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A NEW CLASS OF PULSARS

Binary pulsars, pulsars with millisecond periods and pulsars in globular clusters are distinguished by their evolutionary histories, and are providing tools for fundamental tests of physics.

Donald C. Backer
and Shrinivas R. Kulkarni

In 1939, seven years after the discovery of the neutron, nuclear physicists constructed the first models of a "neutron star." Stable results were found with masses comparable to the Sun's and radii of about 10 km.

For the next three decades, neutron stars remained purely theoretical entities. Then in 1967, radioastronomers at the University of Cambridge observed a radio signal pulsing every 1.337 seconds coming from a single point in the sky—a pulsar.[1] Its source was almost certainly a rapidly rotating, highly magnetized neutron star. The pulsars discovered since then number about 500, and their fundamental interest to astronomers and cosmologists has more than justified the excitement that was sparked by their initial discovery. Increasingly sensitive systematic surveys for new pulsars continue at radio observatories around the world.

According to the prevailing view, the observed beam of radio emission is generated in relativistic currents along certain magnetic field lines. The beam rotates with the neutron star, much like the beacon of a lighthouse, and we observe pulses that repeat at the star's rotation rate as the beam sweeps past the Earth.

Most astronomers agree that pulsars are the progeny of massive stars. When the inert ashes of nuclear burning in the core of a star exceed a critical mass, the core collapses to form a neutron star. An outgoing shock wave, which expels the outer layers to form a supernova, accompanies the collapse. The neutron star, in at least some cases, is a pulsar. Evidence of the combined process of collapse and explosion can be found in the half-dozen pulsars that have been observed at the centers of supernova remnants. Observations of these young pulsars suggest that neutron stars are born with a strong dipole field—strength, 10^{12} G at the surface—and with periods as short as 10 msec. As a pulsar radiates away its rotational energy, its pulse period gradually increases, and the energy in its emission beam decreases, until, after about 10 million years, it disappears from the radio sky. Or at least this is how most pulsars observed before 1982 were thought to behave.

During the last decade a new class of pulsars has emerged, with ages comparable to the age of the universe, or Hubble time, of 10 billion years. This class encompasses three overlapping categories: binary, millisecond and globular-cluster pulsars. Signals associated with one specimen that is both a binary and a millisecond pulsar are shown in figure 1. As a group, these new pulsars appear to be distinguished by an evolutionary epoch during which they accrete mass and angular momentum from a companion star. This process is sometimes referred to as "spin-up," and the pulsars that undergo it are accordingly called "spun-up pulsars." In addition to their obvious interest to astrophysicists, spun-up pulsars are intriguing subjects for diverse kinds of physics experiments. They have been used to test aspects of general

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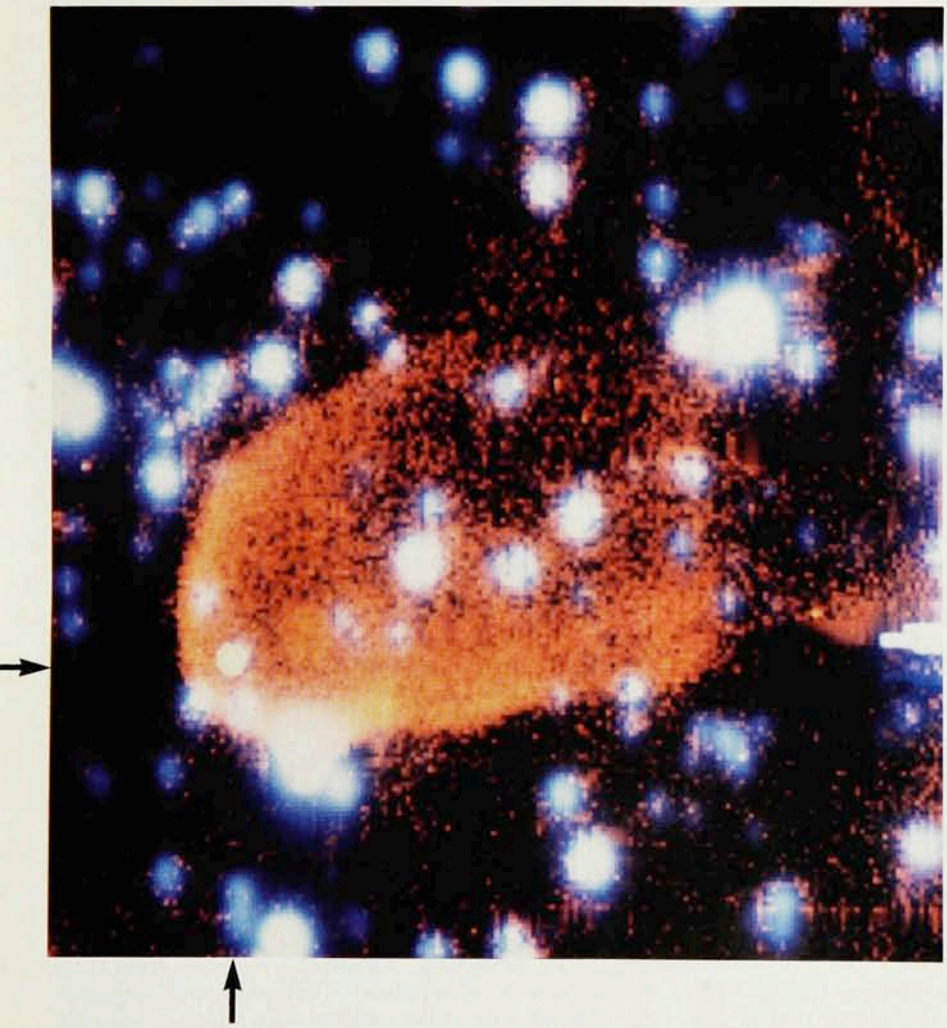


Optical nebula surrounding the binary, eclipsing millisecond pulsar 1957 + 20, depicted in the Balmer-α line of hydrogen. The pulsar is the yellowish star at the intersection of the axes indicated by the arrows. High-energy particles, radiation and magnetic fields ejected from the pulsar push the interstellar medium, producing the brilliant nebula. Its cometary shape is due to the motion of the pulsar toward the lower left (now confirmed from Arecibo timing observations by Marty Ryba, Joseph Taylor and Daniel Stinebring). (Photo taken by Jeff Hester and Shrinivas Kulkarni at the Palomar Observatory.) **Figure 1**

relativity and cosmology, and they may eventually provide for an improved terrestrial time standard. (Recent reviews and conference proceedings on this class of pulsars can be found in references 2–6.)

