NEWS

The Pulsar Menagerie

The lighthouses of the universe take on countless guises, as astronomers have learned to their ongoing delight during the last 4 decades

When pulsars spun their way into astronomical lore in 1967, their debut was hardly glamorous. The radio telescope that found them was not a photogenic dish, but a 4.5-acre British field wired with 2048 gangly aerials. The first signal, spotted in August, was an odd "piece of scruff" embedded within kilometers of chart recordings. Puzzled for months by that flickering light, the University of Cambridge research team called it LGM-1, in case it came from little green men.

By December, it was clear that the pulses—precisely one every 1.33731109 seconds—streamed from an exotic, compact body. The team's first report, led by radio astronomer Antony Hewish, proposed "stable oscillations of white dwarf or neutron stars." But a blaze of research in 1968 left no doubt that the group had unveiled an object prophesied in the 1930s by astrophysicists Walter Baade, Fritz Zwicky, and Lev Landau: an ultradense neutron star, perhaps 20 kilometers across, left by a massive star's death in a supernova explosion long ago.

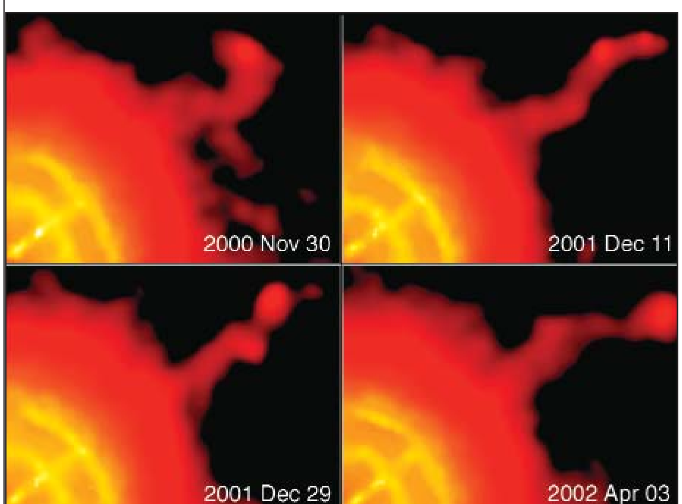
Hewish went on to share the 1974 Nobel Prize in physics—an honor that also should have recognized his graduate student Jocelyn Bell Burnell for her central role in the discovery, many astronomers feel. Since then, a stream of findings has made pulsars the darlings of high-energy astrophysics for theorists and observers alike. "Pulsars have blessed us with stunning and unexpected discoveries every few years," says astrophysicist David Nice of Princeton University in New Jersey.

The iconic Crab

Among the 1500 pulsars now known, just one has an ironclad link to a fiery birth display witnessed by scientists: the famous pulsar inside the Crab Nebula. Chinese astronomers first recorded the Crab supernova as a "guest star" on 4 July 1054. Today, the pulsar's fierce output of energy lights up the blast's expanding tangle of debris.

Giant radio dishes in Green Bank, West Virginia, and near Arecibo, Puerto Rico, spotted the Crab pulsar in 1968. Astronomers were startled by its rapid-fire blips, 30 each second. Even more thrilling was a perceptible change in its spin rate: The Crab's clock was losing 36.5 billionths of a second per day.

The results vindicated a bold model put forward by theorist Thomas Gold of Cornell University in Ithaca, New York. In Gold's view, pulsars were spinning neutron stars that gradually wound down under the influence of intense magnetic fields. Energy lost by a pulsar's deceleration, he reasoned, would illuminate the nebula. Part of the energy would stream into space within two cylinders of light, sweeping through the cosmos like lighthouse beams as the pulsar spun. The broad details of Gold's model still reign today.



High-energy fire hose. The Vela pulsar (bottom left of each image) expels a rapidly fluctuating jet of particles half a light-year long, revealed by the Chandra X-ray Observatory.

The Crab quickly rose to iconic status. But as it turns out, the pulsar is far from typical. It's unusually bright, spewing a huge portion of its energy into radio waves and x-rays. Moreover, it raised hopes that hordes of pulsars would turn up in other supernova remnants, but most searches have struck out. "There is another branch of compact objects created, and they're definitely different from the canonical pulsars everyone expected," says astrophysicist Patrick Slane of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts.

