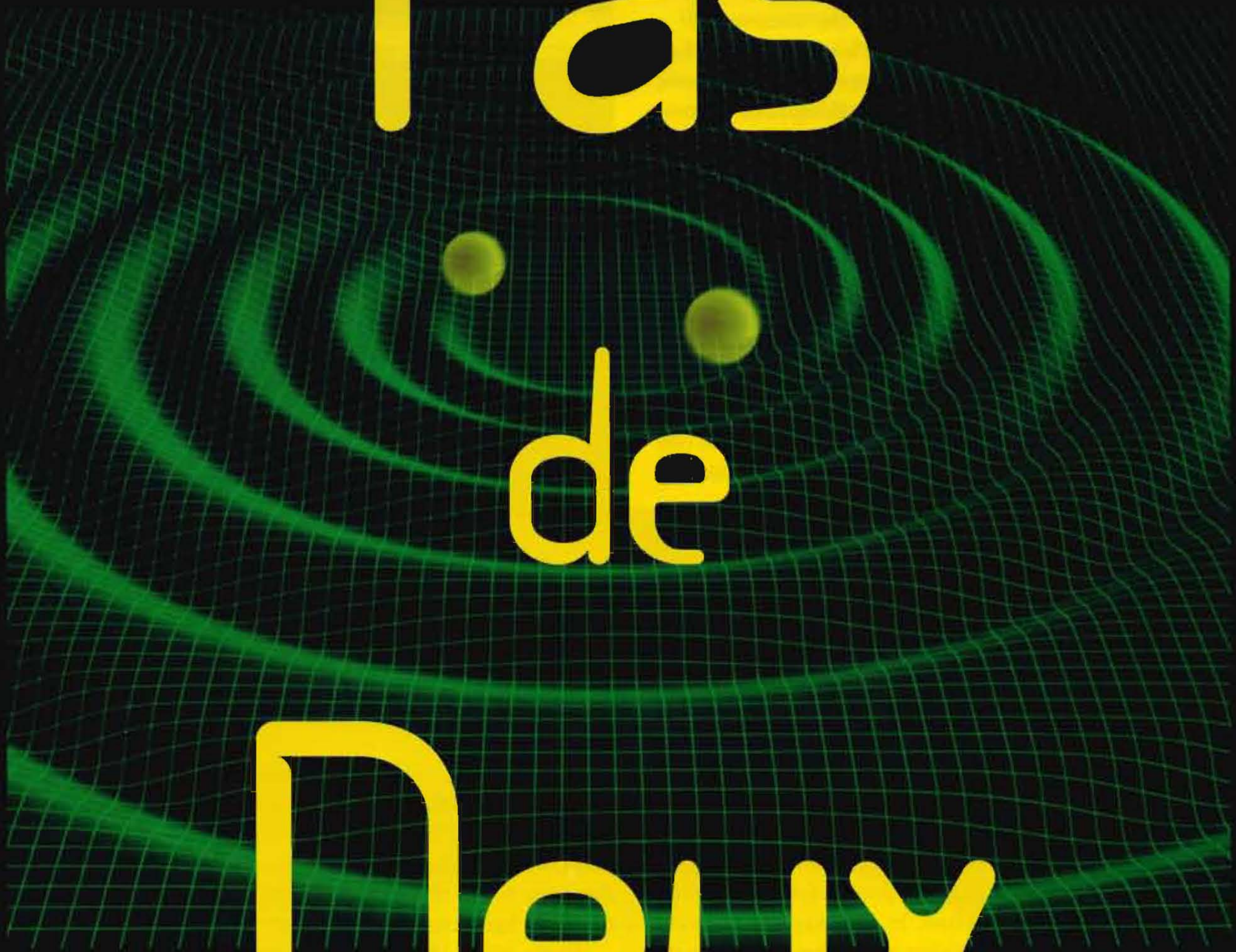
The Nobel-Prize-winning discovery of indirect evidence of gravitational waves came about due to one part ingenuity, one part serendipity, and two parts sheer obstinacy.

# Pas de Deux



by Marcia Bartusiak

*Excerpted from* **Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time**. *Published by the Joseph Henry Press. Copyright 2000, Marcia Bartusiak, Reprinted with permission. All rights reserved. The full text of this book can be found at the Joseph Henry Press web site at www.jhpress.org.*

MARCIA BARTUSIAK'S LATEST BOOK, *EINSTEIN'S UNFINISHED SYMPHONY*, winner of the 2001 American Institute of Physics Science Writing Award (journalist category), describes the exciting 40-year-long quest to capture gravitational waves, the last predicted phenomenon of general relativity yet to be directly detected. New observatories are coming on-line worldwide that may at last discern these vibrations in space-time, providing astronomy with a whole new "sense" with which to explore the cosmos (see "LIGO," page 24). Success is not guaranteed, but gravitational-wave astronomers are emboldened by the powerful indirect evidence that such space-time ripples are real. In the 1970s, two radio astronomers uncovered one of nature's most dependable gravitational-wave emitters in the celestial sky: a pair of neutron stars. This is their story.

