

Explore the **PULSAR** menagerie

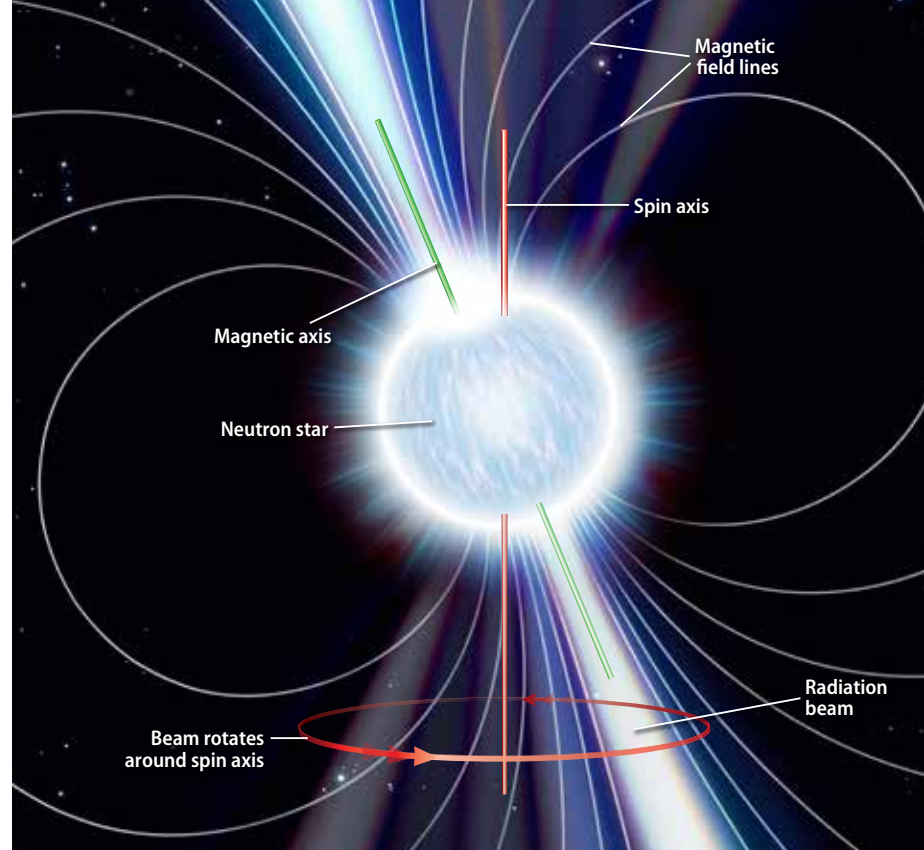
Astronomers are discovering many strange properties of compact stellar objects called pulsars. Here's how they fit together. **by Victoria M. Kaspi**

If you browse through an astronomy book published 25 years ago, you'd likely assume that astronomers understood extremely dense objects called neutron stars fairly well. The spectacular Crab Nebula's central body has been a "poster child" for these objects for years. This specific neutron star is a pulsar that rotates roughly 30 times per second, emitting regular apparent pulsations in Earth's direction through a sort of "lighthouse" effect as the star rotates.

While these textbook descriptions aren't incorrect, research over roughly the past decade has shown that the picture they portray is fundamentally incomplete. Astronomers know that the simple scenario where neutron stars are all born "Crab-like" is not true. Experts in the field could not have imagined the variety of neutron stars they've recently observed. We've found that bizarre objects represent a significant fraction of the neutron star population. With names like magnetars, anomalous X-ray pulsars, soft gamma repeaters, rotating radio transients, and compact central objects, these bodies bear properties radically different from those of the Crab pulsar. Just how large a fraction they represent is still hotly debated, but it's at least 10 percent and maybe even the majority. That the bulk of neutron stars may be peculiar objects that were unimaginable just a decade ago is one of the most startling recent discoveries in astrophysics. It's time to rewrite the textbooks.

Long the pulsar poster child, the Crab Nebula's central object is a fast-spinning neutron star that emits jets of radiation at its magnetic axis. Astronomers detect the radio signature from these jets as pulses. It turns out that scientists are finding other classes of pulsars that don't appear to share traits with the Crab's central object.

