

HULSE AND TAYLOR WIN NOBEL PRIZE FOR DISCOVERING BINARY PULSAR

In the summer of 1974, University of Massachusetts radioastronomer Joseph Taylor and his graduate student Russell Hulse discovered the first binary pulsar. This month in Stockholm, Hulse and Taylor are being honored with the 1993 Nobel Prize in Physics "for [this] discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation." The importance of this new star for the investigation of gravity in the relativistic regime was clear almost from the start.

Taylor, who moved to Princeton University in 1981, has continued to exploit the radio pulses arriving from this first binary pulsar, 17 times every second, to test Einstein's general theory of relativity with increasingly exquisite precision. His most important verification of general relativity, first reported in December 1978, was the indirect discovery of gravity waves: The binary pulsar's orbit is slowly decaying at just the rate of energy loss predicted for the emission of gravitational radiation from this twirling stellar dumbbell. (See Daniel Kleppner's Reference Frame column in PHYSICS TODAY, April 1993, page 9.)

Hulse is also at Princeton. But he's been doing plasma physics at the Princeton Plasma Physics Laboratory since 1977. After finishing his PhD thesis on the discovery of the binary pulsar in the summer of 1975, Hulse took a postdoctoral position at the National Radio Astronomy Observatory in Virginia. "But after two years at NRAO," he recalls, "I assessed the career prospects for astronomers and opted for tokamaks."

Deepest search

In December 1973, six years after Antony Hewish and his student Jocelyn Bell discovered the first pulsar with an array of radio antennas at Cambridge University, Taylor and Hulse went down to the Arecibo radiotelescope in Puerto Rico to carry out a much deeper and more system-



Russell Hulse

atic pulsar search than anyone had yet undertaken. About a hundred pulsars were already known, and they were fairly well understood to be rapidly spinning neutron stars with very strong, off-axis magnetic fields. Energetic charged particles spiraling in such a star's magnetosphere generate radiofrequency beams pointing outward from the magnetic poles. As the very compact neutron star spins with a period of seconds, or even milliseconds, the off-axis radio beams sweep out two celestial cones, like a cockeyed lighthouse. If the Earth happens to lie on one of those cones, we receive the amazingly regular radio pulses characteristic of pulsars.

The 305-meter-diameter Arecibo antenna was, and still is, the world's largest radiotelescope reflector. Lying flat on its back in a bowl-shaped depression in the mountainous island landscape, the giant dish itself cannot move, but the detector at its focus moves enough to let the telescope examine any source within 20° of the zenith. (See the cover of this issue.)

Taylor and Hulse arrived at Arecibo armed with a dedicated minicomputer, a considerable luxury in



Joseph Taylor

those days. Hulse's job was to implement and fine-tune the pulsar-search algorithm. "We wanted to get the greatest possible search sensitivity," Hulse told us, "by doing the best possible signal processing." Three key observational parameters that characterize a pulsar signal are its period, pulse width and frequency dispersion. If one knew these parameters beforehand one could detect a pulsar very readily: Knowing the period, one could synchronously fold the repeating incoming signal, and knowing the pulse width, which is usually a small fraction of the period, one could choose a sampling rate that optimizes the signal-to-noise ratio. Frequency dispersion, caused by free electrons in the interstellar medium, can smear pulses out by more than 100 milliseconds; lower radio frequencies lag behind. The total dispersion is a rough measure of the pulsar's distance from us. One can separate the signal into different frequency bins in a multichannel receiver and then, if one knows the dispersion, one can recover the undispersed signal by applying progressive electronic delays to the higher-frequency bins.

"The problem is, you don't know these parameters when you're looking for new pulsars," Hulse told us. "So we had to search not only the sky but also this three-dimensional parameter space." For every 10-arcminute-diameter patch of sky, the computer had to try half a million parameter sets in hopes of detecting the elusive telltale pulse train. The system was sensitive to pulse periods ranging from 4 seconds down to 33 ms, which was the period of the fastest pulsar then known.