Only a month after finishing his Ph.D. at Harvard University in 1967, Joseph Taylor heard about the discovery of a strange new object in the heavens. "This was a time when the journals were always publishing something quite new, but this was more unexpected than anything I can remember at the time," recalls Taylor. The discovery had been made at a sprawling radio telescope — more than 2,000 dipole antennas lined up like rows of corn — near Cambridge University in Great Britain. Jocelyn Bell (now Burnell), then a graduate student, was one of the laborers. The telescope was designed by Antony Hewish to search for quasars, and it was Bell's job to analyze its river of data, a few dozen meters of chart paper daily.

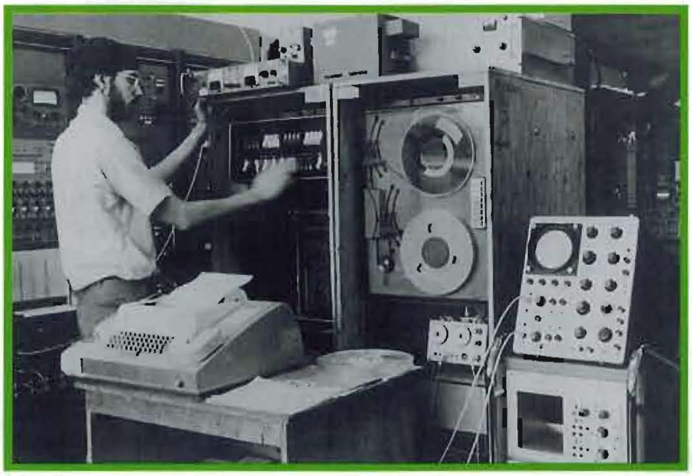
One day she noticed a quarter inch of "scruff" in the record. The signal, it turned out, was a precise succession of pulses spaced 1.3 seconds apart. Within a month, Bell ferreted out the telltale markings of a second suspicious source. By the beginning of 1968, two more were uncovered. A British journalist dubbed the freakish sources pulsars.

Remaining at Harvard as a postdoctoral fellow, Taylor quickly rounded up a team to observe the four pulsars with the imposing 300-foot radio telescope at Green Bank, West Virginia. While the original pulsars had been found by visually searching for specific pulses on a chart recorder, Taylor developed a different strategy to look for more.

A pulsar beeps with a regular beat, but it also has a sort of echo. The high radio frequencies travel faster through the thin plasma of interstellar space than the lower frequencies. Consequently, the differing radio waves start spreading apart, like horses on a racetrack. The high frequency pulse arrives at Earth first, followed by the lower frequencies in quick succession. Taylor and his colleagues wrote a program to look for this distinctive profile, for the first time automating the search with a computer. In this way, the Harvard team found the fifth known pulsar. Within a year, they found nearly half a dozen more. And by then, theorists at last figured out what pulsars were.

They agreed that pulsars were neutron stars, objects first imagined in the early 1930s. A neutron star squeezes the mass of our Sun into a sphere only 15 kilometers across. This occurs when the core of a massive star runs out of fuel. No longer able to withstand the force of its own gravitation, the core collapses, becoming in essence one giant atomic nucleus the size of Manhattan.

**Preceding page: According to Einstein's general theory of relativity, the two neutron stars comprising the binary pulsar radiate gravitational waves as they orbit about a common center of gravity. In the process, they draw ever nearer toward their cataclysmic fate some 240 million years hence. Adapted from an illustration by Matthew Frey, Wood Ronsaville Harlin, Inc. Courtesy of the National Academy of Sciences.**



**Joseph Taylor (above), along with Russell Hulse (below), earned the 1993 Nobel Prize in Physics for their discovery and analysis of the binary pulsar. Courtesy of Rita Nannini and the Nobel Foundation.**

A neutron star spins very fast. Such a rapidly spinning and highly magnetized body acts like an electrical generator. As a result, a neutron star emits narrow and intense beams of electromagnetic waves from its north and south magnetic poles. As on Earth, these poles don't necessarily line up with the star's rotational axes. So, as the star spins, the beams regularly sweep across earthbound telescopes, much the way a lighthouse beam regularly skims across a coastline.

In the fall of 1969, Taylor joined the faculty of the University of Massachusetts at Amherst to help establish the Five College Radio Astronomy Observatory and to continue his pulsar research. How are pulsars distributed through the Milky Way? Could all of them be associated with past supernovae? To get answers, Taylor hoped to double or triple the number of known pulsars by extending his computerized method.