Don Dixon for Astronomy



Radiation beams emanate from a radio pulsar's magnetic axis, which is misaligned from the star's spin axis. As the object rotates, the beams flash the observer and appear as pulses. Astronomy: Roen Kelly

Surveying neutron stars

To properly describe the neutron star population as we understand it is to visit a wild and wonderful “zoo” of objects. Each seems intent on proving itself the most exotic of the lot — not that they need to try that hard.

All neutron stars share some common, bizarre properties. Having masses upward of half a million Earths crammed into a sphere some 12 miles (20 kilometers) wide, these objects are the second most compact known in the universe — after black holes. At a neutron star's center, the density is at least 10 times that within the atomic nucleus; we don't understand the laws of nature within densities this high.

Even more impressive are neutron stars' rapid rotation rates — astronomers know of at least one that completes more than 700 spins per second. Despite the tremendous gravitational pull at their surfaces, neutron stars rotating at these rates are almost certainly slightly pancake-shaped due to the rotation. (On a typical neutron star, you'd be “pulling” a few tril-

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lion Gs, if tidal forces hadn't already shredded you or radiation hadn't zapped you to oblivion.) An open question is just how fast one of these objects can spin without flying apart.

What's in the zoo?

Naïvely, one might think that by being a close cousin of the black hole, a neutron star should not have much “hair” — that

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is, details. Figuratively speaking, however, researchers now realize that neutron stars are awfully complicated. The variety of properties among the different classes is genuinely astonishing.

We've known about the classic young “radio pulsars” since University of Cambridge graduate student Jocelyn Bell discovered the first such object in 1967. Originally, her research group thought the regular radio pulsations were signals from aliens — such consistent signals

were unprecedented in astronomy. Today, we understand that these signals are from rotation-powered pulsars (RPPs): rapidly rotating, highly magnetized neutron stars that produce narrow beams of radiation emanating from their magnetic poles, with the magnetic axis misaligned from the spin axis. This beaming property makes radio pulsars the “lighthouses of the cosmos.” The beamed radiation spans the electromagnetic spectrum, although it generally is most easily observed with radio telescopes. Astronomers know of nearly 2,000 radio pulsars in the Milky Way, most of which inhabit the disk.

Neutron stars, and thus pulsars, are born in supernova explosions. As the slowly rotating progenitor star collapses, physics insists on the conservation of angular momentum — a constraint shared with figure skaters during spectacular spinning stunts. Thus some neutron stars start life spinning rapidly (on average rotating roughly 50 to 100 times per second).

A classic radio pulsar's impressively strong magnetic field acts to “brake” the star — it emits radiation as any rotating magnet must. Such magnetic fields are enormous, on the order of 10^{12} gauss — more than a trillion times as strong as Earth's magnetic field and too high for scientists to reproduce in a terrestrial laboratory. Astronomers infer such fields from the fact that these stars' rotation rates are slowly decreasing — in other words, they are “spinning down.”

The Crab Nebula's radio pulsar powers the surrounding nebula with its intensely magnetized “wind” of highly energetic particles. The pulsar's ambient magnetic field accelerates electrons and positrons, which causes the ghostly white glow within the thermal filamentary remains of the exploded progenitor star. Astronomers detect “pulsar wind nebulae” only in the most powerful pulsars. These nebulae can have dramatic and sometimes puzzling morphologies. For

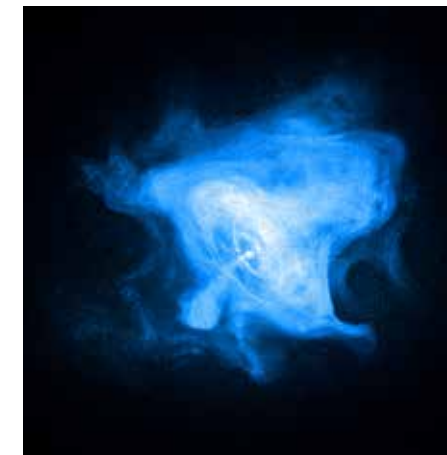
example, the 150-millisecond pulsar PSR B1509–58 powers the X-ray nebula dubbed the “Hand of God.” This huge nebula has fingers of energized material emanating from the central region, which holds the pulsar.