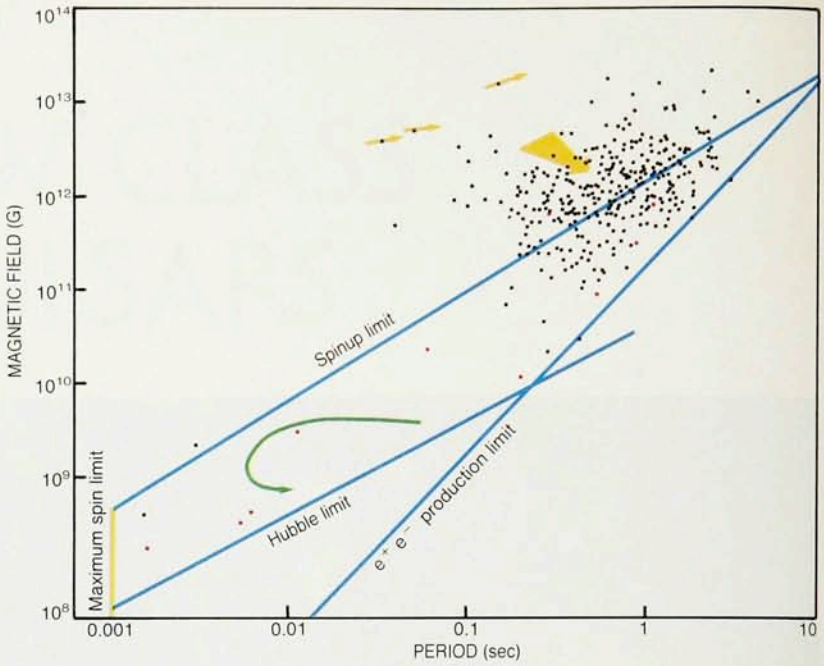
Conventional models

A simple model for a pulsar is a rotating sphere with a moment of inertia I approximately equal to 10^{45} g cm^2, in which a bar magnet of intensity B is embedded at an angle α with respect to the rotation axis. The rotational energy, $\frac{1}{2}I\omega^2$, will decrease at a rate proportional to $B^2\omega^4$ as the pulsar emits magnetic-dipole radiation. The measured second derivatives of the periods of several pulsars approximately agree with this simple model. In this model the surface field strength is estimated from

$$B \sin\alpha = 10^{12}\ \mathrm{G}\sqrt{P\dot{P}_{-15}} \qquad (1)$$

where $P = 2\pi/\omega$ and the period derivative $\dot{P} = \dot{P}_{-15} \times 10^{-15}$ sec sec^{-1}. Pulsars of varying ages distribute in a diagram of B (calculated for $\alpha = \pi/2$) versus P (figure 2).

Despite its rough agreement with experiment, the bar-magnet model is grossly incomplete. In particular, it does not account for the fact that the intense rotating magnetic fields generate strong electric fields that can rip material from the surface of the star. Some of this matter will form a magnetosphere, which corotates with the star out to a radius where the centrifugal force on the plasma



Inferred surface magnetic fields versus rotation periods, plotted for all pulsars with known period derivatives. Single pulsars are plotted in black, binary pulsars in red. Note the concentration of the single pulsars toward the upper right-hand region. The evolutionary paths of three young pulsars are suggested with small yellow arrows, and the inferred direction of evolution from young to old pulsars is indicated by the broad yellow arrow. The blue lines are limits derived from the pulsar models discussed in the text, and the yellow line indicates the maximum rotation frequency that a pulsar can sustain before tearing apart from centrifugal forces. The evolutionary path expected for the binary and millisecond pulsars is shown by a green arrow, moving first toward the spinup limit and then back toward the Hubble and e^+e^- production limits. **Figure 2**

overcomes the restoring force of the magnetic field—the corotation radius. The charge distribution in the magnetosphere adjusts to balance the rotation-driven electric fields. The magnetic field lines that just reach the corotation radius define a toroidal surface about the pulsar. This torus is the boundary between the "closed" magnetosphere—the part of the magnetosphere enclosed by the torus—and the part outside the torus (see figure 3).

Although particles in the closed magnetosphere are trapped, those that enter the open magnetosphere pass into the interstellar medium. In some favorable cases, these particles and the dipole radiation interact with the surrounding interstellar medium to form a dramatic bow shock (figure 1).

The high power of a typical pulsar signal points to its being some form of coherent radiation, which many cosmologists think is generated in a relativistic e^+e^- current in the open magnetosphere along polar magnetic field lines. The e^+e^- cascade discharge that forms this current requires a minimum voltage between the surface of the star and the interstellar medium. This voltage is generated by the pulsar's rotation and is proportional to B/P^2. The absence in figure 2 of pulsars below the line B/P^2 less than approximately 2×10^{11} G sec^{-2} (called the death line) supports these ideas.