Taylor grew up in the 1940s on a farm along the New Jersey shore of the Delaware River. Perhaps it was the farm machinery, but he and his older brother Hal became avid mechanics. They fiddled with all kinds of motors and even erected ham-radio antennas on the roof of their family's

Victorian farmhouse. Taylor's interest in electronics continued through his undergraduate days at Haverford College, where he built a radio telescope for his senior thesis.

By the time he arrived in Massachusetts, pulsars had become his passion. Perhaps there were even new species of pulsars yet to be revealed. In his funding proposal to the National Science Foundation (NSF), Taylor noted that "even one example of a pulsar in a binary system...could yield the pulsar mass, an extremely important number." But he figured the odds were against him. All the pulsars detected so far were solitary creatures. Convinced of the merits of a large computerized pulsar search, the NSF allotted $20,000 for Taylor's project.

Needing assistance, Taylor sought out Russell Hulse, a graduate student looking for a thesis project. Like Taylor, Hulse had been a tinkerer since his youth. When he was nine, he helped his father build a summer vacation home in upstate New York. "Fortunately, I came through the experience with all my fingers intact," Hulse recalls. An eclectic child, he first went through his biology and chemistry phases, dissecting frogs and mixing chemicals. By the age of 13, electronics captured his fancy. Later, he was admitted to the legendary Bronx High School of Science, notable for its Nobel-Prize-winning graduates.

Sparked by a library book on amateur astronomy, he built a radio telescope out of old television parts and army surplus in the backyard of the summer home. The idea of detecting signals was magical to him. "I don't have cable TV even today," he says. "I still get my signals the old-fashioned way, out of the air with an authentic antenna." His handmade telescope never worked, but he was never bored by the attempt.

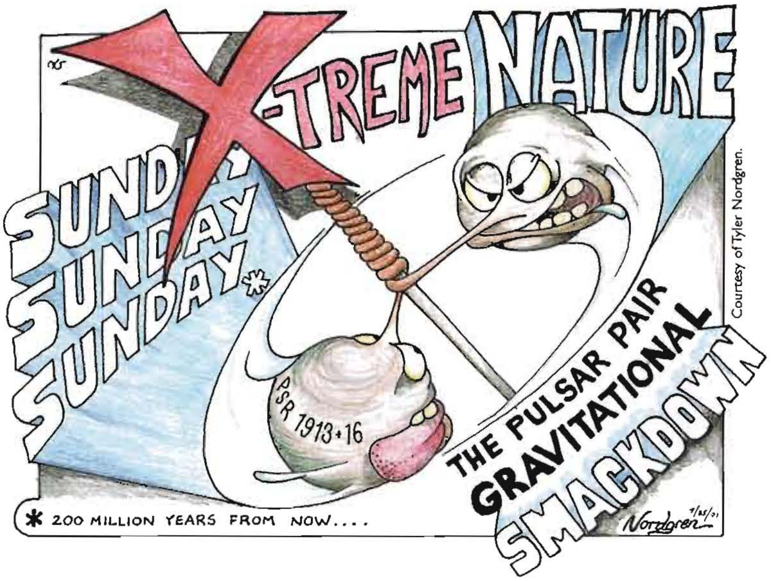
Hulse chose the University of Massachusetts at Amherst for graduate study so he could combine his interest in electronics with astronomy. "Radio astronomy was still new, still rough and tumble," he says. By the time he was ready to tackle his thesis, pulsars were still being found with a hodgepodge of techniques. His and Taylor's plan was to conduct a more systematic search taking advantage of the latest technology — called a "minicomputer," though still as large as a couple microwave ovens — to dig deeper into the galaxy for both weaker and faster pulsars. This required the use of the Arecibo Observatory in Puerto Rico, the largest single radio telescope in the world.

The minicomputer, a Modcomp II/25, was programmed to sweep across a wide range of possible pulse periods and pulse widths in assembly-like fashion as the huge Arecibo dish, which does not move, passively scanned the sky overhead. The aim was to look for a range of pulsars, ones that beeped as fast as 30 times a second or as slow as once every 3.3 seconds. All in all, there were half a million possible combinations. "At each point in the sky scanned by the telescope," notes Hulse, "the search algorithm examined these 500,000 combinations of dispersion, period, and pulse width." This made the search 10 times more sensitive than previous surveys.

The computer was housed in two crude wooden boxes. It had 32,000 bytes of core memory. A teletype was used for input and output, while a tape drive stored the data. To get the maximum processing speed possible, Hulse programmed the computer in assembly language using 4,000 punch cards.