Astronomers recently discovered a likely subclass of radio pulsars called rotating radio transients (RRATs). Unlike classical radio pulsars, these objects seem to emit radio waves intermittently and in short bursts, such that we don't detect a regular pulsation. Why these objects are seemingly incapable of producing consistent regular signals is a mystery. Careful study of the RRAT bursts has revealed that they in fact occur at time intervals that are specific multiples of an underlying periodicity, supporting the idea that such objects are an extreme form of radio pulsar.

While researchers know of only about one dozen RRATs, they easily could have missed a huge population of these objects because of the way sky surveys have looked for radio pulsars. Some astronomers think RRATs could outnumber classical radio pulsars. Modern radio pulsar investigations, such as the Pulsar-ALFA survey currently underway at the 305-meter radio telescope in Arecibo, Puerto Rico, routinely use special software to



The Arecibo Observatory in Puerto Rico is an important tool for finding pulsars. Astronomers use this 1,000-foot-wide (305 meters) radio telescope to scan the skies to locate more of these compact objects. Photo courtesy of the NAIC - Arecibo Observatory, a facility of the NSF



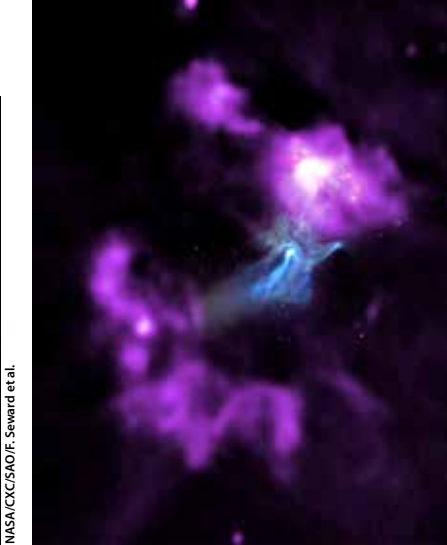
The Crab Nebula's pulsar was one of the first discovered. This radio pulsar's fast rotation rate (about 30 spins per second), combined with a strong magnetic field, generates an intense wind that energizes the surrounding material.

look for isolated single bursts — the RRAT signature.

In isolation

Astronomers had long thought radio emission was the hallmark of neutron stars. But several different subclasses of radio-quiet neutron stars have emerged as attention grabbers in the past decade.

The so-called isolated neutron stars (INs) are rather poorly named given



Young pulsar PSR B1509–58 emits enough energy to light up this massive nebula dubbed the “Hand of God.” The nebula spans some 150 light-years. The neutron star is in the “hand's” center, with finger-like structures energizing knots of material in a neighboring gas cloud. Blue represents the most energetic X-rays and red the least. Gas clouds emitting radio waves show up as purple. NASA/CXC/SAO/F. Seward et al.

that the vast majority of radio pulsars are also isolated but not classified as INs. Researchers have confirmed that there are seven INs, in addition to one candidate object.

