

THE LIFE OF A Neutron Star

THE DEATH OF AN AGED GIANT STAR CAN HERALD THE BIRTH OF SOMETHING MUCH STRANGER

By Joshua N. Winn

a

ll stories about neutron stars begin in one of two ways. One is to try to make your jaw drop by telling how many tons a teaspoonful of neutron-star material would weigh. The answer, for the uninitiated, is about three billion tons. And that's on Earth. The same teaspoonful weighs about 20 quintillion tons on the neutron star itself, or about a quarter of what the Moon would weigh on the Earth's surface.

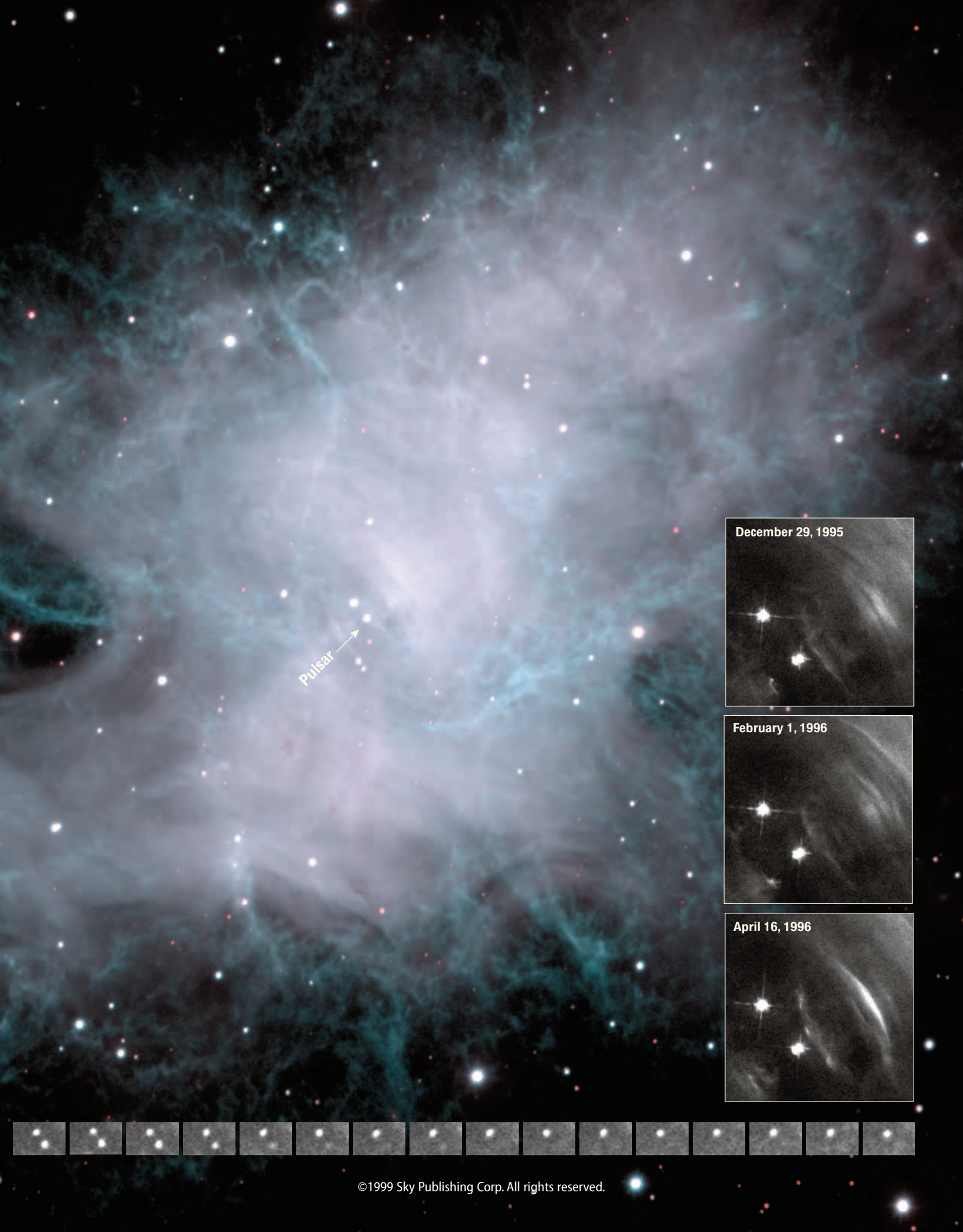
Right: The Crab Nebula supernova remnant is lit up by particles streaming at nearly light speed from the 16th-magnitude pulsar in its heart. This unusually high-resolution image was taken with the 3.5-meter WIYN Telescope at Kitt Peak, Arizona. Courtesy NOAO.

Below: The pulsar flashing in visible light. This sequence of frames steps through the pulsar's 0.03-second cycle a thousandth of a second at a time. In each cycle a strong, brief main pulse is followed by a slightly weaker, longer secondary pulse. Courtesy NOAO.

Far right: Changes near the Crab pulsar. Fine wisps in these Hubble Space Telescope images are moving away from the pulsar's equator at half the speed of light, while a stationary loop near the pulsar fades and brightens. Other images have shown evidence of jets from the pulsar's poles. The frames are 0.5 light-year wide. Courtesy Jeff Hester and Paul Scowen/NASA.

The second traditional opener is to tell the tale of Jocelyn Bell and Anthony Hewish, who in 1967 discovered that such jaw-droppingly dense objects actually exist. While studying the scintillation of quasars with a radio antenna array in Cambridge, England, they found a celestial source of radio pulses that blipped very precisely every 1.3 seconds. They considered all sorts of outlandish explanations for the blips, including superpowerful alien technology. Then, through hard work, they ruled them all out, one by one, except for the outlandish hypothesis that the pulses came from a spinning neutron star.

Before then neutron stars were generally regarded as airy theoretical speculations. Nobody anticipated that a rapidly rotating neutron star can emit intense beams of radiation that sweep around like lighthouse rays, flashing the worlds they intersect. If the beams sweep across Earth we see the neutron star as a radio strobe light. This strobing is the origin of the name *pulsar*.