Hulse carted the minicomputer to Puerto Rico at a fortunate time. The telescope was then undergoing a major upgrade. Many observations were impossible at this time, though pulsar searching could still be carried on. This afforded him more time for his searches. In fact, he stayed at Arecibo for some 14 months — from December 1973 to

**Using the world's largest single radio telescope — the 305-meter Arecibo Observatory in Puerto Rico — Russell Hulse picked up the faint signal of the binary pulsar. Courtesy of Cornell University.**



Courtesy of Tyler Nordgren.

January 1975 — with only the occasional trip back to Massachusetts.

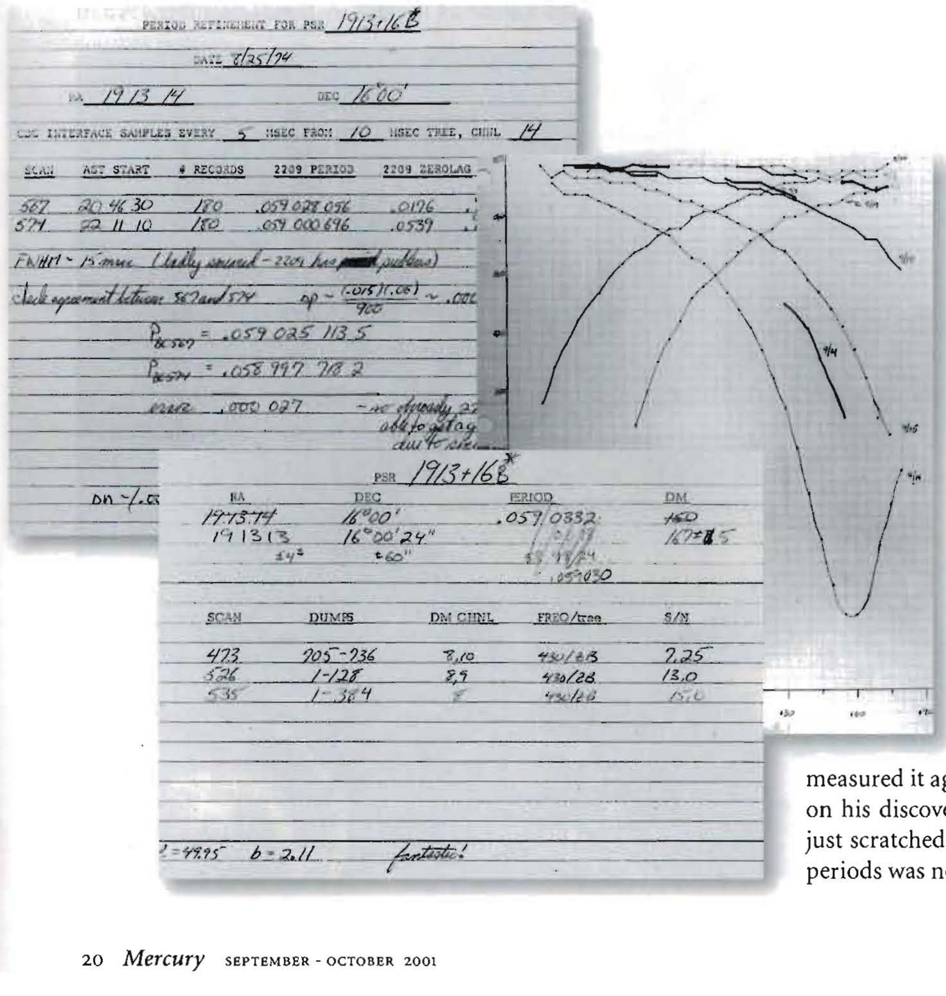
To look for potential pulsar signals, Hulse examined a particular spot on the sky for 136.5 seconds, after which he would begin to scrutinize the next spot over. His prime observing occurred when the plane of the Milky Way passed overhead each day for some three hours. Just before that critical time, Hulse would run a tape, loading his program into the computer's memory. "As a classic computer hacker — and I'm using hacker in the positive sense — I had to make this program run fast enough so that all the data it collected over that three-hour observation window could be processed within 24 hours, before the next observation came up," he says. "I spoke fluent hexadecimal."

During the observation itself, the computer would carry out the dispersion analysis and write its streams of digitized data onto a big magnetic tape. Over the remaining 21 hours of the day, the computer would review the resulting data and look for telltale signs of a pulsar. If the computer found a suspect, it would awaken the teletype and have it type out a cryptic line of information, which Hulse could easily translate.

False leads could arrive from nearby thunderstorms, which were common during the summer. There was one pesky candidate signal that turned out to be emanating from an aircraft warning light on one of the telescope's support towers. And then there were the days that the U.S. Navy held exercises off the coast. "I just sat in the control room," recalls Hulse, "watching signals from the naval radars...jump around on the observatory spectrum analyzer."

