Science AAAS

Observational Properties of Pulsars

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Science **304**, 542 (2004);
DOI: 10.1126/science.1097649

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98. We thank D. Page for providing Fig. 3 and the cooling curves illustrated in Fig. 4. This work was supported in part by the U.S. Department of Energy grant DE-AC02-87ER40317 and by NSF grant INT-9802680.

REVIEW

Observational Properties of Pulsars

R. N. Manchester

Pulsars are remarkable clocklike celestial sources that are believed to be rotating neutron stars formed in supernova explosions. They are valuable tools for investigations into topics such as neutron star interiors, globular cluster dynamics, the structure of the interstellar medium, and gravitational physics. Searches at radio and x-ray wavelengths over the past 5 years have resulted in a large increase in the number of known pulsars and the discovery of new populations of pulsars, posing challenges to theories of binary and stellar evolution. Recent images at radio, optical, and x-ray wavelengths have revealed structures resulting from the interaction of pulsar winds with the surrounding interstellar medium, giving new insights into the physics of pulsars.

Pulsars are naturally occurring celestial objects whose defining characteristic is that the observed emission is a highly periodic pulse train. For known pulsars, the pulse period lies between 1.5 ms and 11 s. These pulsations probably originate as beamed emission from rotating neutron stars—tiny stars, composed predominantly of neutrons, that are formed in the supernova explosions that mark the endpoint of the evolution of massive stars (*1*). The large mass and small radius of a neutron star allows rotation at speeds approaching 1000 revolutions per second and also accounts for the extraordinary stability of the periodicity. Pulsars are also characterized by extremely strong magnetic fields, up to 10^{15} G (10^{11} T) in some cases. The combination of rapid rotation and a strong magnetic field means that a pulsar is an efficient dynamo, generating electric fields of 10^{12} V cm^{-1} or more near its surface. Charged particles are accelerated to ultrarelativistic energies in these large fields, leading to an electron-positron pair production avalanche and ultimately to the generation of a radiation beam. The electrodynamics of the pulsar magnetosphere are complicated [see, e.g., (*2*)], and neither these nor the mechanism responsible for the beamed emission are well understood. Nonetheless, a model in which the radiation is beamed outward from field lines emanating from the magnetic polar caps explains many of the observed properties (*3*).

Although pulsar periods are very stable, they are not constant. All pulsars lose energy, either to magnetic dipole radiation (electromagnetic radiation with a frequency equal to the

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spin frequency of the neutron star) or to charged particle winds, resulting in a gradual increase in spin period. If the magnetic fields have a dipolar form, then the rate of period increase, or spin-down rate, can be used to estimate the pulsar age and the magnetic field strength. Pulsars with typical periods (~1 s) and period time derivatives (~10^{-15}) have ages of 10^6 to 10^7 years and field strengths at the neutron star surface of ~10^{12} G. Pulsars with periods less than ~20 ms are known as millisecond pulsars (MSPs). MSPs are also characterized by spin-down rates four to six orders of magnitude less than those of normal pulsars, implying ages of 10^9 to 10^{10} years and magnetic fields of 10^8 to 10^9 G. About two-thirds of all MSPs are in binary systems, whereas fewer than 1% of normal pulsars are binary (*4*). MSPs probably acquire their short periods through a recycling process in which mass and angular momentum are transferred to an old and slowly rotating pulsar from a binary companion (*5*, *6*).

About 1500 pulsars are known. Almost all of these are located within the Milky Way Galaxy, most within the galactic disk. About half of the 90 known MSPs are found in globular clusters; the high concentrations of stars in the cores of these clusters facilitate the recycling of old neutron stars to millisecond periods. Nine of the 1500 pulsars are located in the Magellanic Clouds, our nearest neighbor galaxies. None have been detected in more distant galaxies. Most pulsars are detectable only at radio wavelengths, but about 30 especially young and short-period pulsars are detectable at optical, x-ray, and even gamma-ray wavelengths. About half of these are detectable only at high energies. Among these are the magnetars, which have periods from 6 to 11 s and period derivatives as large as 10^{-10}, implying magnetic fields of 10^{14} to 10^{15} G. The pulsed emissions in these objects are believed to be powered by decay of the ultrastrong magnetic fields rather than by the neutron star rotational kinetic energy, as would be the case for normal pulsars and MSPs (*7*).