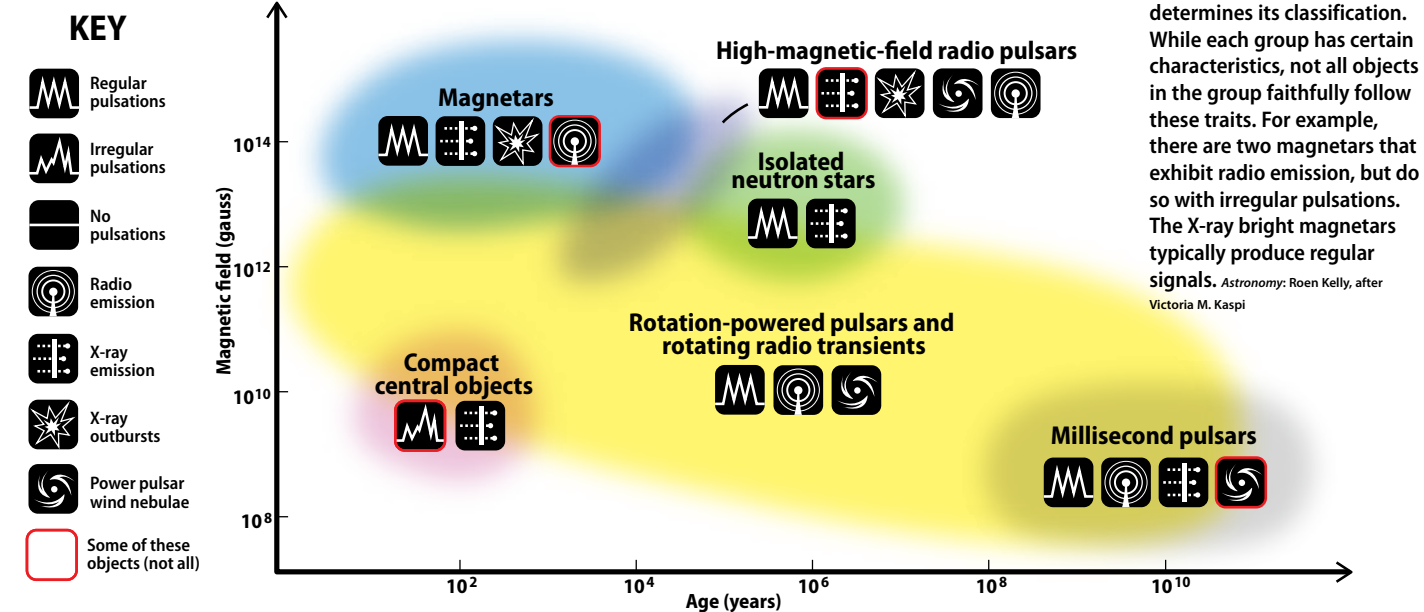
These bodies' defining properties are that they are relatively close to us, have X-ray emission with relatively low X-ray luminosity, and have only a visible-light counterpart. Those INs known are within roughly 1,600 light-years of Earth; beyond that, they're likely too faint for current detectors. They also have relatively long periods as measured with X-ray telescopes, ranging from 3 to 11 seconds. They emit copious X-rays because they are hot due to the decay of a previously intense magnetic field.

Surprisingly, the typical IN has a magnetic field that is somewhat stronger than that of the typical radio pulsar. (The reason for this is unclear, although one theory posits that INs are regular radio pulsars viewed off-beam so that they appear radio quiet.)

Extreme magnets

Then there are magnetars, the “bad boys” of the neutron star population (a description first suggested by my good friend and colleague Maxim Lyutikov of Purdue University). Magnetars are the most spectacular of the group, emitting enormous outbursts of X-rays and gamma rays. At their “baddest,” magnetars can

The lives of pulsars



A pulsar's magnetic field at birth and its age when astronomers observe it likely determines its classification. While each group has certain characteristics, not all objects in the group faithfully follow these traits. For example, there are two magnetars that exhibit radio emission, but do so with irregular pulsations. The X-ray bright magnetars typically produce regular signals. *Astronomy: Roen Kelly, after Victoria M. Kaspi*

briefly outshine all other cosmic gamma-ray sources combined, which, coming from an object only 12 miles (20 km) wide, is impressive. A magnetar's giant flare can release in a matter of seconds as much energy as the Sun produces in thousands of years.

Magnetars appear to come in two flavors: soft gamma repeaters (SGRs) and anomalous X-ray pulsars. The SGRs seem to be the more active of the two classes, exhibiting more frequent and larger bursts. However, some recently detected magnetars have demonstrated properties common to both groups at different times, suggesting either an evolutionary relationship between classes or a continuum of behaviors. Magnetars show relatively long X-ray pulsations, even when not undergoing huge outbursts. Their rapid rates of spin-down imply that magnetars have the highest known magnetic fields in the universe, upward of 10^{14} or even 10^{15} gauss — that's 100 to 1,000 times greater than regular radio pulsars.

Astronomers think magnetars' massive pyrotechnic displays result from crust breaking — a sort of star quake — caused by stress induced by the enormous internal magnetic field. Theory says that at these field strengths, currents within the star dissipate relatively rapidly, resulting in spontaneous magnetic field decay. ("Rapidly" means the field decays on a timescale of only a few tens of thou-

sands of years, unlike in regular radio pulsars, where the fields could be stable for billions of years.) In one theory, INSs started out as magnetars; these extreme magnets would possess the sort of magnetic fields required to result in INS-strength fields much later in life.

