number of radical technological improvements relative to the tokamak. Whereas the plasma in both cases is toroidal, the spheromak containment vessel is not. The S-1 is a 3-meter-diameter affair, shaped something like a hamburger patty. Unlike the toroidal vessel characteristics of tokamaks, the hole of its plasma doughnut is not threaded by coils or inner walls. All field-generating coils are external to the plasma ring. The plasma current itself generates the confining toroidal magnetic field, obviating the need for the toroidal-field coils that thread the hole of a tokamak ring. The S-1 plasma, about the size and shape of a truck tire, is therefore free to move around in its containment vessel.

"If we succeed in forming a stable plasma smoke ring in S-1," Furth told us, "we will attempt to extract it through a porthole." Such a scheme in a commercial reactor would afford the technologically attractive prospect of separating the region in which the plasma is formed and heated from the region where it burns and gives up its heat. One would generate a plasma ring, compress it, heat it and *then* move it to a region surrounded by thermal blankets before adding tritium.

The spheromak configuration was first discussed almost thirty years ago in an astrophysical context by Arnuls Schlüter and Reimar Lüst in Munich, and in the fusion-reactor context by Hannes Alfvén in Stockholm. Unlike TFTR, Furth suggests, the success of S-1 is far from "assured." But if it works, it could be the basis for a commercial fusion reactor that might be far more attractive from an engineering point of view than any of today's mainstream approaches. —BMS

Newly discovered pulsar is 20 times faster than Crab pulsar

Of the more than three hundred known radio pulsars in our galaxy, the most recently discovered is surely the strangest. On 12 November, a group of radio astronomers led by Donald Backer (Berkeley) announced[1] by International Astronomical Union telegram that they had found a pulsar in the constellation Vulpecula with a period of 1.558 *milliseconds*—twenty times shorter than that of the Crab pulsar, the fastest pulsar previously seen. The period of the first recorded pulsar, 1.337 seconds, discovered in 1967 by Jocelyn Bell and her colleagues at Cambridge, is much more typical.

Radio pulsars slow down as they age. Because the Crab pulsar is known from the historical record to be less than a thousand years old (the supernova that gave it birth was observed by Chinese astronomers in the 11th century), previous pulsar searches had restricted themselves to looking for periods longer than about 10 milliseconds. Any pulsar younger than the Crab, it was supposed, would have a nebula bright enough to have been seen anywhere in the Galaxy; and anything older would be slower. Furthermore, the newly discovered pulsar, with a spin rate of 642 Hz, comes perilously close to the upper limit at which neutron stars would be centrifugally unstable—about 2000 Hz. Its equatorial velocity, assuming it to be a neutron star with a radius of about 10 km, is 13% of the speed of light.

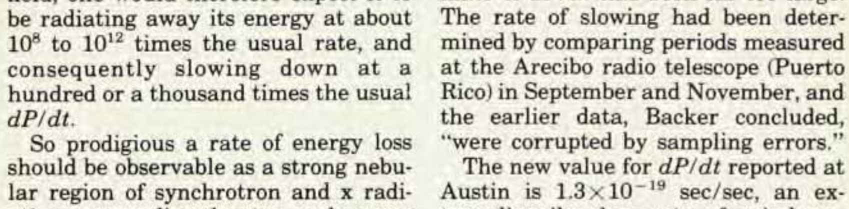
The pulsating radio signals that characterize pulsars represent only a very small fraction of the energy these highly magnetized, spinning neutron stars radiate into their environment. Although the pulsar's principal energy-loss mechanism is thought to involve both electromagnetic radiation and the acceleration of plasma particles by the star's complex, corotating magnetosphere, the expression for the energy-loss rate in most models turns out to look very much like the classical formula for magnetic dipole radiation. For a given magnetic field strength, the rate of energy loss in such models is proportional to P^{-4}, where P is the period of spin and pulsation, and the rate at which the pulsar slows down, dP/dt, goes like P^{-1}.