After each sweep across the Milky Way by the Arecibo telescope moving with the rotating Earth, the computer examined the accumulated search data off-line for possible pulsars. When a candidate was found, the crucial test was to look again in the same direction a few days or weeks later and see if the same signal was still there. If it was, the next order of business was to refine the measurement of the pulse period.

A binary pulsar!

That's just what Hulse was doing on 25 August 1974. He was taking a second look at a very faint pulsar he had first detected on 2 July. With a period of about 59 milliseconds, it was the second fastest pulsar anyone had seen. When Hulse tried to refine the period after the two-hour 25 August observing run, it became clear that something unusual was going on. (The rotation of the Earth and the immobility of the telescope limit observation of the pulsar to about two hours a day.) The computer analysis was alleging that the pulse periods at the beginning and end of the run differed by about 30 microseconds. Given the proverbial stability of pulsars, such an enormous variation was unheard of.

What could be going wrong? "I thought the problem might be that our time resolution was too slow for such a fast pulsar," Hulse told us. "So I reconfigured the hardware to sample the data faster and I wrote a new dispersion algorithm that had to run on a mainframe. Our minicomputer was too slow." Thus fortified, Hulse started looking again on 1 September. But the puzzling variation of the pulse period wouldn't go away. Hulse could now plot this variation during each two-hour run. It was clear that the pulse period was gradually decreasing during each day's run, and each day's observation almost replicated the previous day's. *Almost*, but not quite. "I noticed that if I shifted the second day's curve forward by about 45 minutes it fell neatly onto the previous day's data,"

recalls Hulse. "And then the next day's data turned out to be 45 minutes behind the second day. It looked as if I was seeing the Doppler variation of a pulsar in a *binary* system with an orbital period just 45 minutes shy of commensurability with the Earth's daily rotation."

Binary star systems are about as common as solitary stars like our Sun. But no one had ever seen a *pulsar* with a binary companion. And that made sense: Like all neutron stars, pulsars are born in supernovae, and it was reasonable to assume that a binary star system could not survive so violent a cataclysm. Nonetheless, Taylor had addressed the remote possibility of finding a binary pulsar in his original funding proposal to the National Science Foundation.

The smoking gun

So Hulse appeared to be sitting on an important discovery. But before he called Taylor, who was back in Massachusetts teaching classes, he wanted to be quite sure. Every day's two-hour observation uncovered a new 45-minute segment of the variation curve. Until now Hulse had seen only decreasing periods. But if it really was a binary, he reasoned, the period must eventually bottom out and start climbing. That "smoking gun" finally appeared on 16 September, when, after falling 70 microseconds in less than two hours, the pulse period began increasing. So it was time to call Taylor and give him the good news: The new 59-millisecond pulsar was part of a binary system with an orbital period just 15 minutes shy of 8 hours.

"It didn't take us long to realize we had an important tool for exploiting and testing general relativity," Taylor remembers. "But neither of us was much of a relativist, and the pickings were minimal at the local bookstores. So I drove to Cambridge and loaded up on general relativity texts at the Harvard Coop."

But there were classical chores to be done first. "I had to run off to our astronomy library to learn the standard techniques for analyzing the orbits of ordinary spectroscopic binary stars by measuring the periodic Doppler variation." The regular beeping of a pulsar is quite analogous to a single stellar spectral line. If the star is orbiting around a binary companion, the pulse frequency, just like the frequency of a spectral line, exhibits a periodically varying Doppler shift.

Just by measuring this Doppler variation, the classical astronomer can learn a lot about the binary or-

bits. But not quite everything: In the absence of relativistic phenomena, the Doppler measurements yield only five of the seven parameters needed to characterize the binary system. Instead of revealing, separately, the two stellar masses and the tilt of the orbital plane, the classical analysis yields only the "mass function," a tangled combination of those three parameters. But Hulse and Taylor's classical Doppler analysis did reveal that the pulsar's orbit was highly eccentric.¹ At "periastron," the point of closest proximity, the binary partners are separated by little more than the radius of our Sun. That makes it quite clear that the pulsar's companion is also a "compact object," almost certainly a second neutron star.