At the center

Any census of the neutron star zoo wouldn't be complete without mention of the handful of "compact central objects" (CCOs), so-named because they're

located in the centers of supernova remnants. The poster-child CCO is the central object in the young, oxygen-rich supernova remnant Cassiopeia A. Astronomers have studied this mysterious compact object for about 10 years, most often with the Chandra X-ray Observatory. Particularly puzzling is the CCO's lack of X-ray pulsations. We now classify three other previously mysterious CCOs as pulsars. Astronomers have shown that the CCOs at the centers of supernova remnants Puppis A, Kes 79, and PKS 1209–52 pulsate in X-rays, but with very low rotation slow-

A magnetar's giant flare can release in a matter of seconds as much energy as the Sun produces in thousands of years.

down rates. This implies far smaller magnetic fields than those of typical young radio pulsars. These surprisingly low magnetic fields inspired some researchers to dub them "anti-magnetars," a term that is still somewhat controversial and not universally adopted. One possibility is that these objects emit copious X-rays because they're still quite warm — remnants of the intense heat in their formation in supernova explosions. The neutron star was born spinning relatively slowly and with a low magnetic field.

A neutron star metamorphosis

Recent observations have revealed a connection between high-magnetic-field radio pulsars and magnetars. Astronomers know of seven radio pulsars that have spin-down inferred magnetic fields either extremely close to or higher than bona fide magnetars. My research group has spent years looking for magnetar-like X-ray emission from high-magnetic-field radio pulsars. In these sources, the magnetic field seems high enough that it ought to cause some stress or internal heating with an observational signature similar to that seen in magnetars. However, these

high-magnetic-field radio pulsars tend to be much fainter than typical magnetars, a puzzling result that keeps me up at night.

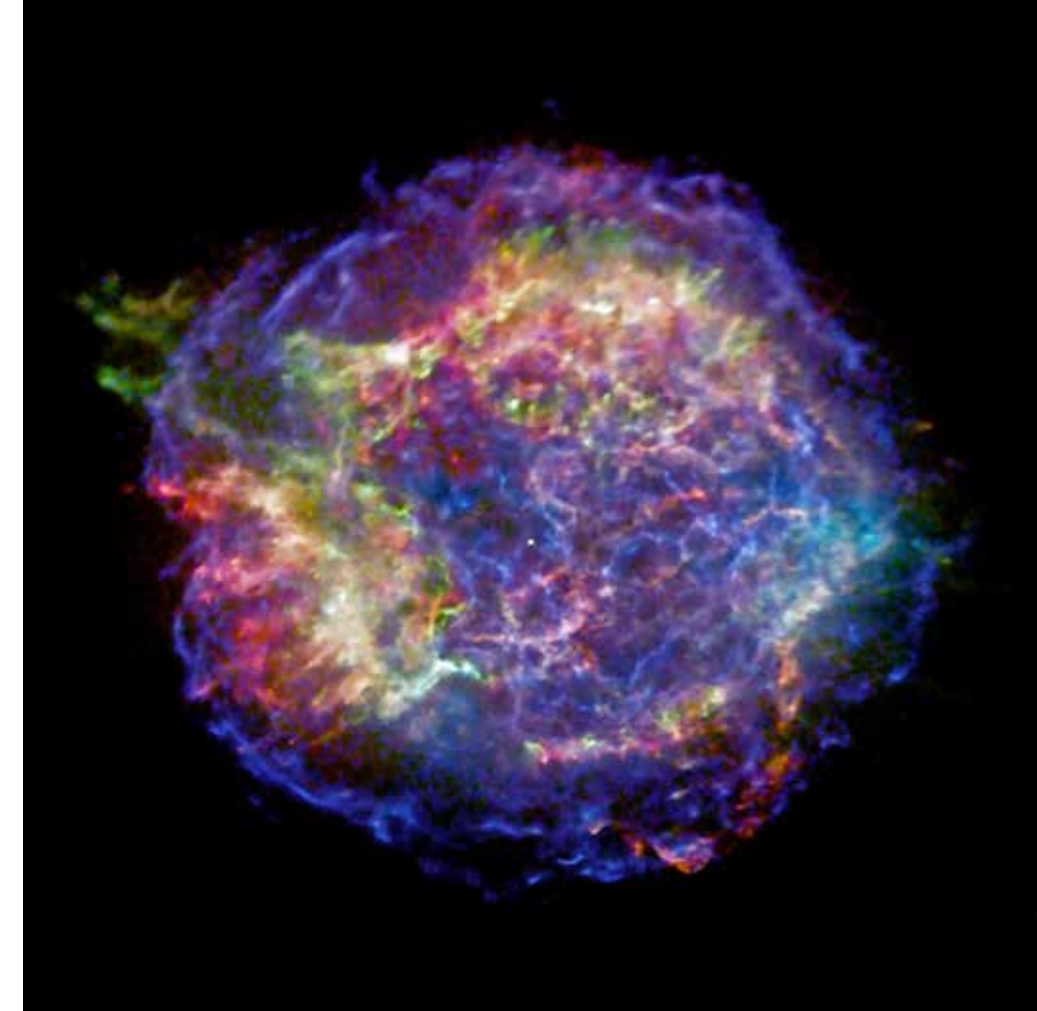
My insomnia was recently given some relief: In 2006, NASA's Rossi X-ray Timing Explorer detected a sudden, few-week X-ray outburst from the well-established, young, high-magnetic-field radio pulsar PSR J1846–0258 located in the supernova remnant Kes 75. Our team, led by my former student Fotis Gavriil, now at NASA's Goddard Space Flight Center, had been monitoring this source patiently since 1999 with no sign of activity. Why the object mysteriously chose 2006 as the year to reveal magnetar properties is a mystery. My student Margaret Livingstone and postdoctoral associate Stephen Ng have used recent X-ray observations to show that the pulsar is more-or-less back to its mild-mannered self, albeit with a few subtle yet intriguing changes. PSR J1846–0258 revealed an interesting Jekyll and Hyde routine.