In polar emission models, the width of the emitting beam is expected to increase as the square root of the rotation rate as the open magnetosphere becomes larger and larger. The observed increase of pulse width with rotation rate at least qualitatively supports this prediction. But such evidence only weakly supports current models of pulsar magnetospheres. A self-consistent theory of the fields and currents in pulsar magnetospheres has yet to be found.[6]

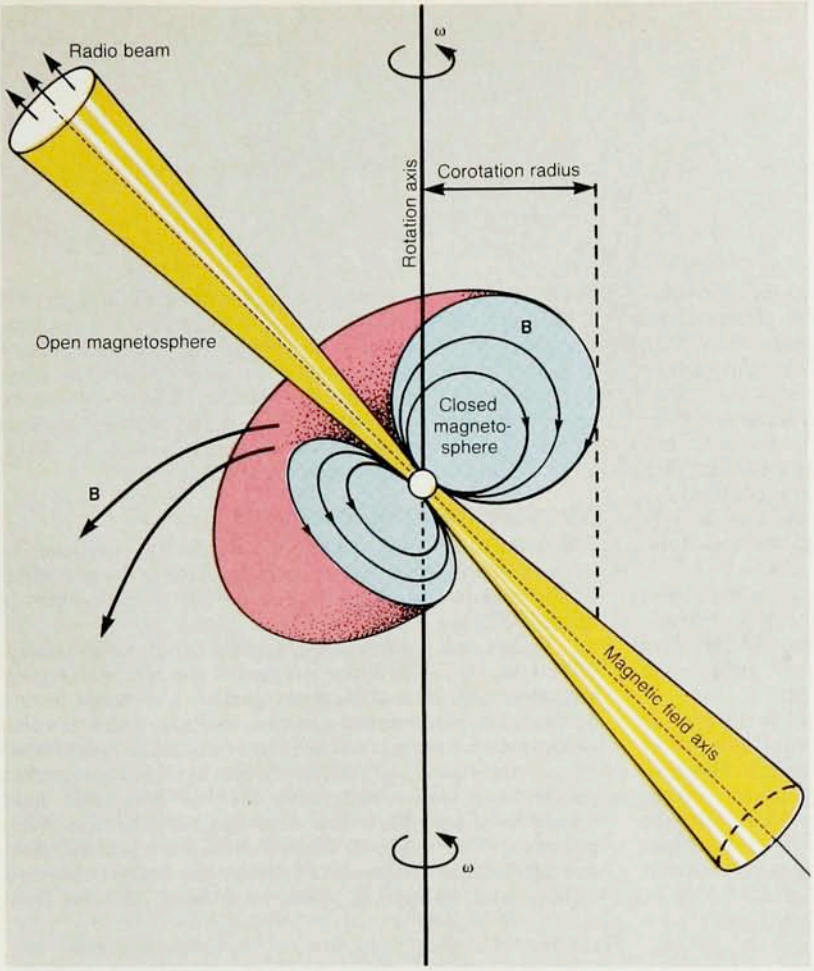
A historical perspective

In the decade following the discovery of the first pulsar, directed and systematic searches at major radio observatories in the UK, the US and Australia uncovered several hundred similar objects. Their rotation periods ranged from 33 msec (for the pulsar in the Crab nebula supernova remnant) to 4.3 sec, with a median value of 0.7 sec. In 1974, using the giant 305-m Arecibo radiotelescope, Russell Hulse and Joseph Taylor discovered the first pulsar in a binary system.[7] The system is named 1913 + 16 for its celestial coordinates of 19 hours and 13 minutes of right ascension and 16 degrees of declination. It contains a 59-msec pulsar in a 7.8-hour elliptical orbit around a companion, which most likely is another neutron star.

In the early 1970s x-ray astronomers, using spaceborne telescopes, independently detected signals from neutron stars. Two classes of Galactic x-ray objects were found: pulsating sources in binary systems near the Galactic plane and unpulsed sources in the central bulge of the Galaxy and in globular clusters. The 150 globular clusters in our galaxy are ancient self-gravitating clusters of 10^5 to 10^6 stars, which are distributed in a sphere mostly outside the plane of the Milky Way. The x-ray emission for both types is most likely blackbody radiation from matter accreted from a companion star, which is heated to approximately 10^7 K as it falls into the deep gravitational potential well of the neutron star.

The first class, x-ray pulsars, probably have strong magnetic fields (on the order of 10^{12} G) that funnel the matter accreted from their massive companions into the magnetic pole regions. Anisotropic radiation from these regions is observed as pulses owing to rotation. Changes in the rotation rate of the neutron star, which result from variable accretion, are observed, and observations of cyclotron emission lines in two of these systems support the high magnetic-field strengths essential to the mass-accretion model. These high-mass x-ray pulsars are obvious progenitors for systems like the binary radio pulsar 1913 + 16, which rotates ten times faster than typical pulsars.

Members of the second class of x-ray-emitting neutron stars, the unpulsed sources, have no bright optical companions and no coherent periodic modulation. Many astrophysicists conclude that these systems also are binaries, consisting of a weakly magnetized neutron star accreting matter from its low-mass companion. Some supporting evidence is the strong bursts observed in 1975



Simplest model of an unpaired pulsar: a rotating neutron star (in white) with a dipole magnetic field at an angle to the rotation axis. Any charged particle that is swept up into the closed magnetosphere (the red torus) will be recycled back towards the pulsar. But particles that travel into the open magnetosphere—constrained to a narrow cone about the magnetic axis—will escape into the interstellar medium, producing the radio beam that we observe on Earth. (Adapted from J. Pasachoff, *Contemporary Astronomy*, W. B. Saunders, Philadelphia, 1977.) **Figure 3**

from bulge x-ray sources and attributed to unstable thermonuclear burning of matter accreted by an unmagnetized (or weakly magnetized) neutron star. The bulge and globular-cluster sources are now collectively referred to as "low-mass x-ray binaries."

In 1982 we and our colleagues discovered the radio pulsar 1937 + 21 with no companion. Its record-shattering rotational period of 1.558 msec made it the first millisecond-period pulsar.[8] Its estimated magnetic field, 10 000 times smaller than that of the typical pulsar, established another record. The discovery of 1937 + 21 reawakened wide interest in pulsar astronomy. Although in hindsight the mass-accreting x-ray pulsars might have been taken as a clue that pulsars could develop extremely high rotation rates, the properties of 1937 + 21 took the entire astrophysics community by surprise. The origin of 1937 + 21 remains a mystery because the lack of a companion seems to preclude a spin-up scenario.

The recent discovery of an eclipsing, millisecond binary pulsar[9], 1957 + 20, suggests a plausible mechanism for the formation of single millisecond pulsars like 1937 + 21. Judging from their durations, the eclipses of 1957 + 20 probably occur when a dense wind of material flowing from the companion star blocks the pulsar's signal. This wind is presumably fueled by matter that has been ablated from the surface of the companion by high-energy photons from the pulsar. Other binary pulsars with even higher ablation rates might completely destroy their companions, leaving behind only a single unpaired millisecond pulsar like 1937 + 21.