Pulsar →



These two ways of introducing pulsars may be obligatory but are somewhat unhelpful. The problem with jaw-dropping statistics is that pulsars are too extreme. Is it really possible to appreciate, with Earthly analogies, a density of 10^{14} grams per cubic centimeter in a gravitational field of 600 billion gs? Even harder is the task of visualizing such a dense, city-size object as it spins furiously, squirting plasma from electric arcs near the poles

of its inconceivable magnetic field and swirling up a superfluid of neutrons in its interior.

The historical approach suffers from the fumbling history of the subject, which obscures the clear picture that finally emerged. The anecdotes surrounding each pulsar puzzle make for instructive tales of research science. But to get to know pulsars, it is probably better to step back. Try to imagine their births; follow their progress as they age; trace their possible fates over billions of years.

Happily, after 30 years of research enough is known of pulsars' lives to write such a biography, even if it must be tentative. Just as ordinary stars evolve from protostellar disks to the main sequence and thence to red giant-hood, so do pulsars have their own distinct and varied careers. And for those who enjoy biographies mainly for the unusual and exotic, pulsars do not disappoint.

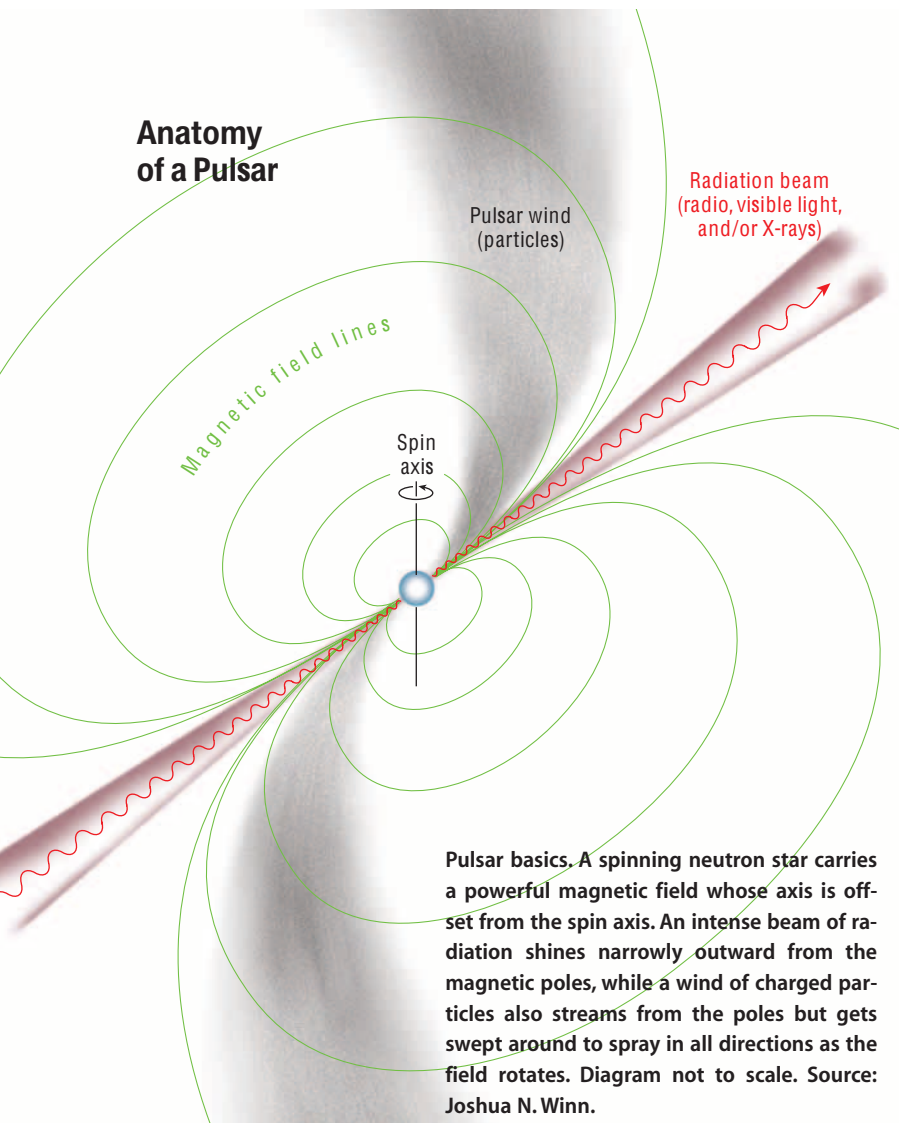
Amid Death, Birth

A biography usually begins with a birth. This one begins with a death. A massive giant star, one with about 10 times the mass of the Sun, has just run out of fuel and is about to expire.

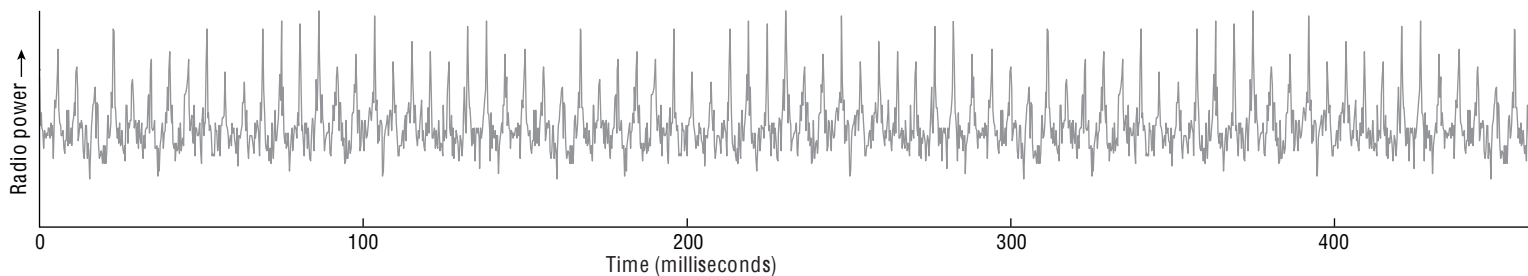
For tens of millions of years the star's core fused hydrogen into helium, thereby producing enough heat and pressure to resist the inexorable inward pull of its own gravity. Eventually the core ran low on hydrogen, contracted, heated up further, and began fusing the helium "ash" left over from hydrogen fusion to make carbon and oxygen. When the helium ran low, these new ashes of ashes were further compressed and heated until they became fuels themselves. So were subsequent rounds of ashes, down through the periodic table, each one fusing less efficiently and yielding less energy than its predecessor.