By the end of his 14-month stay, he had cornered 40 new pulsars. With each new find, he drew a hash mark on the side of his trusty Modcomp II/25. That alone made a nice thesis for Hulse. "It was of course eclipsed by the discovery of what was to become by far the most remarkable of these 40 new pulsars, PSR 1913+16," he says. PSR is astronomical shorthand for "pulsar," while 1913 is the pulsar's right ascension (19 hours and 13 minutes). The 16 is the pulsar's declination. That placed the pulsar in Sagittarius near the border of Aquila.

**Top left: Hulse's painstaking measurements of the period of PSR 1913 +16 showed that it changed by 27 microseconds over an hour. Bottom left: Hulse scribbled the word "fantastic" on his notes when he discovered PSR 1913 +16. But his excitement turned to frustration as he scratched out the pulsar's ever-changing periods. Right: This graph records the crucial moment on September 16, 1974 when Hulse was able to see the period of PSR 1913 +16 rise rather than fall. This observation confirmed his suspicion that the pulsar was a member of a binary system. All images courtesy of The Nobel Foundation.**



PERIOD REFINEMENT FOR PSR 1913+16B*

DATE 8/25/74

RA 19 13 14 DEC 16 00'

CDC INTERFACE SAMPLES EVERY 5 MSEC FROM 10 MSEC TREE, CHNL 14

| SCAN | AST START | # RECORDS | 2209 PERIOD | 2209 ZEROLAG |
|---|---|---|---|---|
| 567 | 20 46 30 | 180 | .059 028 056 | .0176 |
| 574 | 22 11 10 | 180 | .059 000 696 | .0539 |

FWHM ~ 15 msec (badly smeared - 2209 has [illegible] problems)

check agreement between 567 and 574 δp ~ (.015)(.06)/900 ~ .00

$P_{BC567}$ = .059 025 113 5

$P_{BC574}$ = .058 997 718 2

.000 027 — we already [illegible] able to get a g due to [illegible]

DM ~ 1.[illegible]

PSR 1913+16B*

| RA | DEC | PERIOD | DM |
|---|---|---|---|
| ~~19 13 14~~ | 16°00' | .059 0332 | ~~160~~ |
| 19 13 13 | 16°00'24" | [illegible] | 167±[illegible]5 |
| ±4s | ±60" | [illegible] | |
| | | .059030 | |

| SCAN | DUMPS | DM CHNL | FREQ/tree | S/N |
|---|---|---|---|---|
| 473 | 705-736 | 8,10 | 430/28 | 7.25 |
| 526 | 1-128 | 8,9 | 430/28 | 13.0 |
| 535 | 1-384 | 8 | 430/28 | 15.0 |

= 49.95 b = 2.11 fantastic!

Things were routine by July 2, 1974, until one particular signal squeaked by the threshold Hulse had set — just barely. It was an unusual candidate, as its signal was particularly fast with a period of around 58.98 milliseconds (17 "beeps" a second). "It would be the second fastest pulsar known at that time, which made it exciting," says Hulse. Being such a weak signal, though, he was still skeptical. Weeks later, he at last confirmed the source and proceeded to write down the signal's characteristics, tacking on a "Fantastic!" on the bottom of his discovery sheet.

Hulse got back to PSR 1913+16 and his other suspects once again on August 25. This time it was the opportunity to measure their pulse periods more accurately. For the most part, this was a standard procedure: He just measured the candidate once and then measured it again about an hour or so later. But for PSR 1913+16, the period actually changed over that hour. The two measured periods differed by 27 microseconds (0.000027 second). "An enormous amount," says Hulse. "My reaction was not 'Eureka — it's a discovery' but instead a rather annoyed 'Nuts — what's wrong now?'"

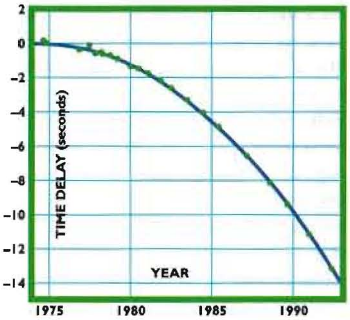
Figuring it was an instrument error, he simply measured it again another day. He kept marking down a new period on his discovery sheet, one after another. After the fourth one, he just scratched them all out in frustration. Obtaining accurate pulse periods was not a requirement for his thesis. Perhaps his equipment wasn't sampling the pulsar fast enough to obtain an accurate fix on its period. He then spent a full week writing a program to handle a faster data stream. He dropped all his other investigations and for two days solely observed this persnickety pulsar. But the problem only got worse. "Instead of a few data points that didn't make sense, I now had lots of data points that didn't make sense," says Hulse. Yet, he did notice some regularities. He saw that the pulsing rate had decreased; the next day, it decreased yet again.