The discovery of 1937 + 21 and, later, 1953 + 29 forcefully drew attention to the evolutionary link between the low-mass x-ray binaries and millisecond pulsars. The evolutionary link was supported by the discovery[10] of a 3-msec pulsar in the globular cluster M28 (see figure 4). There are now a total of 21 binary, millisecond and globular-cluster pulsars (see table).

Pulsar surveys

Radio pulsars emit faint sharply peaked pulses, principally at low frequencies—from 25 MHz to 2 GHz. These signals are dispersed by thermal electrons in the intervening interstellar plasma, which interposes typical electron column densities of about 10^{20} cm^{-2}. The dispersion delays the arrival of low frequencies at the Earth; hence a sensitive search for faint pulsar signals requires rapid sampling of many frequency channels using the largest radiotelescopes. The dispersive delay within a single frequency channel in the detector sets a lower limit on sampling time and, therefore, a lower limit on detectable pulse periods. The total number of power measurements—the product of the number of frequency channels and the number of time samples—establishes the sensitivity of the search. The data sets acquired in typical searches have grown from 10^5 samples in 1975 to 10^8 samples in recent years.

Once the data are recorded, a corrected set is calculated by subtracting the effects of a hypothetical

dispersion; the resultant time series then is examined for periodic components using Fourier analysis. The analysis is repeated for a range of possible dispersions. Candidate pulsar signals down to some minimum intensity threshold are stored for repeat observations. In most of the recent surveys the data are recorded on magnetic tapes and later analyzed by supercomputers. However, we and our colleagues have developed a digital signal processor that performs a real-time search. Such a design is particularly attractive for large surveys, where there are tens of thousands of beam directions, with 10^7 or more samples per beam.

Since 1982, surveys for millisecond pulsars have been in full swing at the large telescopes at Arecibo and Green Bank (USA), Jodrell Bank (UK) and Parkes (Australia). These efforts have uncovered three binary millisecond pulsars: 1855 + 09, 1953 + 29 and 1957 + 20.

The accretion–spin-up model provided the ideological motivation for intensive searches in globular clusters. At present 11 pulsars have been found in clusters. Ongoing searches will undoubtedly uncover dozens more. Searches within clusters can be especially rewarding in that once one pulsar is found in a cluster, the dispersion measure for others is known, and very deep searches can be pursued. Following the discovery of 2127 + 11A in M15 at Arecibo, a very deep search resulted in the discovery[11] of a second pulsar, 2127 + 11B. In conventional search algorithms the sensitivity for binary pulsars is severely reduced when the integration time is more than a small fraction of a binary orbit. A search algorithm that is sensitive to a range of accelerations produced the discovery of a third pulsar in M15, 2127 + 11C, in a highly eccentric 8-hour orbit.[11]

Neutron-star magnetic fields

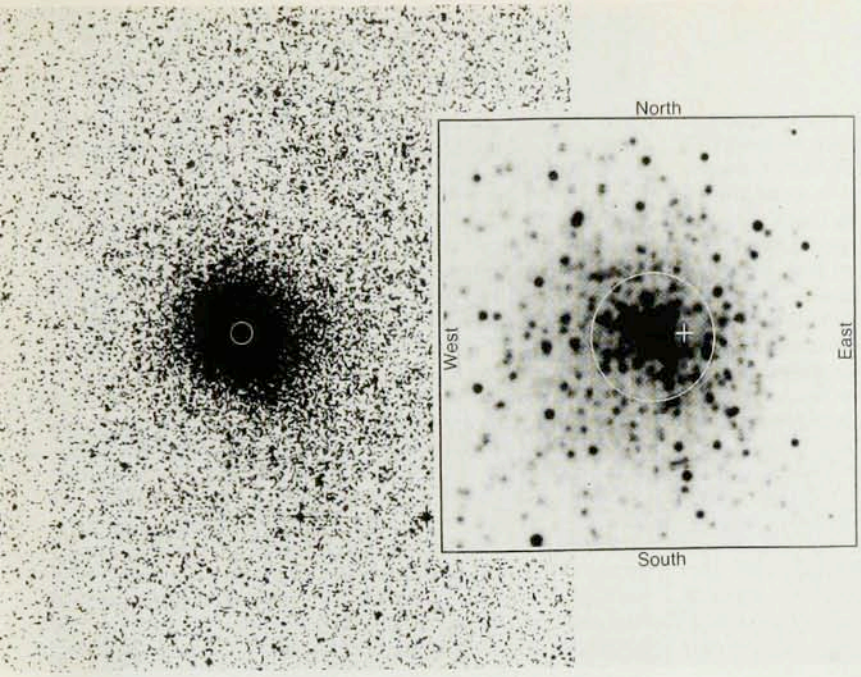
Magnetic fields play a crucial role in the evolution of neutron stars. A unifying model describing the evolution of the magnetic field with time for *all* neutron stars is discussed below.

In figure 2, young pulsars, such as the Crab pulsar, 0531 + 21, lie in the upper left part of the plot with strong magnetic-field strengths, short periods and large period derivatives. Neutron stars in x-ray pulsars, which are also thought to be young, are evidently strongly magnetized (these are not displayed in figure 2). However, most pulsars are older and have weaker magnetic field strengths than either the Crab pulsar's or the x-ray pulsars's. This suggests that neutron-star magnetic-field strengths decay. Exponential decay time scales between 2 million and 10 million years have been deduced from