In the last few days of this increasingly desperate process, the star core burned its hoard of silicon into iron. This is the end. Fusing iron does not produce energy; it *requires* energy. Without a nuclear furnace to oppose it, gravity triumphs — very suddenly.

In less than a second the Earth-size core collapses until it is about 15 kilometers across, compressing electrons and protons so tightly that they merge into neutrons. When the neutrons become packed into contact with each other they can be squeezed no further, due to the repulsion of the strong nuclear force. The core bounces back slightly from its headlong collapse, sending a shock wave outward that turns the fearsome im-

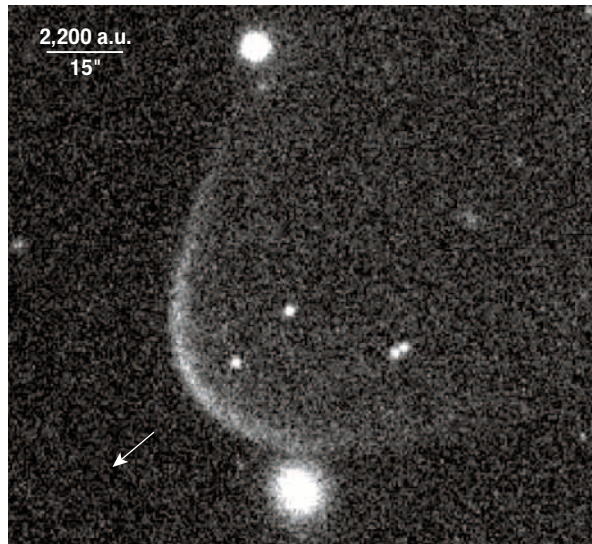


Below: A single second of data from the millisecond pulsar J0437-4715 in the constellation Pictor, the pulsar in the image on the facing page. Its radio blips come at a rate of 173.6 per second and often differ greatly in strength from one to the next. The data were obtained with the Parkes 100-meter radio telescope in Australia by Fronefield Crawford (MIT).



A NEUTRON STAR IS A GARGANTUAN ITS SURFACE. THIS VOLTAGE TEARS

The curved arc in front of the millisecond pulsar PSR J0437-4715 is a striking illustration of the sideways “kick” the pulsar received from its supernova birth. The pulsar closely orbits a white dwarf, the star visible 6 millimeters behind the lower-left edge of the arc. The arrow shows the pulsar’s direction of flight as determined solely by analyzing pulse timings. The arc is a “bow shock” produced where the pulsar’s wind plows into interstellar gas. Note how well the directions match.



plosion into a fearsome explosion: a supernova.

The shock wave erupts outward through the star, blowing away all the mass that is not locked up in the tiny core. The blast bellows out through the interstellar medium, eventually forming colorful, expanding loops and ribbons light-years across, such as those of the Crab Nebula in Taurus (on page 31) and the Veil Nebula in Cygnus.

This pyrotechnic display doubles as an obituary for the original star and a birth announcement for a freakish, undead offspring: a neutron star. This former stellar core has an atmosphere a few centimeters thick, a solid and superdense crust, and an even more compressed liquid interior, formed mostly of neutrons, that is as dense as an atomic nucleus.

A star must have the right mass, between about 8 and 15 times the Sun’s, in order to experience this funeral/baby shower. Less substantial stars do not explode at all; they puff off their outer layers gently and their cores become white dwarfs. Beefier stars explode so mightily that the incipient neutron star is blasted into smithereens or collapses all the way down into a black hole.

Pulsar Youth

The dead parent star bequeaths four extraordinary gifts to a newborn neutron star. The first is a very fast rotation rate, typically 50 times per second. This rapid spin may be a relic of the original star’s rotation (which was perhaps once per day); the core spins up during its contraction by the conservation of angular momentum.

Some of the spin may also be a byproduct of the second gift: a mighty kick that sends the neutron star flying from its birthplace at a speed that can exceed 1,000 kilometers per second. This kick may be caused by violent asymmetry in the supernova explosion.

The third gift from the supernova is extreme temperature. Because a neutron star has such a small surface

compared to its immense mass, it has a hard time radiating away much of its heat. Temperatures of 100,000° to 1 million degrees Kelvin have been measured for a few nearby neutron stars.

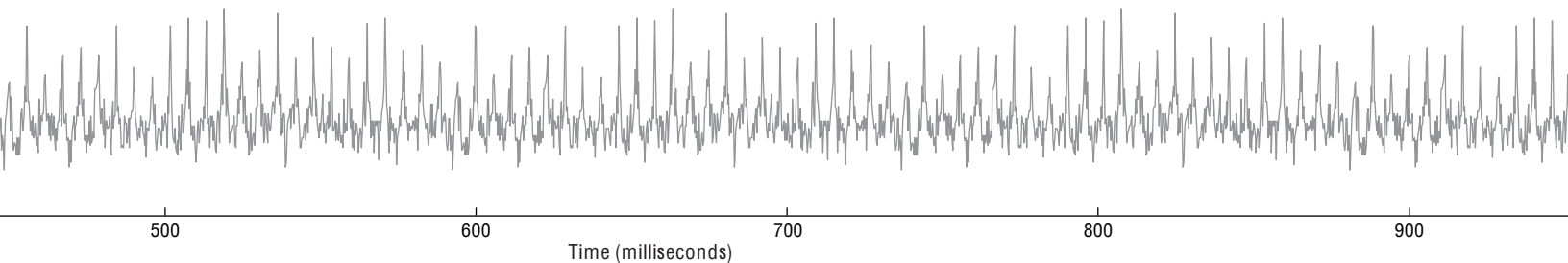
The fourth birthday gift is an immense magnetic field. Young neutron stars typically have magnetic fields a trillion times stronger than Earth’s. Again, this comparison is somewhat futile. It is easier to write the figure, 10^{12} gauss, than to ponder its twelve zeros.

