field configuration at birth.

However, that was not the end of the story. Simulations of luminosity and rotational period consistently predicted slowly rotating pulsars, in conflict with observation. In fact,

astrophysicists have yet to discover an isolated pulsar with a period larger than 12 s. Why do pulsars, especially the more magnetic magnetars and XDINSs, spin down so little?

With José Pons, Viganò and I realized that to match simulations with observations, the deep inner-crust layer needs to have an electrical resistivity high enough to dissipate the magnetic field faster than in conventional simulations. And that could happen only if the inner crust is made of a highly disordered lattice (see panel c of the figure).

According to our analysis, the period bound on isolated pulsars represents the first observational evidence for nuclear pasta—an exotic configuration of nuclei that exists at the extreme magnetic fields and densities of a neutron star. Observations of additional x-ray pulsars, aided by the upcoming generation of x-ray detectors and coupled with refined theory, should help astrophysicists to unravel the composition of a neutron star's crust—that is, to understand matter under some of the most extreme conditions found in the cosmos.

Additional resources

- W. G. Newton, "Neutron stars: A taste of pasta?," *Nat. Phys.* **9**, 396 (2013).
- D. Viganò et al., "Unifying the observational diversity of isolated neutron stars via magneto-thermal evolution models," *Mon. Not. R. Astron. Soc.* **434**, 123 (2013).
- C. J. Horowitz et al., "Dynamical response of the nuclear 'pasta' in neutron star crusts," *Phys. Rev. C* **72**, 035801 (2005). ■