Where young neutron stars fit

The challenge of the past decade continues today: to find a way to unify the surprising diversity of neutron star behaviors into a coherent picture. Interesting ideas are emerging. Astrophysicist José Pons, of Universitat d'Alacant in Spain, and collaborators have recently shown that thermal evolution and magnetic field decay are inseparable in detailed models of neutron star cooling. Temperature affects the electrical resistivity of the star's crust, which in turn affects how the magnetic field evolves. At the same time, the field's decay can produce heat that then affects how temperature evolves.

In this model, neutron stars born with large magnetic fields undergo significant field decay, which keeps them hotter longer. The theory says that magnetars are the highest magnetic field sources, which is consistent with what astronomers observe. The model also explains the puzzling fact that INSs, despite their proximity, all appear to have high magnetic fields relative to the RPP population. The most magnetized sources will remain hottest — hence most easily observed — for longest.

If this unification picture is correct, radio pulsars (and their RRAT subclass), INSs, and magnetars have such disparate properties simply because of their differ-



▲ **Cassiopeia A** is a supernova remnant that holds a compact object at its center. This young, central neutron star emits faint X-rays. *NASA/CXIC/SAO/D. Patnaude et al.*

► **Supernova remnant Kes 75** holds a peculiar pulsar — its magnetic field is more powerful than those of most pulsars, but not as strong as those of magnetars. For a few weeks in 2006, this object underwent sudden X-ray outbursts energetic enough to rival bona fide magnetars. Scientists are working to understand how this object fits into regular radio pulsars and the more extreme magnetars. *NASA/CXIC/GSFC/F. P. Gavriil et al.*



ent magnetic fields at birth combined with their present ages. The scarcely magnetized CCOs fit in as the neutron stars with the lowest magnetic field at birth; they are X-ray hot only because of their young age. High-magnetic-field radio pulsars seem to be a crossroads class. See "The lives of pulsars" on page 48.

There is no shortage of ideas for future tests of Pons' theory of neutron star "grand unification." Deep X-ray observations of high-magnetic-field radio pulsars can determine their characteristic light signatures (called spectra) and fluxes; shallow X-ray observations will monitor and search for magnetar-

like variations. Catching magnetars in outburst will constrain models of these magnets and help astronomers understand crucial parameters like outburst recurrence rate, which is central to understanding how many magnetars the galaxy contains. Systematic timing and spectral studies of newly discovered members of any of the classes will progress the field, given how few RRATs, INSs, CCOs, and magnetars are known. Clearly, neutron star astronomers have their work cut out for them. ☛

Visit www.Astronomy.com/toc for more about magnetars.