Such a field should be intense enough to distort the iron atoms in the neutron star’s crust from their normal shape into long, spiny needles. This is a tough prediction to check. But the strong field has several other effects that are more readily observable.

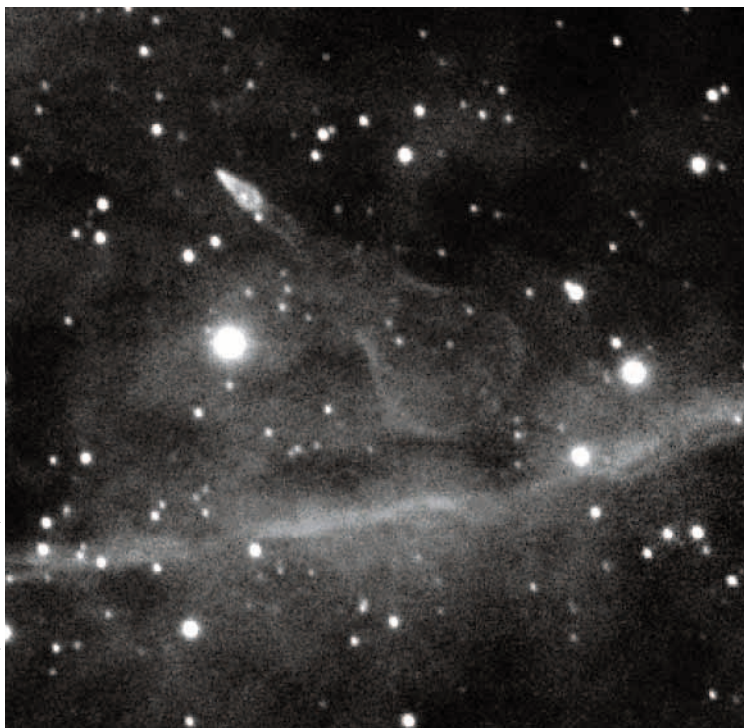
One of them comes about because moving magnets generate voltages, as Michael Faraday demonstrated in 1831. A neutron star is a gargantuan spinning magnet, so a tremendous voltage develops across its surface. This voltage tears electrons, positrons, and ions from the surface and flings them outward into space along the magnetic field lines. This is the pulsar wind.

The wind itself is usually invisible. But if it gets obstructed by the interstellar medium or detritus from the supernova, it becomes turbulent and deposits its energy in a little luminous cloud: a pulsar-wind nebula. By observing these, pulsar devotees can learn about not only the generation of the wind but also the composition of

SPINNING MAGNET, SO A TREMENDOUS VOLTAGE DEVELOPS ACROSS PARTICLES OFF THE SURFACE AND FLINGS THEM AWAY.



19TH-CENTURY PHYSICS SAYS THAT A RAPIDLY SPINNING MAGNET SHOULD BUT THIS DOES NOT EXPLAIN WHY THE RADIATION IS FOCUSED INTO DEATH



JIM CORDES (CORNELL UNIVERSITY)

The Guitar Nebula in Cepheus is an oddly shaped hollow formed by a pulsar wind. The guitar's bright neck is to the upper left; its dim body is just right of center. The million-year-old pulsar, at the tip of the neck, is zipping toward upper left at 1,700 kilometers per second — fast enough that it will escape our galaxy. This is one of nine pulsar-wind nebulae discovered to date.

0.033 second, but its period is growing longer by 0.0000000364 second each day. The lost rotational energy spews into the Crab Nebula; this is the energy source that is making the Crab glow.

The pulse period, P , and the spin-down rate, written \dot{P} ("P-dot"), are the two most important observable facts about a pulsar. If you trust the 19th-century formula telling how much power a rotating magnet radiates, you can use these two numbers to solve for the magnetic field strength. This is how the fantastically large fields of pulsars are deduced.

Astronomers are used to plotting the two most important observable facts for ordinary stars — luminosity and temperature — to form a Hertzsprung-Russell (H-R) diagram. It is an equally useful exercise to plot the P s and \dot{P} s of the thousand-plus known pulsars as the two axes of a graph. From a pulsar's position on the P - \dot{P} diagram, you can estimate the pulsar's magnetic field strength (which is proportional to the square root of P times \dot{P}) and its age (approximately P/\dot{P}). Just as the patterns in the H-R diagram led astrophysicists to an understanding of the main sequence and stellar evolution, the P - \dot{P} diagram has led to an understanding of pulsar evolution.

Anomalous Childhoods

Near the top of the P - \dot{P} diagram on the facing page are four red points, representing a group of unruly young pulsars that have been the subject of intense speculation in the last few years. For some reason they seem to have been born with exceptionally high magnetic fields, 100 times or more than the already ludicrous fields of ordinary pulsars. Consequently they radiate like mad, slow down rapidly, and are therefore seen with rather long periods of 5 or 10 seconds. For some reason, perhaps owing to their intense magnetism, they are seen pulsing only in X-rays rather than radio waves. For all these reasons they are called "anomalous X-ray pulsars," or AXPs.

The two yellow dots, representing close cousins of the AXPs, are named "soft gamma-ray repeaters" (SGRs) because they occasionally lash out with a violent tantrum of gamma rays. There are actually four known SGRs, but \dot{P} has not yet been measured for one of them, and P has yet to be measured for the fourth. In fact, until 1998 it was not obvious that SGRs had anything to do with pulsars, because it was only then that X-ray pulses were reported between the gamma-ray eruptions.

Do not be fooled by the label "soft." This adjective describes the relatively low energy of each individual gamma-ray photon, but the total output of an eruption

the surrounding medium.

A second consequence of the intense magnetic field is, of course, the pulsing itself. The magnetic poles of neutron stars emit narrow beams of radiation in addition to the wind of particles. The magnetic axis is offset from the pulsar's spin axis (much as the Earth's magnetic and geographic poles do not coincide, though presumably for entirely different reasons). So the beams wheel around the sky as the neutron star rotates. The beams of many young neutron stars, such as the Crab and Vela pulsars, overflow with the whole electromagnetic cornucopia from radio waves to visible light to gamma rays. Older pulsars usually stick to radio.