As determined by the observed P and dP/dt, most pulsars appear to have surface magnetic field intensities on the order of 10^{12} gauss. (Our Sun, for comparison, has a surface field of about *one* gauss.) If the newly discovered millisecond pulsar had such a typical field, one would therefore expect it to be radiating away its energy at about 10^8 to 10^{12} times the usual rate, and consequently slowing down at a hundred or a thousand times the usual dP/dt.

So prodigious a rate of energy loss should be observable as a strong nebular region of synchrotron and x radiation surrounding the star, such as one sees for young, fast pulsars like the Crab. Neither the Einstein x-ray telescope nor the radio observations have seen any such extended source associated with the millisecond pulsar, nor has one seen the shell of supernova remnant debris one would expect with such a rapidly spinning, and therefore presumably young, pulsar.

The first November telegram reported a dP/dt of a few times 10^{-14} sec/sec, suggesting an age of only a few thousand years and a power output a thousand times that of the Crab. Such a high rate of rotational energy loss excited widespread enthusiasm that gravitational radiation from the star might be seen by a number of gravitation-wave detectors sensitive in the kilohertz range. This first flush, however, was dampened a month later at the 11th Texas Symposium on Relativistic Astrophysics in Austin, when Backer reported[2] that the original estimate of dP/dt had been far too large. The rate of slowing had been determined by comparing periods measured at the Arecibo radio telescope (Puerto Rico) in September and November, and the earlier data, Backer concluded, "were corrupted by sampling errors."

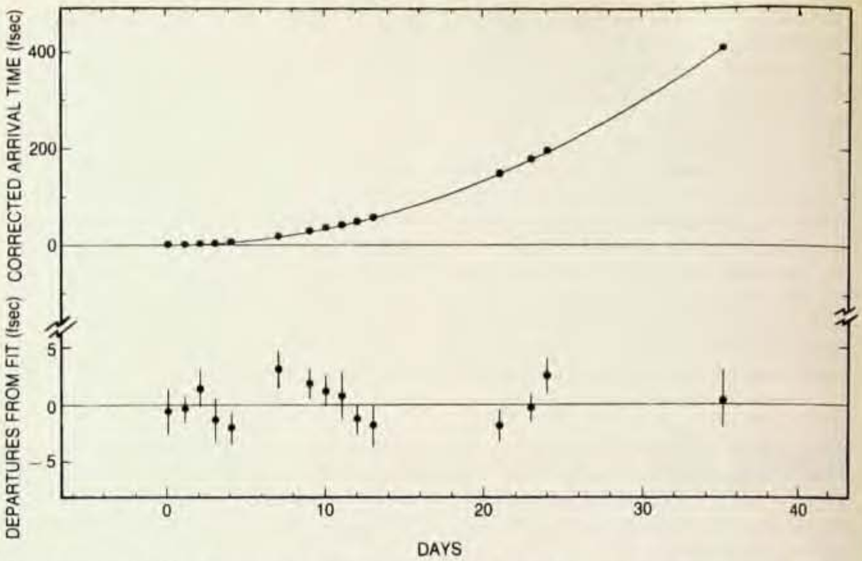
The new value for dP/dt reported at Austin is 1.3×10^{-19} sec/sec, an extraordinarily slow rate of spindown, corresponding to an age estimate of several hundred million years and a power output five hundred times less than the Crab. The fastest pulsar turns out to have by far the slowest deceleration. How could a pulsar so old be spinning so rapidly and losing energy so slowly? On the other hand, when the original very rapid spindown rate of 10^{-14} sec/sec was announced, a number of theorists had quickly point-



Waveform of the pulsating radio signal from the millisecond pulsar recently discovered at Arecibo by Donald Backer and his colleagues. The full period of 1.558 milliseconds shows a primary peak separated from a secondary peak by about 180°. The two peaks presumably come from the opposite magnetic poles of the rapidly spinning neutron star. Most of the pulse width seen here is attributed to the signal-averaging instrumentation rather than the intrinsic signal.