The supernova explosion created by the formation of a neutron star generally leaves a bright supernova remnant (SNR) formed by the interaction of the expanding ejecta from the explosion with the surrounding interstellar medium. For at least 10^4 years and generally longer, the pulsar lies within this expanding shell. Such associations provide the opportunity to investigate the properties of newly formed neutron stars and the evolution of SNRs. For many of these young pulsars, some of the spin-down luminosity is directly observable as a pulsar wind nebula (PWN) surrounding the pulsar. Recent observations of PWNs show complex structures related to the spin axis of the pulsar, giving us a new window into the electrodynamics of pulsar magnetospheres.

Pulsar Searches and Timing

During the first 30 years of pulsar astronomy (1967 to 1997), about 700 pulsars were discovered. Over the past 6 years, the number of known pulsars has more than doubled, mostly as a result of extensive radio surveys using the Parkes 64-m radio telescope (New South Wales, Australia) but also including a small but interesting sample of pulsars discovered through x-ray observations. The Parkes multibeam pulsar survey (*8*–*11*) covered a 10°-wide strip of the southern galactic plane from galactic longitude 260° through the Galactic Center to longitude 50° and has discovered more than 725 pulsars. This success was mainly due to the high sensitivity of the survey, made possible by a multibeam receiver that enables simultaneous observation of 13 different patches on the sky. The multibeam receiver operates in the 20-cm band (center frequency 1374 MHz) with a bandwidth of nearly 300 MHz. A companion survey undertaken by a group from Swinburne University that covered two adjacent strips between galactic latitudes of 5° and 15° using the same receiver system (*12*) was optimized for detecting MSPs. This survey discovered 69 pulsars, eight of which had the short periods and small period derivatives characteristic of recycled pulsars.