His thinking shifted at this point. He became convinced that the pulsar's period was actually changing, that it wasn't just an instrument error. He spent hours visualizing a spinning pulsar, trying to imagine how it might slow down. Finally, the image of a binary pulsar came to mind. At that point, Hulse didn't know that Taylor had mentioned the possibility of finding such a system in the NSF proposal. In such a binary, the pulsar would be orbiting another star. The period would regularly rise and fall due to the orbital motion. When the pulsar moves toward Earth, its pulses are piled closer together and its frequency appears to rise slightly; when moving away from us, the pulses get stretched and the frequency decreases.

In his gut, Hulse knew he was right, but he had to see the "turnaround," the moment when the pulsar starting approaching Earth in its orbit, causing its frequency to increase. Finally, on September 16, he saw it. His notebook records the proof. He had been processing the data in five-minute intervals, and every time the computer arrived at a period for that five-minute span, he marked it down on his graph paper. "Every one of those dots was a separate little triumph," he recalls. "The real exaltation was seeing it hit the bottom and then turn around. There wasn't any doubt that it was a binary system. I drove back home that night, down the winding roads from the observatory, thinking, 'Wow, I don't believe this is happening.'"

He quickly mailed Taylor a letter moaning about the extra work the pulsar had created for him. But he decided the news couldn't wait. With telephone connections so difficult from Arecibo, Hulse used the observatory's short-wave radio link to Cornell University. Cornell, in turn, patched the call via a phone line to Amherst. Taylor, immediately recognizing the import of Hulse's find, flew down to Puerto Rico with better pulsar timing equipment.

Taylor and Hulse confirmed that the two objects were orbiting each other every 7 hours and 45 minutes. That meant they were moving at about 300 kilometers per second, a thousandth the speed of light. One was surely a neutron star, because of the pulsing, the other was likely a neutron star as well, because it was not large enough to eclipse the pulsar. The size of the binary's orbit is not much bigger than the radius of the Sun, a relatively slim 700,000 kilometers. With such intriguing properties, Taylor and Hulse immediately recognized that they had been handed the perfect relativistic test bed on a silver platter.

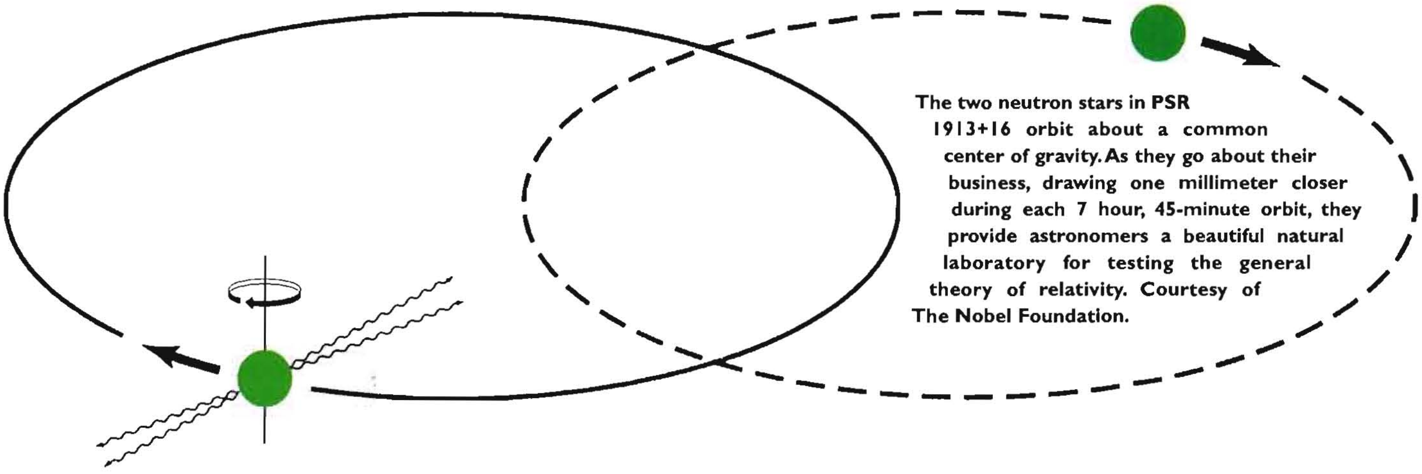


**This is the stuff of which Nobel Prizes are made. The decay of the binary pulsar's orbital period (green dots) perfectly matches the theoretical prediction (blue line) of general relativity that the system loses orbital energy as it emits gravitational waves. This graph offers critical observational support for general relativity. Courtesy of Joseph Taylor.**

Up until the discovery of the binary pulsar, tests of general relativity were primarily carried out within our solar system. With PSR 1913+16, experimental testing of relativity extended into the galaxy. With general relativity, space-time became the universe's flexible stage, a rubbery structure that stars, planets, and galaxies could bend and dent in intriguing ways. This new outlook had dramatic consequences. It meant that, when an object embedded in space-time gets moved or jostled, it can generate ripples in this space-time fabric.