How does the magnetic field generate such intense beams of radiation? Another bit of 19th-century physics says that a rapidly spinning magnet should radiate electromagnetic waves. But this does not explain why the radiation is focused into Death Star-caliber beams. Proposing theories for how this happens is a cottage industry. Most of the guesses say the beams arise among electrons that are torn from the magnetic poles in bunches, thereby acting coherently, much as the atoms in a laser radiate coherently.

Powerful as pulsar radiation beams are, they represent only about a thousandth of the total power that pulsars fling away into their surroundings. This estimate follows from the observation that pulsars tend to slow down. Their rotational energy must be going somewhere, and the energy in the pulsations is not nearly enough to account for it. The other 99.9% is probably fed into the pulsar wind and other, unseen, radiation. The Crab Pulsar, for example, ticks once every

RADIATE ELECTROMAGNETIC WAVES. STAR-CALIBER BEAMS.

The periods and spin-down rates of 722 pulsars. This “*P- \dot{P}* ” diagram is to pulsars what the Hertzsprung-Russell diagram is to stars: a way to sort out the different varieties and track their evolution. A pulsar’s position in the diagram tells its magnetic field (green lines) and age (red lines). When a pulsar evolves to the right across the “death line,” it stops pulsing.

is fearsome. Consider the one detected on August 27, 1998, by seven independent satellites. It came from an SGR in the constellation Sagittarius and was the most intense burst of gamma rays ever recorded from space — powerful enough to cause a brief but very obvious change in the ionization state of the Earth’s ionosphere (January issue, page 22).

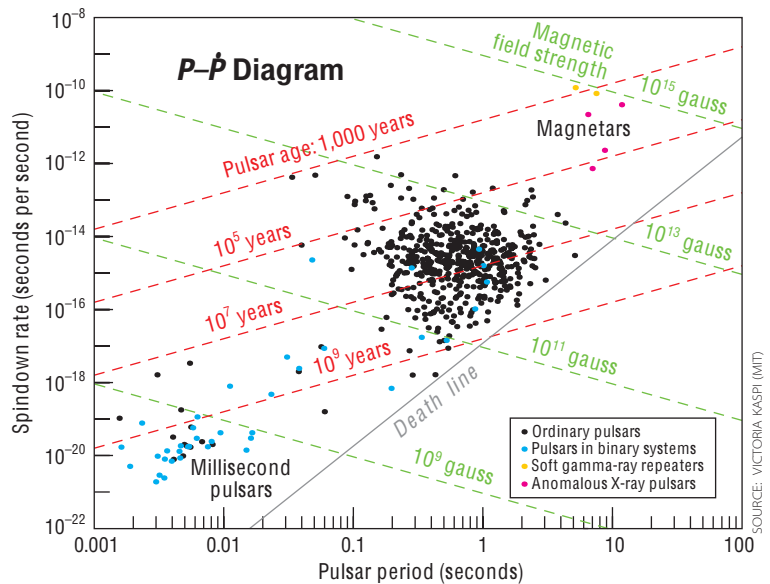
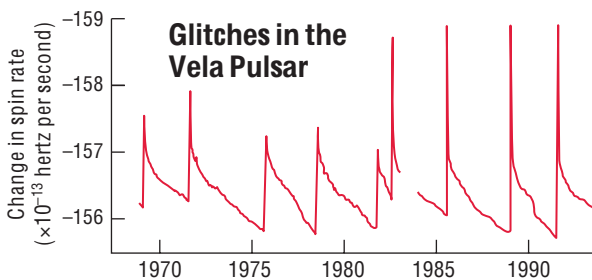
The best guess for the cause of such a gamma-ray storm is a pulsar-quake. The crust of a pulsar is composed of a rigid, superdense form of iron, which quivers in response to any variations in the magnetic field. Enormous stresses in the crust develop until eventually it cracks, like a fabulously exaggerated earthquake, releasing a blast of energy.

We can therefore tentatively identify AXPs and SGRs as two names for basically the same thing: unusually magnetic neutron stars. Some astronomers have taken to calling them both “magnetars.” But this is the most speculative part of the biography. These objects may represent an important alternative childhood for pulsars, though some theorists are holding off on this interpretation until certain questions can be answered. For example, exactly why, and how often, are pulsars endowed with such potent magnetism in the first place? And why do they pulse in X-rays, but not in radio waves?

Adolescent Crises

Less controversial is the story of how the bulk of known pulsars, represented by the mass of black dots in the center of the *P- \dot{P}* diagram, age and evolve. These spend their childhoods as radio pulsars. Because they are constantly flinging away their rotational energy, they slow down as they grow up. An aging pulsar therefore follows a rightward track (increasing *P*) on the *P- \dot{P}* diagram.

The slowing process is usually extremely steady. But a few young pulsars have adolescent crises called “glitches.” A glitch is an abrupt little jump in spin rate: a minor act of rebellion against the monotonous slowdown.



Every few years, for example, the steady stutter of the Vela pulsar quickens (almost instantaneously) by a few extra parts per million, then resumes its slowdown. This may not sound like much. But because neutron stars are so massive and spin with so much inertia, even such a small speedup indicates a huge shift of rotational energy.

Glitches are rare but scientifically valuable. They are observable manifestations of a pulsar’s inner workings, like the telltale waveforms of an electrocardiogram. Glitches hold out the hope that we can learn more about the rather mysterious nuclear processes that take place deep within neutron stars, amid pressures and densities far higher than the wildest dreams of Earth-bound experimenters. This means you must brace yourself for a rather exotic explanation of glitches.

At first glitches were thought to be tiny starquakes (with crustal readjustments of about 1 micron) caused by stresses that develop in the crust as a pulsar slows down. But these days, at least some of them are believed to be something less obvious. They probably originate beneath the crust of a pulsar, in a dense mantle of heavy nuclei permeated by a superfluid of neutrons. A superfluid is a liquid in which the most bizarre aspects of quantum mechanics, usually hidden away at the level of single atoms, come out to prance upon a large-scale stage. One consequence is that superfluids, famously, lack viscosity, allowing them to flow effortlessly through even the tiniest pores.