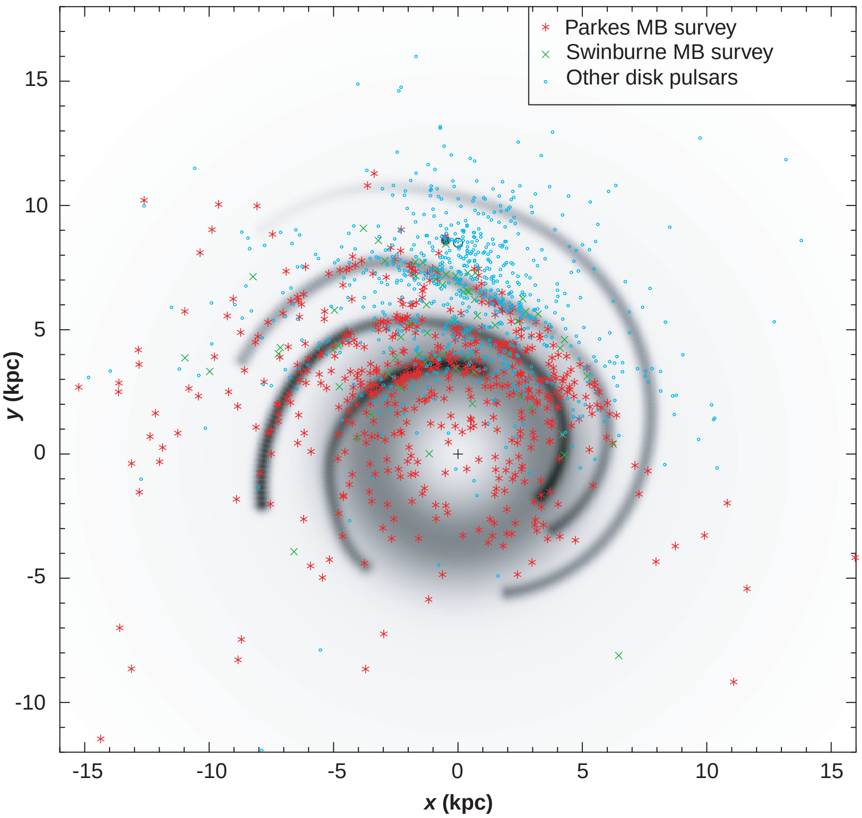

Fig. 1. Distribution of known galactic disk pulsars projected onto the galactic plane (*44*). The axes are in units of kiloparsecs, where 1 kpc is about 3260 light-years, with the Galactic Center at the origin and the Sun at (0.0, 8.5). The grayscale represents the distribution of interstellar free electrons according the Taylor and Cordes model (*45*). Interstellar dispersion is proportional to the column density of free electrons, so pulsar distances can be estimated by integrating the electron density model until the observed dispersion is reached. MB, multibeam.

The known pulsars are widely distributed across the Galaxy (Fig. 1). However, the observed distribution is affected by selection effects, the most important of which is survey sensitivity. Because of the limited sensitivity of earlier surveys, most previously known pulsars are concentrated within a few kpc of the Sun, whereas the recently discovered pulsars are more widely distributed. In particular, many are at distances comparable to or greater than that of the Galactic Center, allowing investigation of interstellar medium properties in the central regions of the Galaxy. For example, measurements of the Faraday rotation of pulsar signals have shown that the galactic magnetic field is basically azimuthal and coherent over large distances, with several reversals in direction probably associated with the spiral-arm structure of the Galaxy (*13*).

By accounting for survey selection effects, it is possible to characterize the galactic pulsar population. Most such analyses assume a cylindrically symmetric distribution about the axis of galactic rotation for the parent population. One such analysis, which includes the multibeam sample, shows that the radial distribution for normal pulsars peaks at about 4 kpc from the Galactic Center and that there are about 25,000 potentially observable pulsars (i.e., those beamed toward us) in the Galaxy (*14*).

The plot of pulsar period (P) versus period derivative $\dot{P}$ (Fig. 2) distinguishes the different classes of pulsars. The majority of pulsars are near the center, with periods of ~1 s and period derivatives of 10^{-16} to 10^{-14}. MSPs are at the lower left, and they all lie below the spin-up line (the minimum spin period attainable by accretion from a companion star), consistent with expectations based on the recycling mechanism. The group of long-period x-ray pulsars at the upper right are the magnetars. In the simplest model, pulsars are born with short periods and relatively high spin-down rates and migrate to longer periods along lines of constant magnetic field at ever-decreasing rates. The thinning out of the distribution at longer periods implies that pulsar luminosities decay with increasing period, so that most have become undetectable by the time they reach the right edge of the distribution.

An important result from the Parkes multibeam pulsar survey is the discovery of a new population of relatively long-period pulsars that have very large spin-down rates and hence are young with high implied magnetic field strengths (Fig. 2). The youngest pulsar discovered in the survey, PSR J1119-6127, has a rather average pulse period of 407 ms but a characteristic age of only 1700 years (*15*). With their high $\dot{P}$ values, these pulsars move quickly across the P-$\dot{P}$ diagram. The fact that we observe a substantial number of them implies that these high-field pulsars have a high birthrate. Analysis of the Parkes multibeam sample (*16*) shows that pulsars with implied surface magnetic fields greater than 3×10^{12} G account for about half of the total birthrate.