Binary, millisecond and globular-cluster pulsars

Name[1]	Rotation period (msec)	Time derivative of period (10^{-18}sec sec^{-1})	Orbital period (days)	Mass function ($M_\odot$)	Eccentricity
0021 − 72A (g)	4.5	—[2]	0.02	1.6×10^{-8}	0.33
0021 − 72C (g)	5.8	—	...[2]	...	...
0655 + 64 (f)	195.7	0.68	1.03	7.1×10^{-2}	<0.00005
0820 + 02 (f)	864.9	103.9	1232.47	3.0×10^{-3}	0.01187
1516 + 02A (g)	5.5	—	...	...	...
1516 + 02B (g)	7.9	—	—	—	—
1620 − 26 (g)	11.1	0.82	191.44	8.0×10^{-3}	0.02532
1639 + 36 (g)	10.4	—	...	...	...
1746 − 20 (g)	288.6	—	—	—	—
1820 − 11 (f)	279.8	1378	357.76	6.8×10^{-2}	0.79462
1821 − 24 (g)	3.1	1.62	...	...	...
1831 − 00 (f)	520.9	14.3	1.81	1.2×10^{-4}	0.0001
1855 + 09 (f)	5.4	0.02	12.33	5.6×10^{-3}	0.00002
1913 + 16 (f)	59.0	8.64	0.32	1.3×10^{-1}	0.61713
1937 + 21 (f)	1.6	0.11	...	...	...
1953 + 29 (f)	6.1	0.03	117.35	2.4×10^{-3}	0.00033
1957 + 20 (f)	1.6	0.02	0.38	5.2×10^{-6}	0.000
2127 + 11A (g)	110.7	− 20.0	...	...	...
2127 + 11B (g)	56.1	—	...	...	...
2127 + 11C (g)	30.5	—	0.34	1.5×10^{-1}	0.68
2303 + 46 (f)	1066.4	569.3	12.34	2.5×10^{-1}	0.65838

[1] "(g)" indicates a globular-cluster pulsar; "(f)" denotes a pulsar in the field (that is, not in a cluster).
[2] A long dash indicates a measurement that has not yet been made. An ellipsis occurs wherever a row containing data of a non-binary pulsar intersects a column whose heading makes sense only for binary systems.



The globular cluster M28, home of the first known cluster pulsar, 1821 − 24. The larger image is a photograph of a 21.5-arcminute square centered on M28. The inset is a charge-coupled-device image of the cluster's core, with the pulsar indicated by the cross hairs. In both pictures, the white circle represents the extent of the 21-arcsecond core centered on the optical centroid of the cluster. (Photo taken at the Schmidt Telescope of the Royal Observatory in Edinburgh, UK. CCD image obtained at the 1.5-meter Cerro Tololo telescope. From ref. 10). **Figure 4**

analysis of the pulsar population. Field decay is also supported by kinematical studies of pulsars.

Many issues concerning field decay are controversial. Some researchers note that equation 1 gives only the projection of B onto the pulsar's equatorial plane, and that any change in the pulsar's deceleration might just as easily come from the evolution of the angle α as from a true change in the magnetic field. Indeed, an analysis of polarized pulse profiles[12] seems to provide observational evidence for the gradual decay of α. Those who support the idea of magnetic-field decay might endeavor to beat the skeptics by pointing out that equation 1 is a *vacuum* solution, whereas a real pulsar has a magnetosphere, which may render the value of α unimportant as far as the torque is concerned.

Independent evidence for magnetic-field decay is found in the location of binary pulsars in figure 2. In a binary pulsar system, matter from the companion settles into an accretion disk around the neutron star.[13] The interface between the disk and the neutron star's magnetosphere occurs at the radius where the outward pressure of the compressed magnetic field is equal to the inward pressure of the falling matter. This is the so-called Alfvén radius, and it is directly proportional to B. Thus the equilibrium rotation period P_{eq} is just the Keplerian period of the accretion disk at the Alfvén radius:

$$P_{eq} = 2 \text{ msec } (B/10^9 \text{ G})^{6/7} \qquad (2)$$

In figure 2 the millisecond and binary pulsars are nicely closeted between the spin-up line, defined by equation 2, and the Hubble limit, which is set by spin down during the age of the universe. Since the Alfvén radius depends on the strength of the magnetic field and not on its orientation, we conclude that, in the millisecond binary pulsars and in low-mass x-ray binaries, the magnetic field, and not merely its equatorial component, is weak.

On the other hand, optical observations of the white dwarf companions of binary pulsars (see, for example, figure 5) strongly suggest that the field strengths of some neutron stars do not decay. Observations reveal that in two cases the white dwarf is cool and hence quite old—several billion years. (White dwarfs shine because of stored heat; hence their surface temperatures essentially reflect their ages.) A two-component model consisting of a "crustal" field of initial strength of approximately 10^{12} G, which exponentially decays, and a "core" field of 10^8 to 10^{10} G, which essentially remains unchanged, can satisfactorily explain the magnetic-field strengths in both pulsars and x-ray binaries.[14] An equally good alternative is one in which the field decays as a power law: $B(t) \alpha t^{\alpha}$. All this discussion shows that our understanding of this important phenomenon is poor and incomplete.

Binary pulsar evolution in the Galactic disk

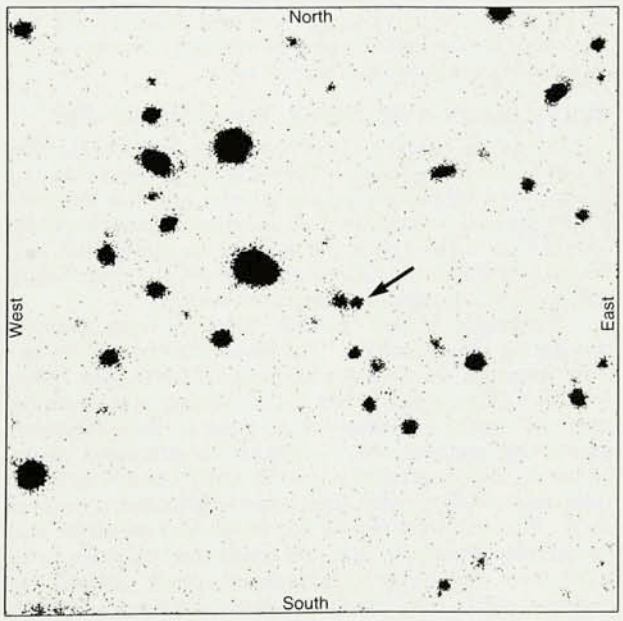
A total of nine binary pulsars have been found in the disk of our Galaxy (see table). They can be divided into two groups—the high-mass binary pulsars and the low-mass binary pulsars—based on their measured mass functions, $(m_2 \sin i)^3/m^2$. Here m_2 is the mass of the companion, m is the total mass and i is the angle between the line of sight and the orbital angular-momentum vector.