ed out that this figure was highly implausible. It implies a very young pulsar. Why then is there no evidence of supernova debris, and why don't we see many slightly older pulsars spinning almost as fast? Among the skeptics was Jonathan Arons (Berkeley), who concluded from the absence of a nebular x-ray or radio source that dP/dt must be less than 3×10^{-19} sec/sec, and from the *presence* of the pulsating stellar radio signal that it must be larger than 3×10^{-21}. Jacob Shaham and his colleagues at Columbia predicted[3] from a specific model that dP/dt would turn out to be on the order of 10^{-19} sec/sec or less. Backer cautions that the observational determination of 1.3×10^{-19} is still burdened by a considerable uncertainty.

Although the theoretical models addressing themselves to the new millisecond pulsar differ from one another in detail, a consensus appears to have developed that the object is quite old and that its present slow rate of spindown is explained by its anomalously weak magnetic field—only 10^8 or 10^9 gauss. The power output of a neutron star with magnetic field B is found in most models to scale like B^2/P^4. With so weak a field, the millisecond pulsar would presumably not be radiating observable radio pulses but for its extraordinarily high spin rate.



The slowing of the millisecond pulsar is determined by measuring pulse arrival times over 35 days at Arecibo with a timing apparatus developed at Princeton by Joseph Taylor. If the period were a constant 1.5578064490 millisec, all the data points in the upper display would lie on the abscissa. The best-fit parabola through these points gives a slowing rate of 1.3×10^{-19} sec/sec. The lower display shows the departure of the data points from this best fit.

Search. Now that it is known to be a pulsar, the new object is referred to as PSR1937 + 214. But it has in fact been listed for twenty years in the 4th Cambridge Catalogue of Radio Emitters under an older name—4C21.53. The 4th Cambridge Catalogue is dominated by extragalactic radio emitters (radio galaxies and quasars) and extended intragalactic sources (clouds of ionized hydrogen and supernova nebulae).

A number of peculiar properties of 4C21.53 eventually led to its unmasking. In 1972 its radio image was discovered to twinkle as a result of its passage through the solar wind emitted by our Sun. Such "interplanetary scintillation" indicates an apparent object size of less than an arc second—just as optical twinkling due to atmospheric perturbation distinguishes stars from planets. But because 4C21.53 lies within a few degrees of the Milky Way in the direction of the galactic center, one would not expect it to exhibit interplanetary scintillation, no matter how small it is, if it were indeed extragalactic. Passage through the entire galactic disk on its way to us would broaden its image beyond the twinkling limit by scattering in the interstellar medium. This was the first clue that 4C21.53 included a compact radio source in our own galaxy.

Backer's curiosity was aroused by 4C21.53 in 1979 when radio observation below 100 MHz by J. J. Rickard and Will Cronyn (Clark Lake Observatory) indicated that its spectral intensity fell rapidly with increasing frequency. Although its pulsation had not yet been seen, such a steep radio spectrum is characteristic of pulsars. Furthermore, Backer noted that a flat-spectrum source, 60 arcseconds-wide,found in a higher-frequency radio survey, lay very close to the position given for 4C21.53 in the Cambridge Catalogue. Knowing that the interferometrically determined Cambridge positions were occasionally in error by one order in the interference pattern, Backer speculated that the two objects were in fact coincident, the 60-arcsecond object being a supernova remnant in which 4C21.53 was an imbedded pulsar.

But why then had 4C21.53 not been seen to pulsate? Dispersion in the interstellar medium indicated that it was only 2 kiloparsecs (6000 light years) away; the corresponding temporal broadening would not be sufficient to wash out a pulsar signal. Backer concluded, therefore, that the pulsar must have a period shorter than 10 msec—at least three times faster than the Crab. A slower pulsar would already have been detected. He submitted this conjecture for publication in 1979. It was rejected as "too speculative."