Einstein's test bed

Another graduate student was central to the next pulsar triumph. This time, the Nobel committee rewarded both the student and his adviser with the physics prize, in 1993.

The setting was a search for new pulsars in 1974 at Arecibo Observatory. Russell Hulse, working under astronomer Joseph Taylor of the University of Massachusetts, Amherst, devised a computer algorithm that picked out pulsars 10 times more sensitively than did previous efforts. One object, called PSR B1913+16 for its sky coordinates, spun 17 times per second—but its timing pattern kept changing. "My reaction was not 'Eureka, it's a discovery,' but 'Nuts, what's wrong now?' " recalls Hulse, now a fusion scientist at the Princeton Plasma Physics Laboratory. "I was frustrated and annoyed."

Vexation turned to elation when Hulse divined the truth: The pulsar darted in an 8-hour orbit around another body. Taylor rushed to Arecibo, and the pair confirmed the system that became known as the Hulse-Taylor binary. The pulsar's orbit revealed that its partner was a nonpulsing neutron star. Taylor worked with astrophysicist Joel Weisberg, now at Carleton College in Northfield, Minnesota, and others to show that Einstein's general theory of relativity was needed to describe the strong gravitational embrace of the two objects—the first such test outside our solar system.

Most critically, the team showed that the two bodies inexorably spiral together, at exactly the rate predicted by Einstein 60 years earlier. Gravitational waves carry away the lost orbital energy. "It's indirect, like showing that radio waves exist because you know the radio transmitter uses power," Hulse says. "But it was the first evidence for the existence of gravitational waves."

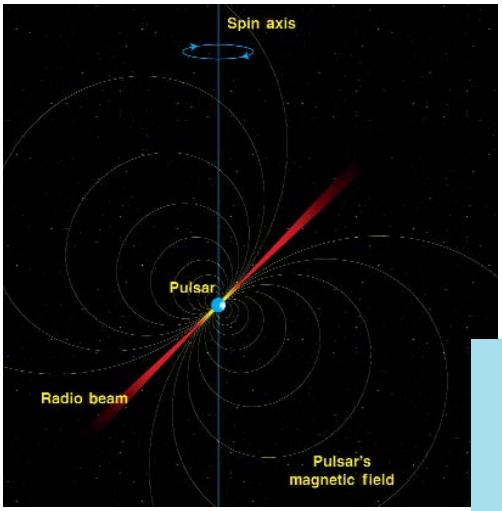
Outrageous spin

By the late 1970s, research on pulsars had dwindled, says astronomer Donald Backer of the University of California (UC), Berkeley. It was a perfect time for a whopper, and Backer's team found it at Arecibo in 1982: PSR B1937+21, rotating a jaw-dropping 642 times per second. Yet another graduate student, Shrinivas Kulkarni (now at the California Institute of Technology in Pasadena), made the key initial find at the telescope.

This "millisecond pulsar" sparked a theory frenzy. It was nowhere near a supernova remnant, but its rotational speed—exceeding 1/10th the speed of light at its equator—looked like that of a freshly minted neutron star. Astrophysicists Malvin Ruderman, the

CREDIT: NASA/CXC/PSU/G. PAVLOV ET AL.

late Jacob Shaham, and colleagues at Columbia University in New York City suggested that the pulsar was old but got a new lease on life by yanking material from a companion star. Gas plunging onto the greedy neutron star spun it up to outrageous rates, like a mer-



Tilt-a-whirl. Misalignment between a pulsar's spin axis and magnetic axis sends an inclined radio beam whirling into space.

ry-go-round getting constant shoves.

Since then, astronomers have found nearly 100 such "recycled" pulsars. Some are isolated, but others have a partner in the process of being eaten or literally blown away by the pulsar's radiation. For instance, the "black widow" pulsar, found in 1988 by astronomer Andrew Fruchter of the Space Telescope Science Institute in Baltimore, Maryland, and co-workers, may evaporate its low-mass companion star within a billion years.

Oddly, searches have yet to expose a faster pulsar than PSR B1937+21. "It seems the spin-up mechanism can't push them much below 1.5 milliseconds," says astronomer Richard Manchester of the Australia Telescope National Facility in New South Wales. A more frantic spin rate may make neutron stars so unstable that they emit gravitational waves, putting the brakes on their acceleration.