Nevertheless, there is one way in which the nuclei of the mantle obstruct the flow of the liquid. The angular momentum of a superfluid is broken up into discrete chunks — tiny quantized vortices instead of big, smooth swirls. These microscopic vortices can become pinned to heavy nuclei.

As the pulsar slows down, the vortices migrate outward to the crust in order to adjust to the new speed. The nu-

Most pulsars slow down at a very steady rate, but a few show slight, sudden “glitches” in their periods. The young Vela Pulsar is especially glitch-prone. Plotted here are tiny accelerations (upward jumps) and decelerations (downward drifts) in the neutron star’s spin during 24 years. From *Pulsar Astronomy* by Andrew G. Lyne and Francis Graham-Smith.

lei resist this flow by pinning some of the vortices. From time to time the outward force overcomes this resistance catastrophically; the vortices fly outward all at once and deposit their rotational momentum into the crust, thereby causing it to speed up slightly and abruptly.

Marriage

After 10 million years or so, there comes a point when the pulsar stops pulsing. It eventually spins too slowly to induce the powerful voltage that sustains the radiation beams. The beams fade below detectability or even shut off entirely. This is why there are no observed pulsars in the lower-right portion of the P - \dot{P} diagram, beyond what is called the “death line.” After they cross this line, pulsars rest in peace.

This might seem to be the end of the pulsar biography. It is indeed the end for a solitary pulsar, a spinning spinster with no companion. But if a pulsar is a member of a close binary-star system, much more interesting things lie ahead. As with human marriages, the partnership can cause a profound renewal.

At first blush it seems unlikely that a pulsar would have a companion. Wouldn't the supernova that produced the pulsar — powerful enough to illuminate a galaxy and kick away the pulsar at 1,000 km per second — always break a binary system apart? Not always. A famous theorem predicts that if less than half the total mass of the binary is ejected during a spherical explosion, the partnership stays intact. The situation is more complicated for an asymmetric explosion, but in fact

IF A NEUTRON STAR IS ORBITED BY IT UP UNTIL IT SPINS ALMOST 1,000

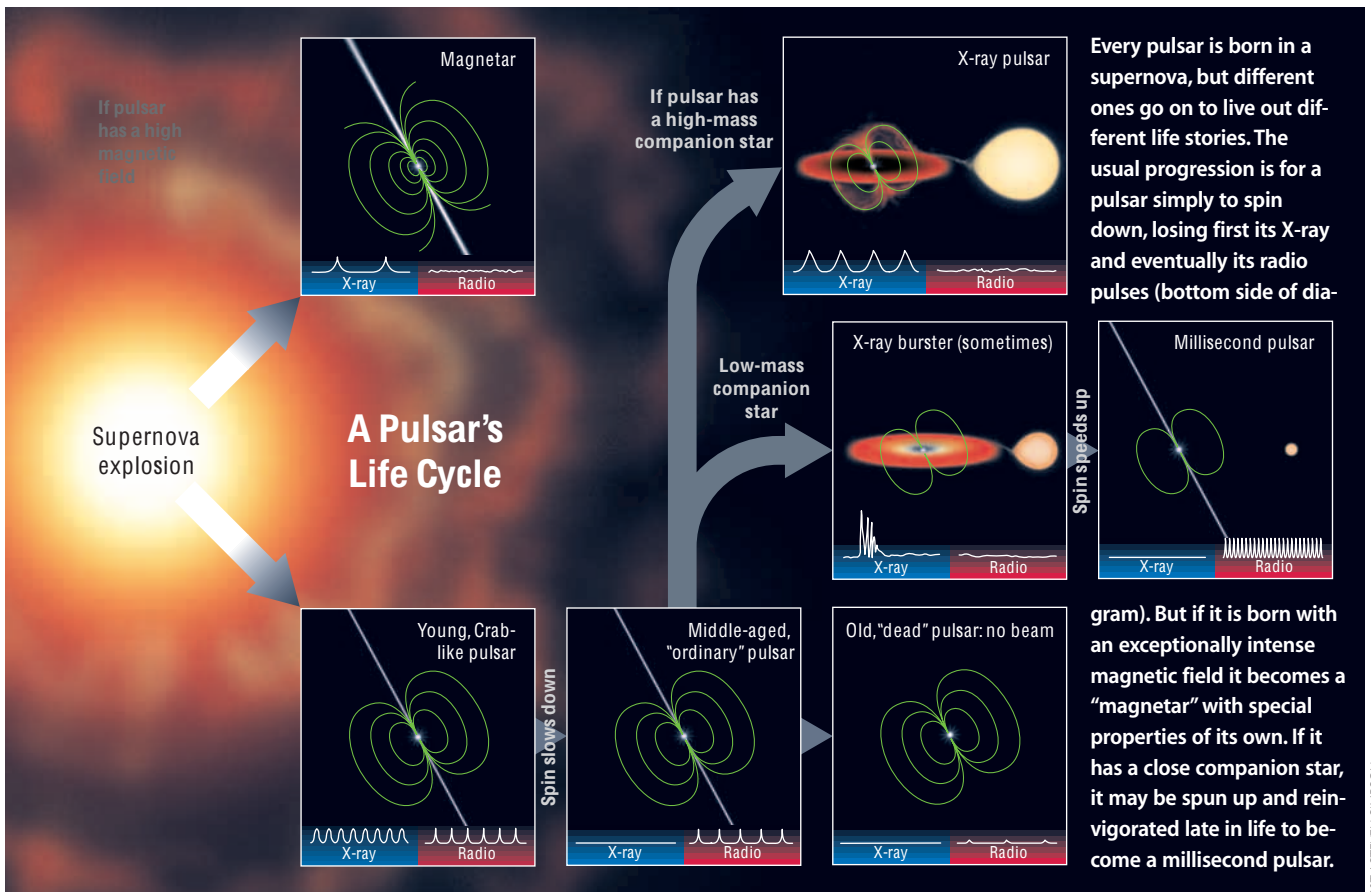
dozens of pulsars show a precisely periodic modulation in their pulse rates that can be explained only by the to-and-fro tugging of an orbiting companion.