High-mass binary pulsars descend from binaries containing massive stars. The more massive of the two (the "primary") evolves quickly into a neutron star. After several million years, when the secondary star is on the verge of death, it begins losing mass to its companion, generating beamed x-ray emission as discussed above. However, if the secondary is sufficiently massive (greater than eight solar masses), then it too will become a neutron star. The explosive birth of the second neutron star usually decouples the pair and sends the two stars flying away from each other at substantial speeds. Indeed, the observed space velocities of pulsars are large, approximately 200 km/sec. However, in some rare cases, a highly eccentric system, such as 1913 + 16, is formed. The existence of these systems suggests an alternative to the ablation scenario by which an isolated millisecond pulsar like 1937 + 21 might be created. To wit, a short-period, very eccentric binary might emit enough gravitational radiation that the two stars eventually spiral down into a single neutron star.

The origin of the low-mass binary pulsars is less clear.

The naive model starts with a neutron-star primary and a secondary that is a hydrogen-burning ("main sequence") star of roughly one solar mass. After a few billion years the secondary expires and, under suitable conditions, starts dumping matter onto the primary. By this time, the magnetic field of the neutron star is down to its low, core value. With such a weak field, the neutron star accretes mass fairly isotropically, and the x-ray emission caused by the accretion is therefore unpulsed. At this intermediate stage the system can be observed as a continuous x-ray source, that is, a low-mass x-ray binary. The mass transfer gradually widens the orbit and spins up the neutron star. The final state would be a low-mass white dwarf in a wide, nearly circular orbit around a highly spun-up pulsar.

Although observations broadly support this scenario, it is difficult to understand how a weakly bound, low-mass binary system could survive the supernova explosion that accompanies the birth of the neutron star. Consequently, some astrophysicists have suggested the possibility that the primary stars in these systems started as massive white dwarfs and became rapidly rotating pulsars only after a sufficient amount of matter was accreted from the secondary—the so-called accretion-induced-collapse hypothesis. This hypothesis solves the disruption problem previously discussed, but it has serious theoretical difficulties. To begin with, the white dwarfs observed seem to eject most of the accreted matter, so that they have no substantial net gain in mass. Furthermore, there is some observational evidence that accreting white dwarfs explode (in so-called type Ia supernovas), leaving no stellar remnants. Finally, there is no obvious reason why the neutron star formed by this channel (if at all) should be born with millisecond periods and low magnetic-field strengths.



White-dwarf optical companion (indicated with an arrow) of the binary pulsar 0655 + 64. The presence of a cool, and therefore ancient, white dwarf in this binary system is evidence that the magnetic field of its companion, a neutron star, is essentially constant (see text and ref. 14 for discussion). **Figure 5**

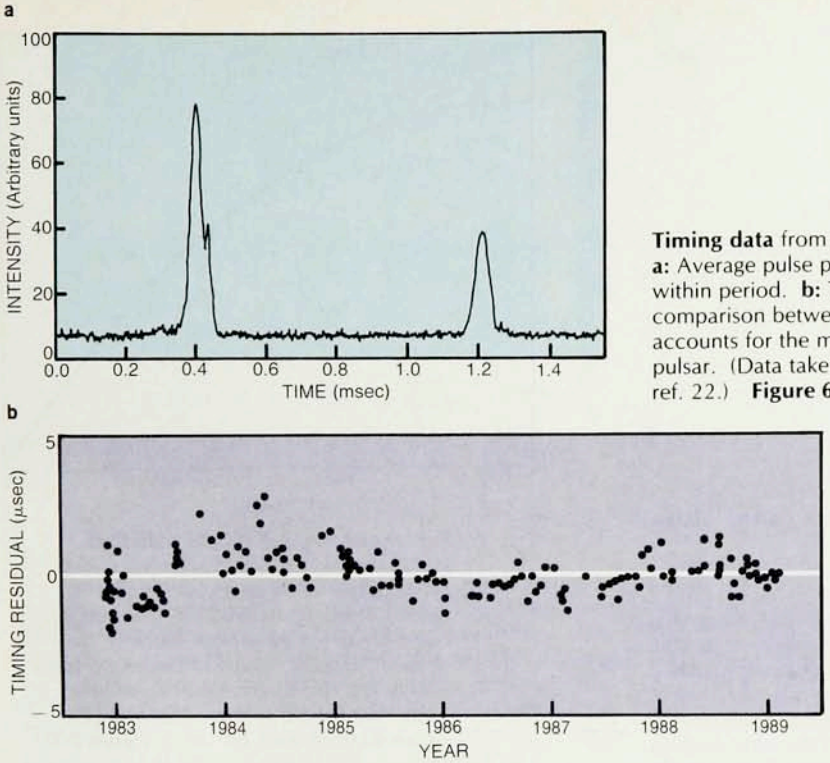
The birthrates of the low-mass binary pulsars indicate yet another disquieting insufficiency in the previously discussed standard scenario. If low-mass x-ray binaries are indeed progenitors of the low-mass binary pulsars, then the birthrates of the two species should be equal, assuming that their populations have reached a steady state. However, careful analysis reveals that in the Galactic disk the birthrate of low-mass binary pulsars—such as the millisecond pulsar 1855 + 09—is *at least* 100 times that of the low-mass x-ray binaries. We can think of two possible solutions to this inconsistency: Either there are a large number of systems in which mass transfer is occurring but which do not emit x-ray radiation, or the evolution of x-ray binaries is considerably faster than the models predict. The millisecond pulsar 1957 + 20, in which the companion is ablated by pulsar radiation, provides a dramatic example of hastened evolution. In a similar way, x rays from the accretion disk might also enhance the mass transfer by heating the companion.[15] Whether such feedback processes can hasten evolution by a required two orders of magnitude remains to be seen.