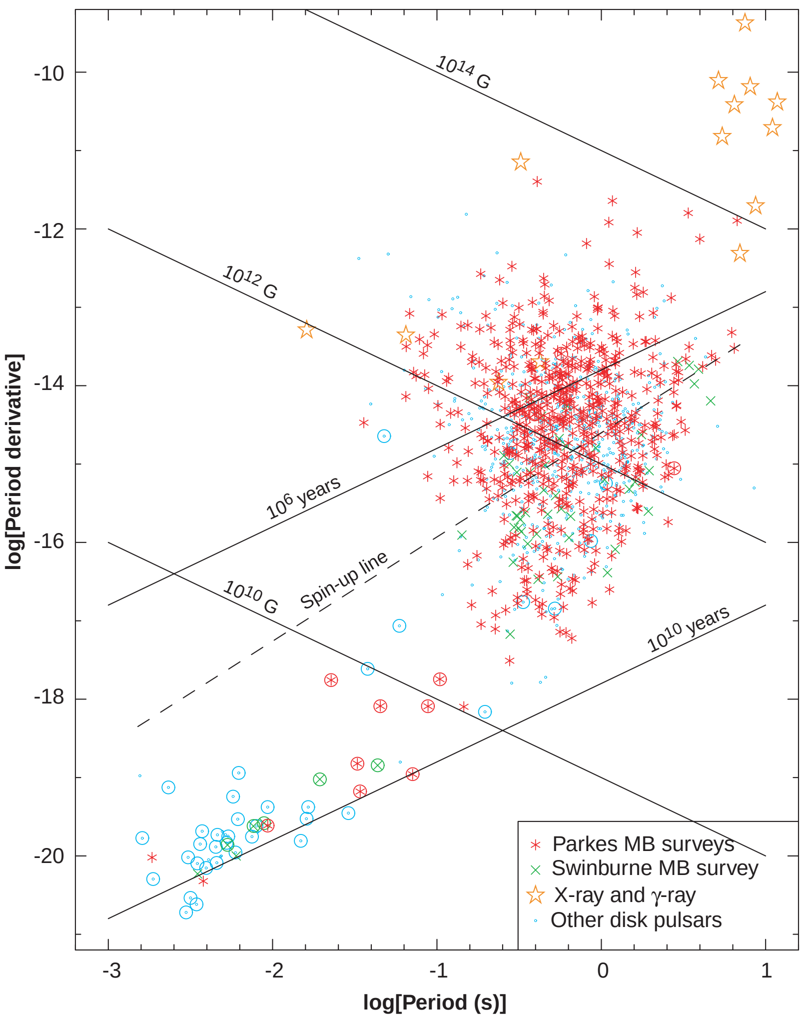

Fig. 2. Distribution of known galactic disk pulsars in the period–period-derivative plane (*44*). Pulsars detected only at x-ray and higher energies are indicated by open stars; pulsars in binary systems are indicated by a circle around the point. Assuming spin-down due to magnetic dipole radiation, we can derive a characteristic age for the pulsar, $\tau_c = P/(2\dot{P})$, where P is the pulsar period and $\dot{P}$ is its first time derivative, and the strength of the magnetic field at the neutron star surface, $B_s = 3.2 \times 10^{19}\,(P\dot{P})^{0.5}$ G. The characteristic age represents an upper limit to the true age, as it assumes that the pulsar was born spinning infinitely fast. Lines of constant characteristic age and surface magnetic field are shown. All MSPs lie below the spin-up line. The group of x-ray pulsars in the upper right corner are known as magnetars.

Several of the newly discovered pulsars have periods of 6 or 7 s and period derivatives of 10^{-12} or so, which puts them in the part of the P-$\dot{P}$ diagram occupied by the magnetars (*17*). Observationally, magnetars have been identified as two somewhat distinct classes of object—anomalous x-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs)—but recent observations of hard-spectrum x-ray bursts from an AXP (*18*) have blurred the distinction. The x-ray/gamma-ray luminosity of magnetars is in the range 10^{34} to 10^{36} erg s^{-1}, much too large to be accounted for by the decay of rotational kinetic energy (*7*). Nonetheless, magnetars are believed to be neutron stars rotating at the observed pulse period and hence are "pulsars." Evidence for this includes association of some magnetars with SNRs and the observation of period glitches, a phenomenon well known in radio pulsars, in at least two AXPs (*19*). It remains a puzzle why radio pulsars and magnetars have such different emission properties despite their similar periods and implied surface magnetic field strengths.