What happens next in such a system depends upon the companion's mass. High-mass stars evolve into red giants much more quickly than low-mass stars do, since they are hotter and use up their hydrogen fuel more rapidly. We must follow each of these two possibilities, high-mass and low-mass, separately.

First we'll trace the case of a high-mass companion — one with, say, 15 solar masses. This sort of star runs low on hydrogen and becomes a red giant after little more than 10 million years. The red giant overflows its personal space; its outer layers are shorn off by the tidal force of the neutron star. (We should stop calling it a pulsar since it has probably stopped pulsing by now.)

This material does not drop straight onto the neutron star's surface, however. Because of its angular momentum (sideways orbital momentum), it forms a thin disk of gas, an *accretion disk* that spirals in like a whirlpool. Along the way the gas is sheared by friction until it becomes hot enough to emit a torrent of X-rays. The system becomes a “high-mass X-ray binary.” These often appear in the sky as randomly flickering X-ray sources.

At this stage the neutron star may also resume puls-



A CLOSE STELLAR COMPANION, INFALLING MATTER CAN TORQUE TIMES A SECOND.

ing — but only in X-rays and by an entirely different mechanism than the one powering its youthful career as a radio pulsar.

This mechanism relies on the neutron star's strong magnetic field. The accretion process tends to weaken the magnetic field of a neutron star over millions of years, so the oldest neutron stars tend to have weak fields — a trend visible in the $P-\dot{P}$ diagram on page 35. However, a high-mass X-ray binary must be relatively young (because high-mass stars themselves do not live very long). So its magnetic field does not have time to decay very much. The infalling material becomes locked to the strong field lines, which converge at the magnetic poles. The accreting material is therefore channeled like the arc of a welder's torch down onto the poles, which glare brightly in X-rays. As the neutron star rotates, these hot spots flash in and out of view and we see flashes of X-rays.

Eventually the companion star may be totally unwrapped by accretion, or else it too may explode in a supernova, presenting another challenge to the binary partnership.

An example of such a twice-tested marriage is PSR 1913+16, a binary pair of neutron stars near the Aquila-Sagitta border locked in a close, 7.75-hour orbit. Only one of them is still pulsing. This system is famous because the periodic modulations in the pulsar's rate can be measured accurately enough to reveal that the orbit is losing energy — the stars are slowly, almost imperceptibly, spiraling in toward one another. The rate of this energy loss is precisely the rate at which the two whirling masses should radiate away energy as gravitational waves. This discovery, the first confirmation that gravitational radiation exists, earned Joseph Taylor and Andrew Hulse the Nobel Prize in physics in 1993.

Neutron stars with low-mass companions (say, two solar masses) must wait much longer, typically billions of years, for their opportunity to shine as X-ray binaries. Only then do their slowly evolving companions swell into red giants and spill material into an accretion disk. By then the magnetic field has decayed to 1 percent or less of its original value, because accretion weakens it.

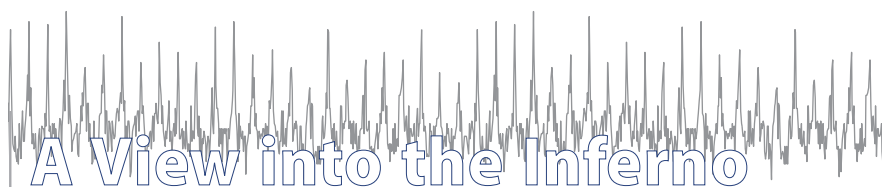
This is still a princely magnetic field, compared to those we are used to, but it almost never suffices to channel the infalling matter into hot spots on the neutron star's surface. Instead, the accretion disk spreads the material more evenly around an equator. The star still flickers erratically as a “low-mass X-ray binary” but usually does not pulse.

Resurrection

Beneath all the flickering, something wonderful may be happening. The neutron star in a low-mass X-ray binary, which long ago slowed down and hobbled past the death line, can be completely rejuvenated. In fact, its companion may even cause the pulse of the elderly

neutron star to race more rapidly than it ever did as a youth. As the material from the companion spirals down through the accretion disk, its orbital speed grows. Just before the material finally skims into the neutron star's surface, it is orbiting faster than the neutron star is rotating — so when it crashes it speeds up the star's spin. In this way the infalling matter can torque up the neutron star until it is spinning almost a thousand times per second.

The freshly invigorated neutron star can make itself known to the outside world in three different ways. First, it may reveal its spin rate directly by pulsing in X-