Globular-cluster pulsar evolution

The discovery of spun-up pulsars in globular clusters refocused attention on the issue of neutron stars in these systems. A simple hypothesis is that cluster pulsars are the neutron-star remnants of primordial massive stars that did not escape their parent cluster during their violent formation and were subsequently spun up.[16] The primordial neutron stars that form the current pulsars either were born in binary systems or acquired a companion following an inelastic collision with a field star. Dissipation of tides induced in the field star expends thermal energy, allowing the field star to be gravitationally captured by a neutron star. In a typical rich cluster, roughly 10% of the neutron stars are expected to have captured a partner by the present epoch. During a subsequent accretion phase, these paired systems would be visible as low-mass x-ray binaries, and their final product might be the low-mass binary pulsars observed. In addition to the capture process discussed above, direct hits of a passing star by a neutron star may also lead to a spun-up isolated pulsar. Once formed, the tidal binaries can be perturbed by passing stars, and, in extreme cases, the spun-up pulsar can be liberated from the binary system.

The clusters as a whole are not stationary over time but pass through high- and low-density phases driven by dynamic interaction between the stars. In the high-density state all above processes should clearly be enhanced.

A recent study that analyzes the successes and failures of the many pulsar searches concludes that there are about 10^4 active radio pulsars in the Galactic globular clusters,[17] although most of these are too faint to be detected. Since only 10% of the primordial neutron stars that remain in the clusters after their formation eventually undergo tidal capture, the total number of neutron stars in clusters is deduced to be an astounding 10^5! In our view such a high number is inconsistent with both the conventional model previously discussed and the accretion-induced models[18] (unless most accreting white dwarfs, regardless of mass or



Timing data from the millisecond pulsar 1937 + 21. **a:** Average pulse profile displaying two strong emission peaks within period. **b:** Timing residuals that result from comparison between observed arrival times and a model that accounts for the motion of the Earth and the rotation of the pulsar. (Data taken at the Arecibo Observatory, reported in ref. 22.) **Figure 6**

chemical composition, can form millisecond pulsars). Furthermore, producing such a prodigious number of neutron stars would very likely make a cluster gravitationally unstable in its formative stages. The ongoing searches for globular-cluster pulsars should eventually help to solve this puzzle, providing a new window on the formation of these ancient subunits of our Galaxy.

So far, we have presented the standard views of the formation and evolution of spun-up pulsars, introducing possible modifications to accommodate new observations—for example, in explaining the birthrate discrepancy, the evolution of the magnetic field and the formation of isolated millisecond pulsars. But despite these modifications, several sticky issues remain. First, we have yet to demonstrate that low-mass x-ray binaries are really the progenitors of the millisecond pulsars. The conclusive proof—coherent pulsations from a low-mass x-ray binary system—has never been observed and is a principal objective of current searches. Second, the formation of wide binaries, like the binary pulsar 0820 + 02 with a four-year orbit, is quite difficult to understand within the standard framework. Such systems can more easily be understood in the accretion-induced collapse model. Third, the origin of pulsars in globular clusters is not well understood in any model.

Our discussion can best be summarized by saying that while great progress has been made in observing this new class of pulsars, their origins are still cloaked in mystery.

Pulsars as celestial clocks

Although the current understanding of spun-up pulsars is far from complete, these pulsars can still be used for a variety of astrophysics applications. Their strikingly regular rotation periods make them ideal celestial clocks. In that capacity spun-up pulsars have been used to test general relativity, and they may provide a means of improving the terrestrial time standard.

Measuring the arrival times of pulsar pulses requires a number of simple steps that must be carried out with extreme precision.[19] First, pulse profiles (see figure 6a) are integrated during a several minute observation; this usually requires removal of the dispersion of the signals by hardware and software techniques. The epoch of the first sample in each integration is recorded by reading the observatory atomic clock and later correcting the observatory time scale to an international time scale with data from the Global Positioning System of satellites or a similar time-transfer system.

Determining the rotational properties of a pulsar requires a transformation of pulse arrival times from the observatory space–time frame to that of the neutron star with an accuracy of at least 100 nanoseconds. A relativistic time transformation removes both the periodic components of the time dilation and gravitational redshift ($v^2/c^2 \approx 10^{-8}$) and the delay produced by the gravitational-mass space–time distortion of the Sun. The required spatial transformation relies on an accurate table, or ephemeris, of the Earth's position relative to the center of mass of the solar system. Earth ephemerides are based on models of solar system dynamics that are constrained primarily by planetary radar data obtained over previous decades and optical observations taken over the past few centuries. With microsecond-precision timing, positional accuracies exceeding 0.0004 arcsecond can be obtained. Even pulsar distances of up to 15 000 light-years can be measured by determining the curvature of the pulse wavefront over the solar system from observations made at various points in the Earth's orbit.

Precise measurement of the amount of intervening plasma is perhaps the simplest use of binary pulsars as measuring devices. The column density of electrons is obtained directly from timing observations at multiple radio frequencies. Secular variations of these column densities provide a unique and direct measure of the turbulence in the interstellar plasma, which mediates cosmic-ray propagation.

After applying all the necessary transformations and corrections, one can finally determine the rotational parameters of the neutron star. The model for the arrival time, t_N, of the Nth pulse consists of a simple polynomial

in pulse number with coefficients for the initial phase, period and higher derivatives:

$$t_N = t_0 + PN + \tfrac{1}{2}\dot{P}PN^2 + \tfrac{1}{6}\ddot{P}PN^3 \qquad (3)$$

Deviations from the arrival times calculated from this rotation model—referred to as timing residuals—are used to update both the rotation model and the parameters used for data corrections (figure 6b). These trends can lead to extensions of the model to include such effects as random adjustments of the moment of inertia of the star and, in the case of globular-cluster pulsars, unmodeled gravitational accelerations.