MSPs are extremely good clocks, with a period stability rivaling that of the best terrestrial atomic clocks. This stability makes possible a wide range of interesting investigations. Some of these—for example, tests of gravitational theories—involve studying the relativistic perturbations in binary pulsar periods (*4*). Timing of MSPs in the globular cluster 47 Tucanae has resulted in the first detection of the intracluster gas expected from the evolution of cluster stars, albeit at a much lower level than predicted (*20*). MSP timing has also set lower limits on the stellar mass-to-light ratio in globular cluster cores (*21*). Combining of data from many MSPs spread across the sky to form a "pulsar timing array" has the potential to define a new long-term standard of terrestrial time, to refine our knowledge of solar system motions, and even to detect gravitational waves passing over Earth (*22*). Such gravitational waves may be dominated by a stochastic background from events in the early universe, such as galaxy formation. MSP timing has already put limits on the energy density of such a background, constraining theories of the early universe (*23*, *24*). Gravitational radiation from massive black-hole binary systems in the cores of galaxies may be detectable with a pulsar timing array (*25*, *26*). Such detections would give us new insight into galaxy formation and evolution as well as the physics of black holes.

Young Pulsars, Supernova Remnants, and Pulsar Wind Nebulae

Supernova remnants typically are detectable for a few tens of thousands of years before they fade into the interstellar medium. In contrast, pulsars live for 10^6 to 10^7 years, and so it is not surprising that the majority of pulsars have no identifiable association with a SNR. However, the youngest pulsars should be associated with a SNR, and in general they are. The number of believable associations has climbed by about 50% in the past few years to about 30, with x-ray observations making an important contribution. As an example, PSR J1846-0258, which has a pulse period of 324 ms and a characteristic age of only 720 years, was discovered through an observation by the Rossi X-ray Timing Explorer (RXTE) of a nearby unrelated source (*27*). This pulsar is centrally located within the SNR Kes 75 and is associated with it. Despite deep searches, the pulsar has not been detected at radio wavelengths (see Fig. 2). In a similar story, PSR J0537-6910, which has a pulse period of only 16 ms (the shortest known among the young pulsars), was discovered in RXTE data and is associated with N 157B, a young Crab-like SNR in the Large Magellanic Cloud (*28*). Again, there is no detectable pulsed radio emission.

In the past few years, the Chandra X-ray Observatory has imaged numerous SNRs in our Galaxy. Many of these have unresolved point sources, in some cases surrounded by a region of hard x-ray emission, a combination that may be interpreted as a pulsar surrounded by a PWN. These results motivated a series of searches at radio and x-ray wavelengths for pulsed emission from the putative pulsar. G292.0+1.8, a young oxygen-rich SNR located about 5 kpc away in the disk of the Galaxy (Fig. 3), has a point source with a power-law spectrum, which suggests that it is a pulsar, and the surrounding emission has the characteristics of a PWN. A 10-hour observation in the direction of the point source, using the Parkes radio telescope (*29*), revealed a faint pulsar, PSR J1124-5916, with a pulse period of 135 ms and a characteristic age of 2900 years. X-ray pulsations at this period were later detected from the point source, confirming the identification. This pulsar has a spin-down luminosity of 1.2×10^{37} erg s^{-1}; less than 1% of this luminosity is required to power the x-ray PWN. In an almost exactly parallel story, a weak radio pulsar, PSR J1930+1852, with similar properties to those of PSR J1124-5916, was detected at the location of an x-ray point source within the Crab-like SNR G54.1+03 through Arecibo observations (*30*).