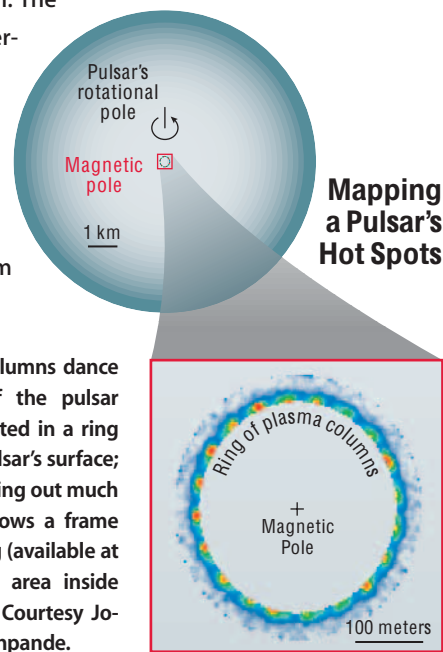


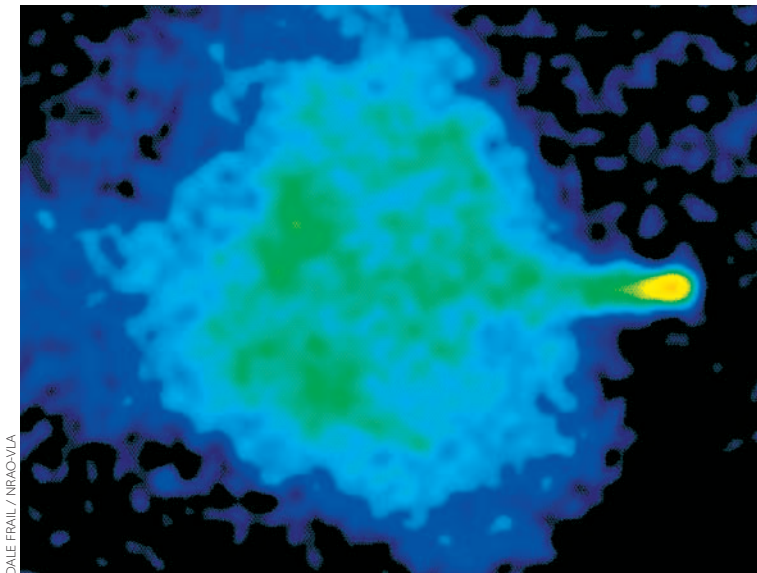
A View into the Inferno

An extraordinary map of detail at the surface of a neutron star was recently announced by Joanna Rankin (University of Vermont) and Avinash A. Deshpande (Raman Research Institute, India). By analyzing “subpulses” in the pulsar B0943+10, located 3,000 light-years away in Leo, they were able to map a ring of 20 emission beams that marched around the star's magnetic pole every 40 seconds. The beams probably represent tall columns of plasma — giant electric sparks seen end on, the channels for the intense voltage erupting from the star's surface and feeding a radio-emitting region some 100 to 300 kilometers up.

The ring of columns was only 300 meters across at the star's surface. Each column was only about 20 meters wide, yet it emitted a thousandth the power of the Sun. The ring remained stable for several minutes of observation as it danced its circle; then it broke into just two spots. Mapping such small features so far away was equivalent to resolving a bacterium at the distance of Jupiter.

Tall electric sparks or plasma columns dance around the magnetic pole of the pulsar B0943+10. The columns are rooted in a ring just 300 meters across on the pulsar's surface; they emit radio waves after fanning out much higher up. The enlargement shows a frame from a movie of the swirling ring (available at www.uvm.edu/~jmraink/). The area inside the ring could not be mapped. Courtesy Joanna Rankin and Avinash A. Deshpande.





This radio image (obtained with the Very Large Array) shows a pulsar emerging like a bullet from the Duck Nebula, an obscure supernova remnant in Sagittarius. The pulsar was kicked hard enough at birth to overtake the decelerating shell of the supernova explosion. The radio emission near the pulsar comes from its wind striking interstellar gas.

long-dormant radio beams, but the beams remain muffled until the accreting material thins out.


This is the origin of the millisecond radio pulsars — the spry senior citizens of the pulsar population, which occupy the small clump in the lower left corner of the $P-\dot{P}$ diagram. The fastest one known rotates 667 times per second. This, for a city-size ball as massive as the Sun, is supremely impressive. In addition, the pulse rates of these millisecond pulsars are extraordinarily stable — as precise as the best atomic clocks or better, when averaged over many years. Their spin-down rates are so slight that it takes billions of years for them to slow by much. They have never been seen to glitch. In fact, some scientists hope that the world's system of Coordinated Universal Time might be smoothed out a bit by routinely consulting the millisecond pulsars. Nature has beaten the best clock technology we have yet invented — with a simple mechanical clock, the steady spinning of a massive ball.

The End

It is with these wizened oracles of time that our biography ends. It has been a long journey, from birth in a supernova to a youth of rapid pulsing to a quiet midlife interlude before, in some cases, intricate interactions with a companion.

Some individual pulsars do not fit neatly into this group biography. For example, the 6.2-millisecond pulsar PSR B1257+12 in Virgo has at least two planets orbiting it. The precision of this pulsar clock is fine enough to reveal the gravitational tugs of these bodies, which have masses of about 3.4 and 2.8 Earths. There is no question whatever that they are real; even the slight gravitational perturbations that the planets exert on each other have been tracked in the pulse rate! How such bodies got there (presumably after the supernova exploded) is surely an interesting tale, one that remains unknown.

Furthermore, since pulsar science is presently so active, some of these episodes will undoubtedly have to be revised soon — the role of the magnetars, for example. Entirely new episodes may have to be added — such as, for instance, if the cores of some neutron stars are so highly compressed that they consist not of neutrons but some more exotic form of matter.

What may mean most to those outside the experts' corridors, however, is simply the realization that utterly fascinating physical events can still lie in a star's future long after its ordinary nuclear-powered lifetime ends. 

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rays if its magnetic field is still strong enough to channel the accreting material into a hot spot. This should be quite rare. As mentioned earlier, it is usually the high-mass X-ray binaries that are young and strongly magnetic.

That may be why only one such recycled X-ray pulsar has ever been discovered. Its name is SAX J1808.4–3658, and it pulses at the breathtaking rate of 402 times per second. Discovered in May 1998, it is a clear case of an old neutron star caught in the act of rejuvenation.

Another, more subtle, way that recycled pulsars reveal their fast spin rates is during an X-ray burst, a magnificent flare that low-mass X-ray binaries sometimes emit. These bursts usually happen because a critical mass of

NATURE HAS BEATEN THE BEST CLOCK TECHNOLOGY YET INVENTED — WITH A SIMPLE MECHANICAL CLOCK, THE STEADY SPINNING OF A MASSIVE BALL.

fresh nuclear fuel has been spread onto the neutron star's surface by the accretion process. The surface ignites in a huge thermonuclear blast. These explosions are the X-ray analogs of classical or recurrent novae (which happen on the surfaces of white dwarfs). Within these X-ray bursts are faint, very rapid, almost-periodic X-ray flutters. Nobody is sure what the flutters represent, but perhaps an epicenter of the explosion on the neutron star's surface acts as a temporary hot spot, causing the neutron star to look like a temporary X-ray pulsar.

The last way that an elderly, spun-up neutron star can display itself is by waiting until the accretion finally stops (because the companion star's outer layers are totally devoured) and then turning on again as a radio pulsar. How this happens, in detail, is unknown. Apparently the rejuvenation process suffices to reignite the