Relativistic precession

Objects of roughly solar mass orbiting each other in such tight orbits experience gravitational fields ten thousand times stronger than the Sun's field at Mercury. And their orbital velocities exceed that of our swiftest planetary companion by an order of magnitude. One makes the comparisons to Mercury, of course, because it is the only planet close enough to the Sun and fast enough to exhibit an observable general relativistic effect: The relativistic precession of Mercury's perihelion is a minuscule 43 arcseconds *per century*. That's about how much the binary pulsar's periastron precesses in a single day. It's not just the stronger gravitational fields and the higher velocities; it's also the pulsar's conveniently short orbital period of less than 8 hours, as compared with Mercury's 3 months, that contributes to the rapid accumulation of precession angle. (The asteroid Icarus, discovered in 1950, also exhibits observable relativistic precession. In 1996, the next time Icarus close enough, the recently upgraded Arecibo telescope should be able to make very precise radar measurements.)

By the time Hulse finished his PhD thesis in the summer of 1975, he and Taylor had measured a precession rate of $4 \pm 1.5^\circ$ per year for the binary pulsar. (Nowadays it's known to 6 significant figures.) You can't predict this rate unless you know the masses of both stars in the binary system. Therefore, in the absence of independent knowledge of the individual masses, the precession measurement was not yet an explicit test of general relativity. In fact it was just the reverse; it was an exploitation of a relativistic effect to measure stellar masses. If one measures the periastron precession together with

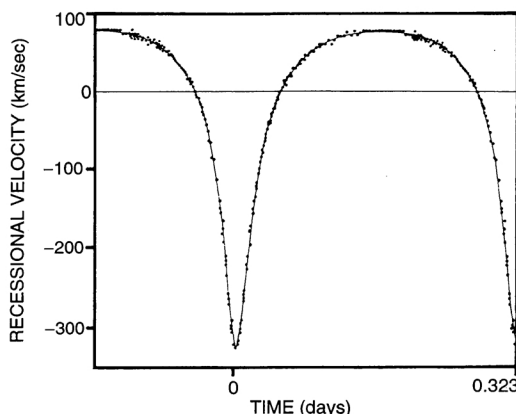
another relativistic effect—the combined time delay of the pulsar beeps by gravitational redshifting plus ordinary special-relativistic time dilation—one has enough parameters to characterize the binary system completely, assuming that the theory is correct.

By 1978, careful observation of this delay and the periastron precession had revealed that the masses of the 59-millisecond binary pulsar and its companion were both very close to 1.4 solar masses, the “Chandrasekhar limit” at which white dwarf stars collapse explosively. That finding strengthens the conclusion that the 59-millisecond pulsar’s companion is also a neutron star. Now, after two decades of painstaking measurements of nothing but a train of radio blips by Taylor and his colleagues,² the two masses are individually known to 2 parts in a thousand. Thus general relativity has become a tool for weighing astrophysical systems. It’s the variety of new mass dependences introduced by the relativistic effects that lets one go beyond what classical Newtonian analysis can reveal about a binary star system.

Gravity waves

With the individual masses reasonably well measured by 1978, general relativity now offered an explicit prediction for the rate at which the orbits of the binary pulsar system decay by gravitational radiation: The orbital period should get 75 microseconds shorter every year. A measurement of this tiny decay rate, it was clear, would be a real test of the theory. At a conference in Munich in December 1978, much sooner than most colleagues expected, Taylor announced that he and his partners Lee Fowler and Peter McCulloch had accomplished the measurement. Shortly thereafter the group was joined by Joel Weisberg, who was to become one of Taylor’s closest collaborators over the years. By 1983 the accumulated data yielded a measured decay rate of 76 ± 2 $\mu\text{sec}/\text{yr}$. Even though Einstein’s gravity waves had not been detected directly, it was now hard to doubt their existence.