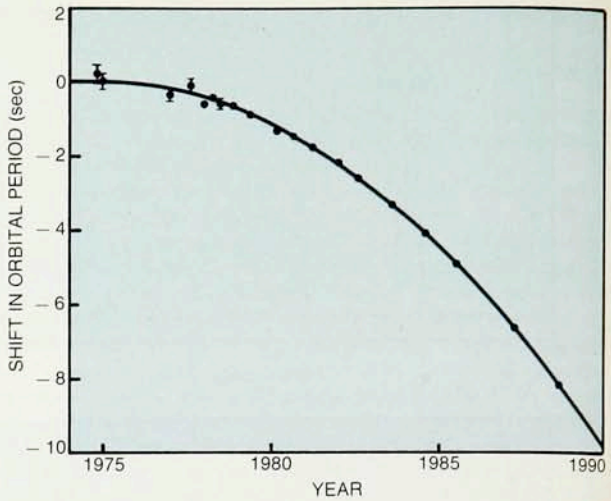
Relativistic binary pulsars

The binary pulsars 1913 + 16 and 2127 + 11C provide the sort of data needed for the study of relativistic gravity. Timing observations of 1913 + 16 by Joseph Taylor and Joel Weisberg[20] are consistent with a model of two point masses in the framework of weak-field general relativity. Taylor and Weisberg's high-precision data enable a number of relativistic, or post-Keplerian, parameter determinations.

The largest relativistic effect is the steady advance with time of the moment of closest approach, or periastron point, of the two stars. The periastron point advances at 4.22° per year, which is 100 times the perihelion-advance rate of Mercury. The next largest effect is the relativistic time transformation mentioned above: The rotation period of a pulsar in an elliptical orbit is not constant when viewed by an observer at rest outside the system. The measurement of these two relativistic effects enabled Taylor and Weisberg to determine that the pulsar and its companion had masses of 1.444 $M_\odot$ and 1.386 $M_\odot$, respectively.[20]

With the masses and orbital parameters of 1913 + 16 in hand, one can use general relativity to predict the decay of the orbital period due to gravitational radiation. Such predictions made for 1913 + 16 agree with theory at the 1% level (see figure 7), thus providing the only experimental evidence for gravitational radiation. The 1913 + 16 data have also been used to establish an upper limit on the secular variation of the gravitational constant and to look for evidence of the geodetic precession predicted by general relativity.

The long span of observations of 1913 + 16 allows testing of more complete models of relativistic binary dynamics than the two-point-mass model discussed above. Thibault Damour and Nathalie Deruelle[21] have presented a parameterized post-Keplerian formulation that accurately mixes the strong-field effects of general relativity in the vicinity of the neutron stars ($Gm/rc^2 \approx 1$) with the weak-field effects of their interaction ($Gm/rc^2 \approx 10^{-6}$). The additional observables in this approach provide crucial cross checks on the consistency between theory and observations.



Evidence for gravitational radiation. Observations of the gradually decreasing orbital phase of binary pulsar 1913 + 16 (filled circles) agree to within 1% with the curve predicted by general relativity (also shown). The decreasing phase results from energy loss due to gravitational radiation. (Data taken at the Arecibo Observatory. Figure adapted from ref. 20.) **Figure 7**

Millisecond pulsars as cosmology probes

Precise pulsar-timing measurements also can be used to study the background of gravitational radiation from violent events in the early universe. Gravitational radiation passing by the Earth creates an apparent Doppler shift of a pulsar signal that depends on the relative directions of the gravitational radiation and the pulsar. Time variations of the radiation would then lead to time variations in the Doppler shifts of an array of pulsars.[19] Timing residuals of a pulsar can then be converted directly into an upper limit on the spectrum of gravitational background radiation.

The microsecond timing residuals for 1937 + 21 (figure 6b) provide a strict upper limit on the background spectrum for periods around one year.[22] This limit is 10^{-6}, expressed as a ratio of the energy density in a band of gravitational radiation with periods near one year and the energy density required to close the universe. This limit is very close to the level predicted by models that use cosmic strings as seeds for galaxy formation.[23]

The limit placed on gravitational background radiation by pulsar timing will decrease with time T as T^4 if errors in the time scale, ephemeris and propagation are insignificant and the pulsars themselves are stable. Data from an array of precisely timed pulsars, taken at different observatories, are required to remove the influence of such errors. For example, slow variations in the reference atomic time scale can be recognized because they affect all observations, independent of direction. The fractional frequency stability of 1937 + 21 calculated from the data in figure 6b is 10^{-14} on time scales of around one year, rivaling the best international time scales. The present uncertainties in the ephemeris will lead to errors with a dipole signature in the various pulsar directions. Pulsar timing data may then be useful in improving the

accuracy of parameters of the solar system model.

Pulsar timing data, in addition to setting upper limits on gravitational background radiation, may someday enable its detection. The proposed method relies on the fact that a gravitational wave with polarized amplitudes h_+ and $h_\times$ distorts the space–time metric. As previously discussed, these distortions of the metric would cause Doppler shifts in the signals of various pulsars, with a signature that depends on direction, as given by

$$z = \frac{(\alpha^2 - \beta^2)h_+ + 2\alpha\beta h_\times}{2(1+\gamma)} \tag{4}$$

where α, β and γ are the direction cosines of the pulsar–Earth line with respect to a set of coordinates in which the gravitational wave travels in the $+z$ direction.[24] The quadrupole and higher-order components of this angular distribution would be distinct from the monopole and dipole effects discussed above. Pulsar timing-array observations have begun at a number of observatories around the world—Arecibo and Green Bank in the US, Jodrell Bank in the UK, Nançay in France, Usada in Japan and Parkes in Australia—in an effort to detect the temporal and angular signatures in millisecond pulsar timing residuals.

Outlook on the future

The study of neutron stars has shifted into high gear with the discovery of binary, millisecond and globular-cluster pulsars, and the large number of searches under way suggests that interest will remain high in the coming decade. The newest models represent a synthesis of radio and x-ray observations, and center on the ideas of magnetic field decay, accretion and related astrophysics. The rapidly growing list of pulsars in globular clusters, whose dense cores are nurseries for binary systems, will continue to reveal secrets of neutron star evolution, to shed light on star formation at early epochs and to provide probes of cluster dynamics.

The uncertainty of our present concepts about neutron-star astrophysics stands in sharp contrast to the precision available in pulse timing. Upgrades of existing radiotelescopes and construction of new telescopes will allow continued improvements of these remarkable measurements. Monitoring pulse arrival times will provide new, more precise tests of general relativity and increasingly precise measurements of cosmological parameters. At the same time, these data may improve the terrestrial time scale and contribute to more accurate models of solar system dynamics.

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