The planetary surprise

Millisecond pulsars are the best clocks in the universe, slowing down by less than a billionth of a second per year. "They're like perfect flywheels, almost as simple as any of Einstein's *Gedanken* [thought] experiments," says astrophysicist Stephen Thorsett of UC Santa Cruz. This precision led to the next pulsar bombshell in 1992: the first planetary system beyond our own.

The "pulsar planets" surfaced when astrophysicist Alexander Wolszczan of Pennsylvania State University, University Park, and radio astronomer Dale Frail of the National Radio Astronomy Observatory in Socorro, New Mexico, saw minuscule fluctuations in the arrival times of pulses from PSR B1257+12. Their model suggested that two planets, a few times larger than Earth, tugged the pulsar to and fro ever so slightly as they orbited.

The claim was controversial, but Wolszczan thinks the impact was worth the early catcalls. "After a relatively short period of disbelief, the average reaction was that the existence of planets around a neutron star must mean that the planet-production process in general was a robust one," he says. Indeed, more than 100 other planets are now known, although PSR B1257+12 is still the only burned-out corpse of a dead star known to have a planetary system.

The pulsar is special in another way, too: Further analysis of its signals revealed a closely orbiting third planet, much smaller than the other two. The masses and relative positions of the three planets are "shockingly similar to our inner solar system," Wolszczan notes.

Double the pleasure

The latest stunner was anticipated for years: two pulsars deadlocked in a tight orbit. The new system, detected by the Parkes Radio Telescope in Australia and announced in January, will likely provide even more stringent tests of general relativity than the Hulse-Taylor binary (*Science*, 9 January, p. 153).

Already, astrophysicists are mystified by the energetic interplay between the neutron stars. Intense winds from the faster rotating pulsar create a tear-shaped shock wave around the slower pulsar. Teams are probing this process as one pulsar dips behind the other, every 2.4 hours.

In one interpretation of the data, the fast pulsar is churning out 100,000 to 1 million times more charged gas than expected from the seething region above its surface, says theorist Jonathan Arons of UC Berkeley. "The physics is not quite incredible, but it's close," he says.

As searches for new pulsars continue, astronomers await the next varieties on their wish list. These include a pulsar orbiting a black hole and a submillisecond pulsar, spinning faster than 1000 times per second. "The record of history in this field shows that if we can think about it, we'll find it," says Backer.

And after 37 years, the remaining questions haven't lost any luster. Why do nearly all pulsars contain about 1.35 times the mass of our sun? How do some supernovas expel pulsars into space at more than 1000 kilometers per second? What controls whether pulsars are born as "magnetars," with ultrastrong magnetic fields (see p. 534)? Stay tuned; more pulsar programming is heading your way.

–ROBERT IRION

Pulsars Surf the Cosmic Waves

Imagine floating in the middle of a large lake, where you can't quite see the shore. If people throw big rocks into the water, you'll feel a riot of ripples. With the right tools, you might be able to tell how many rocks splashed in—and how big they were.

In space, the "rocks" are binary pairs of giant black holes at the cores of galaxies, and the "ripples" are gravitational waves. Long before they crash, the spiraling black holes churn the waters of spacetime. The waves, spanning light-years, traverse the entire universe. As each one passes by, it distorts the apparent distances between objects in a subtle but distinct pattern.

Millisecond pulsars surf those waves. As they bob to and fro, their signals arrive in telescopes on Earth at slightly different times. By timing an array of such pulsars for years, astronomers think they might spot the imprints of gravitational waves in this decade—perhaps beating out several major physics experiments on the ground.

Astronomer Donald Backer of the University of California, Berkeley, thinks his team is "within a factor of 5" of the necessary precision to detect the waves, using about a dozen pulsars in the Northern Hemisphere. And in Australia, a group is using the Parkes Radio Telescope, which has discovered two-thirds of all known pulsars. But the project is no day at the park, notes Richard Manchester of the Australia Telescope National Facility: "You need 20 pulsars in all quadrants of the sky, submicrosecond times of arrival, and weekly or biweekly monitoring. That's hard work."

–R.I.

Blip, blip. Australia's 64-meter Parkes Radio Telescope finds pulsars in bunches.