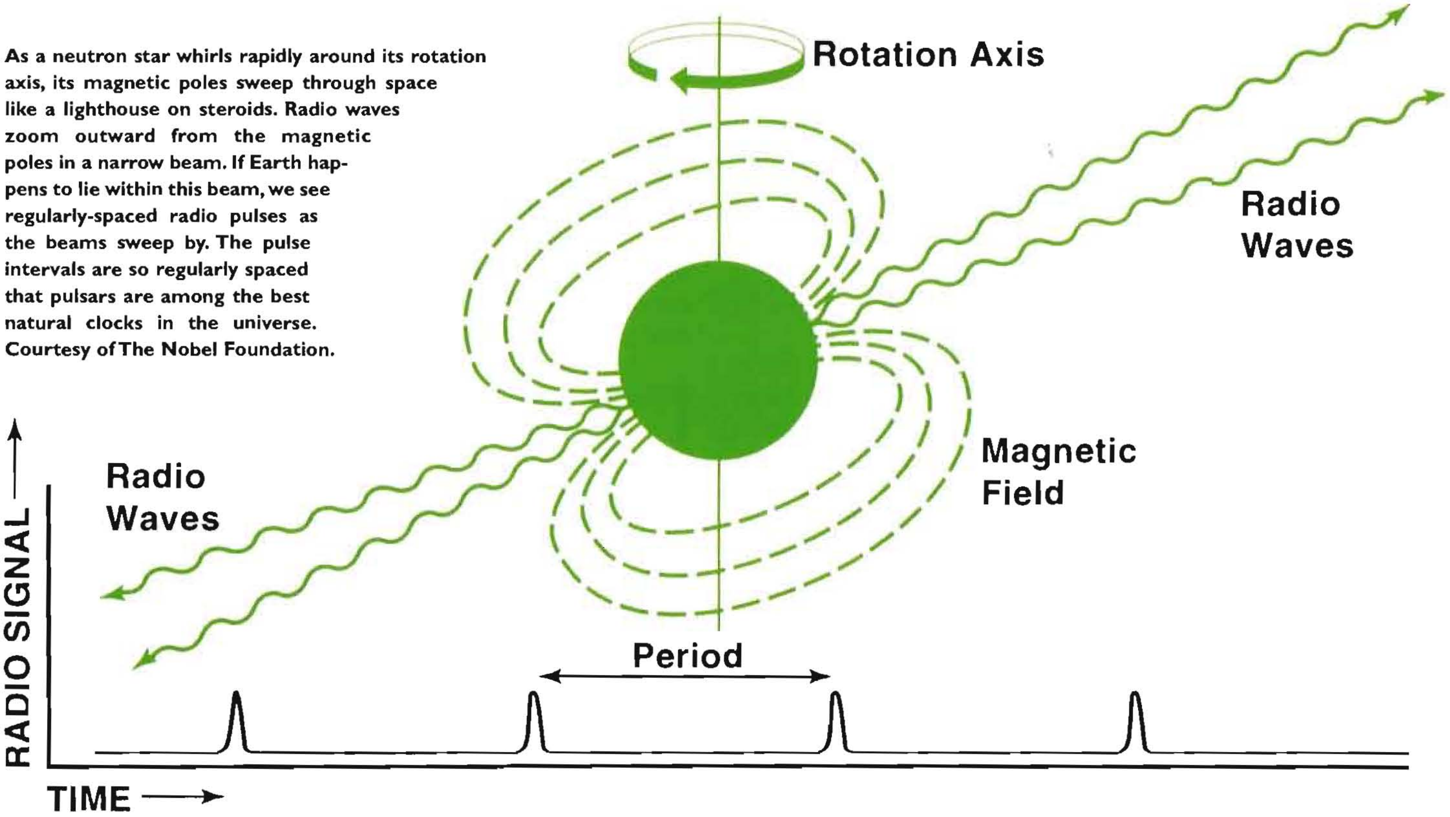
Jiggle a mass to and fro and it will send out waves of gravitational energy, akin to the way a ball bounced on a trampoline sends vibrations across the canvas. These waves alternately stretch and squeeze space — stretch and squeeze somewhat like the bellows of an accordion in play. The strongest waves emanate from the most violent events the universe has to offer: stars crashing into one another, supernovae erupting, and black holes forming. These waves would be lethal near merging neutron stars, but by the time the gravitational waves strike Earth, they are little more than subatomic flutter.