The measurement of so small an effect so quickly owes much to Taylor’s metrological skills. But the unusual stability of the 59-millisecond pulsar also deserves a share of the credit. Its pulse period (not to be confused with the orbital period) is slowing down by only a quarter of a nanosecond per year. That’s 50 000 times slower than the pulse decay rate of the 33-millisecond pulsar in the Crab nebula, which was born in a supernova recorded by Chinese as-



First binary pulsar's periodically varying recessional velocity, as determined from Doppler shifting of the 59-msec pulse rate, showed that the pulsar was circling a companion in an eccentric orbit with a period of 7 hrs, 45 min. Because one doesn't know the rest-frame pulse rate, there is an unknown additive recessional velocity of the binary system as a whole. (Adapted from ref. 1.)

tronomers in the 11th century. The unusually slow decay rate of the 59-millisecond pulsar strongly suggests that it's a very old neutron star that was “spun up” in its slow dotage by sucking up material and angular momentum from its binary partner. “Ours was the first discovery of such a recycled pulsar,” Taylor told us. “Most of the others are spun up to even faster pulse rates, on the order of a millisecond.”

The first of the real millisecond pulsars was discovered in 1982. Like their 59-millisecond precursor, they all exhibit stabilities that rival the best atomic clocks. Though it's presumed they were all spun up by companions, some of those companions seem to have been consumed in the process. All but a handful of the 40 binary pulsars discovered to date have the fast pulse rate and slow pulse-rate decay that suggests they've been recycled.

In addition to gravitational redshift and simple time dilation, general relativity predicts yet another contribution to time delay, first pointed out by Irwin Shapiro at MIT in 1964. This “Shapiro delay” is, in effect, a slowing of the speed of light in the spacetime warp of a strong gravitational field. Taylor has indeed detected the Shapiro delay of radio pulses from the binary pulsar. “It’s gratifying that our measurement of this delay agrees with general relativity,” Taylor told us. “But our precision here isn’t really good enough for a serious test of the theory. And besides,” Taylor added, “Shapiro himself already measured this delay to much greater precision in the 1970s,” with solar system radar and satellite signals grazing the Sun.

The laureates

Taylor did his undergraduate work in physics at Haverford College, near his native Philadelphia. He received his

PhD at Harvard in 1968, working under radioastronomer Alan Maxwell. Taylor’s thesis research involved exploiting occultation by the Moon to determine the directions of radio sources. Coming to the University of Massachusetts in 1968, Taylor became one of the organizers of the Five College Radio Astronomy Observatory, a joint undertaking of the university and four nearby colleges: Amherst, Hampshire, Mount Holyoke and Smith. “The first instrument we built in that year just after Bell and Hewish found the first pulsar,” Taylor recalls, “was an array of small, low-frequency radiotelescopes designed explicitly to observe pulsars.”

Hulse, a native New Yorker, got his bachelor’s degree in physics at Cooper Union. “For graduate school I chose the University of Massachusetts because of its radioastronomy group,” Hulse told us. “I had actually fooled around with building an amateur radiotelescope in high school.” Hulse is the fifth graduate of the Bronx High School of Science to win the Nobel Prize in Physics. “I came to ham radio by way of radiotelescopes,” said Hulse. “In Joe’s case it was the other way around.”

Nowadays Hulse is a research physicist on the team that does fusion-energy experiments at Princeton’s large TFTR tokamak. He was busy preparing for a plasma physics conference when the prize was announced in October. “They hastily organized a talk for me,” he told us. “It was the first astronomy talk I’d given in a long time. At times like this, your old notebooks and a copy of your thesis come in handy.”

—BERTRAM SCHWARZSCHILD

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2. J. H. Taylor, J. M. Weisberg, *Astrophys. J.* **345**, 434 (1989). ■