Backer asked colleagues at Arecibo and Owens Valley (California) to look for rapid pulsation in the 4C21.53 radio signal. Nothing was found. These observations were "too cursory," Backer told us. "In hindsight I now know that we should have looked more seriously."

In 1981 Backer asked Miller Goss at Groeningen (Netherlands) to produce a high-resolution map of the 4C21.53 region with the Westerbork radio telescope. The result confirmed the steep radio spectrum, but it indicated that the 60-arcsecond flat-spectrum source was not coincident with the compact, steep-spectrum source. (We now know that the originally catalogued 4C21.53 signal is in fact a composite of three independent sources, one of them extragalactic.) Subsequent searches for a fast pulsar signal last spring at Arecibo and the Very Large Array in New Mexico turned up nothing.

Discovery. Finally last September Backer's tenacity bore fruit. He asked Shrinivas Kulkarni, a Berkeley graduate student on his way to Arecibo, to look again for pulsation, and he asked Goss to measure the polarization of the 4C21.53 radio emission. Goss wired Backer that the radiation was indeed 30% polarized—an extraordinarily high level of radio polarization, seen only in pulsars. A few days later Kulkarni was given unscheduled access to the Arecibo telescope to record the radio signal from 4C21.53 for a few brief intervals totaling 7 minutes. Fourier analyzing the data, he found two frequency peaks—one at 642 Hz and a second-harmonic peak at twice that frequency. But the peaks came and went. The signal was present for only 3 of the 7 minutes, and on two subsequent days it was not seen at all. "We were quite excited," Backer told us, "but we feared it might be a false alarm."

Early in November, Backer, Kulkarni and their colleagues Carl Heiles

(Berkeley) and Michael Davis (Arecibo) were granted seven nights of recording time at Arecibo. They quickly reconfirmed the 642-Hz pulsation with more sophisticated equipment, and they found that the pulse shape was quite stable. At a spin rate so close to the centrifugal breakup limit, Backer explained, one might have expected to see considerable rotational instability.

They also observed interstellar (as distinguished from interplanetary) twinkling, a clear indication that the pulsating source was smaller than one *micro*arcsecond. This interstellar scintillation, caused by minute-to-minute fluctuations in the interstellar medium, explained the erratic signal seen two months earlier.

From the small apparent difference between the September and early November data, the group deduced and reported a spindown rate of about 10^{-14} sec/sec. "This report of dP/dt in the first telegram, which I now regret, was premature," Backer concedes. As the group continued to record the signal from the object newly christened as PSR 1937 + 214, it became clear that the period was stable to at least one part in 10^{-6}, indicating[4] a much slower dP/dt.

In late November, Joseph Taylor (Princeton) joined the group at Arecibo with specialized equipment he had developed to measure the orbit decay of a binary star system by gravitational radiation (see PHYSICS TODAY, May 1979, page 19). With this equipment the group measured the period derivative of 1.26×10^{-19} sec/sec reported in December at Texas. The primary source of the considerable uncertainty remaining in this determination is the uncertainty in the position of the pulsar, which one needs in order to correct for the motion of the Earth.

In the usual scenario, a radio pulsar is born when a supernova explosion leaves behind a neutron star with sufficiently strong magnetic field and rapid spin. If the spin and magnetic axes are not aligned, one gets a "lighthouse effect." The collimated radiation from the acceleration of highly relativistic electrons emerging at the magnetic poles will appear as a pulsed radio signal to an observer in the cone swept out by the radio beam as it precesses about the spin axis. As it ages, the neutron star slows and its magnetic field decays. Eventually, after 10^7 or 10^8 years, it ceases to be a pulsar.