When Einstein first derived the formula indicating that two objects orbiting each other would release gravitational waves, he also recognized that the two objects would be drawn closer and closer, due to the loss of energy. PSR 1913+16 was the perfect candidate to test this out. Imagine a twirler's baton spinning in a pool of water. The motion would create a set of spiraling waves that move outward. Similarly, the motion of these two neutron stars



**The two neutron stars in PSR 1913+16 orbit about a common center of gravity. As they go about their business, drawing one millimeter closer during each 7 hour, 45-minute orbit, they provide astronomers a beautiful natural laboratory for testing the general theory of relativity. Courtesy of The Nobel Foundation.**

**As a neutron star whirls rapidly around its rotation axis, its magnetic poles sweep through space like a lighthouse on steroids. Radio waves zoom outward from the magnetic poles in a narrow beam. If Earth happens to lie within this beam, we see regularly-spaced radio pulses as the beams sweep by. The pulse intervals are so regularly spaced that pulsars are among the best natural clocks in the universe. Courtesy of The Nobel Foundation.**



should emit waves of gravitational energy that spread outward from the system. With energy leaving the binary system, the two neutron stars would then draw closer together. Their orbital period would shrink. But seeing such an effect required great patience.

While Hulse went on to other endeavors, Taylor and several colleagues continued to travel to Arecibo to monitor PSR 1913+16. Year by year they would spend two or more weeks measuring the system as precisely as they could. To detect any changes in the binary's orbital motions required extraordinary measurements. The system is located some 16,000 light-years away, so its signal is very weak. Taylor's group had to build a special receiver that could better analyze the signal. It took four years of monitoring before they could finally detect a very slight change in the orbit of the two neutron stars. The answer arrived after analyzing some 5,000,000 pulses. The orbit was definitely shrinking. The binary system was losing energy and the neutron stars were drawing closer together. More than that, the energy loss was exactly what was expected if the system were losing energy in the form of gravitational waves alone.

The news was first released at a symposium in Munich, Germany, in December 1978. Initially, there were doubts. Some wondered whether there was a third object within the system, which would upset the calculations. Or maybe there was dust and gas present in the system, which could also explain the losses. But additional measurements over the years — with better and better receivers — only improved the accuracy.

Taylor's graph, plotting the ever decreasing orbital period, is a showpiece of science. The measured points lie smack dab on the path laid down by general relativity. The measured energy loss due to gravitational radiation agrees with theory to within a third of a percent. Such accuracy has been described as "a textbook example of science at its best." Over each revolution around each other, in the continuing *pas de deux*, the two neutron stars in PSR 1913+16 draw closer by a millimeter. The two stars will collide in about 240 million years.

Hulse actually left the field of radio astronomy a few years after his momentous find. Wanting to be near his girlfriend, he took a job at the Princeton Plasma Physics Laboratory in 1977, where he continues to work as a principal research scientist on computer modeling. Taylor, meanwhile, carries on his pulsar work, in and around his new duties as Dean of the Faculty at Princeton University. Their old minicomputer is gone, long cannibalized for parts, but Hulse does retain his original printouts on newspaper-like green paper. "It's such hacker stuff. I read it now in a daze," says Hulse with a chuckle. "I enjoyed doing it once."

Hulse had sighted the first pulsar of his search on December 8, 1973. Exactly 20 years later, he was standing at a podium in Stockholm, Sweden. He and Taylor had just received the 1993 Nobel Prize for Physics for their masterpiece of measurement. In the lecture, Hulse described his work as "a story of intense preparation, long hours, serendipity, and a certain level of compulsive behavior that tries to make sense out of everything that one observes." He didn't ignore a troublesome observation. He tackled it with fervor, finding for Taylor and the astrophysics community the perfect laboratory for relativistic physics.

There had been controversy when Jocelyn Bell Burnell was denied a share of the 1974 Nobel Prize in Physics for her role in the discovery of the pulsar. The coveted award went to her advisor, Hewish, instead. This antistudent bias changed with the discovery of the binary pulsar. "It was very much a joint effort," says Taylor, a man well known in the astronomical community for his generosity and gentlemanly spirit. "Yes, one of us was a student, but there was no question that Hulse's work was an essential part of the operation." Taylor invited Jocelyn, his longtime friend, to accompany him and his wife to Sweden for the award ceremonies.

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*Science writer MARCIA BARTUSIAK regularly reports on the fields of astronomy and physics in a variety of national publications. She is the author of two previous books,* Thursday's Universe *and* Through a Universe Darkly. *Her website is www.marciabartusiak.com.*