In a variation on this theme, Chandra imaging revealed a point source near the center of 3C 58, another SNR with properties similar to those of the Crab Nebula, and pulsations at a period of 66 ms were directly detected in the x-ray data (*31*). Analysis of an earlier RXTE observation confirmed the detection and gave a value for $\dot{P}$ showing that the pulsar, PSR J0205+6449, is young. PSR J0205+6449 was later detected in radio observations made with the 100-m Green Bank Telescope (*32*). Like the Crab Nebula, 3C 58 has an association (admittedly less certain than that of the Crab) with a supernova observed by the Chinese 823 years ago. If this is accepted, the fact that the pulsar's characteristic age of about 5400 years is greater than the true age of 823 years implies that the pulsar was born with a period of ~60 ms, not too different from its present value. PSR J1811-1925 is another pulsar with a similar period, 65 ms, which was detected in an x-ray observation by the Advanced Satellite for Cosmology and Astrophysics of the SNR G11.2-0.3 (*33*, *34*). This SNR has an even less certain association with a supernova recorded 1618 years ago. The pulsar's characteristic age is about 24,000 years, again suggesting an initial period close to its present value. There is no radio detection of PSR J1811-1925.

The association of PSR J1119-6127 with the SNR G292.2-0.5 has a somewhat complementary history. As mentioned above, this is the youngest pulsar discovered in the Parkes multibeam pulsar survey, with a characteristic age of only 1700 years, not much more than that of the Crab pulsar (1240 years). One might therefore have expected a strong SNR to be associated with this pulsar, but SNR catalogs contained no such source. However, a faint ring of emission centered on the pulsar was visible in the Molonglo Galactic Plane Survey, and observations with the Australia Telescope Compact Array (Fig. 4) showed that this is a SNR associated with the pulsar (*35*). This demonstrates that young SNRs need not be strong radio sources. Undoubtedly, there are many other similar young SNRs in the Galaxy that remain unrecognized.

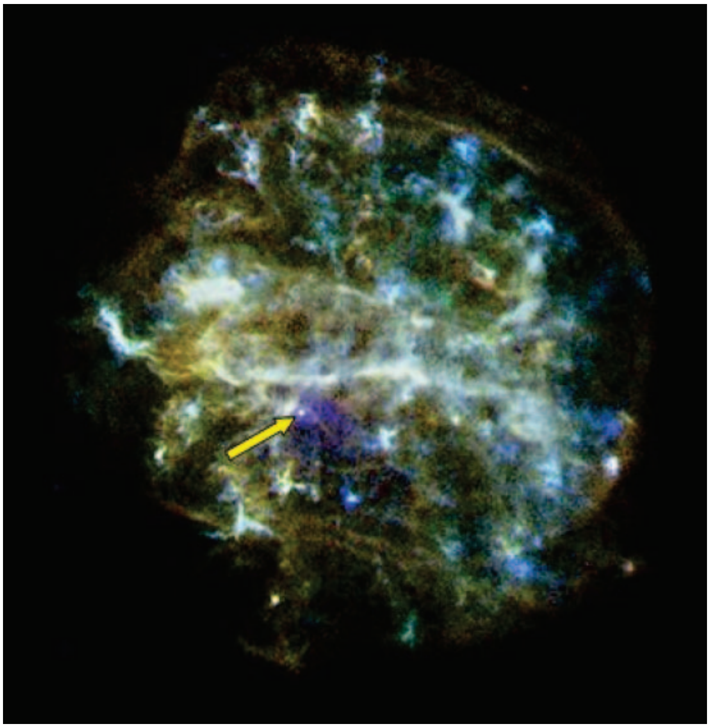

Fig. 3. Chandra x-ray image of the SNR G292.0+1.8. The arrow marks the point source identified with the 135-ms pulsar PSR J1124-5916. The darker blue region surrounding the point source is x-ray emission with a hard power-law spectrum, believed to be a synchrotron emission from a relativistic pulsar wind. Credit: NASA/Chandra X-ray Center (CXC)/Rutgers University and (*46*).