How then do we come to find a pulsar with an apparent age (determined by its slowing rate) of half a billion years spinning much faster than its juniors? Shaham and his colleagues Ali Alpar, Malvin Ruderman (both at Columbia) and Andrew Cheng (Rutgers) suggest that 1937 + 214 was once a slowly spinning, old neutron star with a relatively weak field of a few times 10^8 gauss and a low-mass, close binary partner. The transfer of material from the now departed, low-mass companion star, they argue, is responsible for spinning the neutron star up to pulsar speed. The accreting material forms a spinning disk around the neutron star, coupling to its corotating, plasma-filled magnetosphere. The weaker the magnetic field of the neutron star, they calculate, the smaller will be the inner radius of the accretion disk. The rotation speed of the disk material is simply given by Kepler's laws; the smaller the radius, the faster it rotates. If the inner edge of the accretion disk is spinning faster (slower) than the magnetosphere, it tends to spin the neutron star up (down). The weaker the field, therefore, the more the accretion of material from the binary partner will spin the neutron star up.

We are likely to see such accretion-generated ultrafast pulsars even if the phenomenon is quite rare, Ruderman told us, because they live so long; their anomalously weak magnetic fields dictate a very slow rate of energy loss. He points out that the few known examples of pulsars with living binary partners are among those with the weakest apparent magnetic fields. A plausible class of ancestors for the accretion-generated ultrafast pulsars, the Columbia group suggests, are the binary x-ray sources that one finds predominantly in the central bulge of our Galaxy. These are thought to be long-lived neutron stars generating continuous (non-pulsing) x-ray emission as they accrete matter from a lighter companion star with an orbital period of a few hours or days. Although these "bulge x-ray sources" can be seen from everywhere in the galaxy, the eventual pulsars would be visible only at distances up to a few kiloparsecs.

This scenario, in its broad outlines, is gaining acceptance among adherents of the "standard model" of pulsar behavior. Arons suggested a similar scheme, as do Andrew Fabian and his coworkers[5] at Cambridge and V. Radhakrishnan and G. Srinivasan[6] at the Raman Institute (Bangalore).

Curt Michel and Alex Dessler at Rice, however, have for several years dissented from the standard model, arguing that it does not deal adequately with the balance of positive and negative charge expelled by the corotating magnetosphere. To solve this "charge closure problem," they contend, one needs to invoke a fossil disk of material left over from the supernova explosion or the accretion from a binary partner. All radio and x-ray pulsars must have such Saturn-like disks, they contend.

The electromagnetic coupling of this fossil disk with the magnetosphere, they argue, is an essential ingredient of the mechanism by which the pulsar slows down. After the discovery of 1937 + 214, Michel and Dessler (now at the Marshall Space Flight Center) were quick to point out that the rate of energy loss in their model varies as P^{-3} in contrast to the P^{-4} dependence of the standard models, which do not assume the existence of fossil disks. Thus they claim to have a natural explanation for the "unexpectedly" slow rate of energy loss by ultrafast pulsars. The millisecond pulsar "is nothing special," Dessler told us. It's simply an ordinary pulsar with a magnetic field about a hundred times weaker than most, he contends.

In a very recent conversation, Arons told us that he is having second thoughts. Spinning an old neutron star up to a millisecond period by accretion from a binary partner, he now believes, would involve an implausibly large mass transfer—at least a tenth of a solar mass. He now proposes that the millisecond pulsar was born in isolation, between 10^5 and 10^6 years ago, with a field of less than 10^9 gauss. New surveys sensitive to periods of less than 0.1 seconds should find more such objects, he expects.

Whatever the ultimate explanation for the slow deceleration of the newly discovered millisecond pulsar, Backer told us, it provides us with our best clock in the sky. It could prove useful, he suggests, in improving our determination of the masses of the outer planets. —BMS

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in brief

The Model A stellarator, the very first experimental device built for magnetic-confinement fusion studies at the Princeton Plasma Physics Laboratory, has been given to the Smithsonian Institution. The figure-eight shaped device was designed by Lyman Spitzer. He and astronomer Martin Schwarzschild wound the instrument's copper coils themselves in 1952. □