Together, these observations show that young pulsars and young SNRs have a wide range of properties. Some young pulsars are relatively easy to detect at x-ray wavelengths but are difficult or impossible to detect at radio wavelengths. This may be because the radio beam is narrower than the x-ray beam and misses us as the pulsar rotates. Alternatively, it may be that some young pulsars are simply intrinsically weak at radio frequencies. Observed SNR properties can be influenced by a number of factors. The evolutionary state of the exploding progenitor star affects the mass and velocity of the ejecta. Perhaps even more important, the history of stellar-wind mass loss influences the environment into which the supernova explodes, which in turn affects the morphology and brightness of the resulting SNR. The birth properties of the neutron star also have an influence, especially on the PWN. Fast young pulsars with moderate magnetic field strengths, such as the Crab pulsar and PSR J0537-6910, have a high spin-down luminosity (which scales as $\dot{P}/P^3$) and a relatively long lifetime, powering strong PWNs, whereas long-period, strong-field pulsars such as PSR J1119-6127 have a much smaller integrated energy loss over their short lifetime and hence have weak or undetectable PWNs.

Theoretical models have tended to treat PWNs as expanding spherical bubbles of relativistic gas contained by an external medium. Although this remains broadly true, recent x-ray, optical, and radio images of the surroundings of young pulsars have revealed a complex pulsar wind structure. Chandra x-ray images of the nebulae surrounding the Crab and Vela pulsars (Fig. 5) show toroidal and jet structures, demonstrating that pulsar winds are far from isotropic (*36*, *37*). The symmetry of these systems indicates that both structures are related to the rotation axis of the underlying pulsar: the jets along the polar axis, and the toroidal structures in or near the equatorial plane. Images of the Crab Nebula taken at intervals of weeks and months by the Hubble Space Telescope and Chandra (*38*) show that the wind structures are dynamic, with moving features implying outflow velocities on the order of half the velocity of light in the equatorial disk and the polar jets. It remains a challenge for pulsar theorists to account for even the broad characteristics of these outflows. For the Crab and Vela pulsars, the projected direction of the pulsar rotation axis implied by the x-ray data is very close to the projected direction of the pulsar's space velocity (*39*, *40*); this result has interesting implications for the origin of neutron star velocities (*41*, *42*). A recent analysis (*43*) suggests that this correlation holds for several other pulsars with associated PWNs.

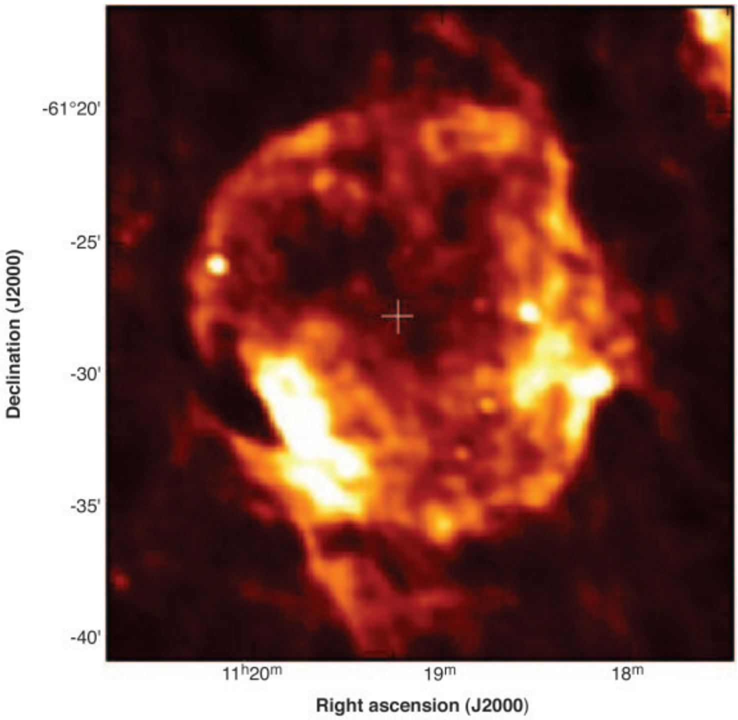

Fig. 4. Radio image of the SNR G292.2-0.5 obtained with the Australia Telescope Compact Array at 1.4 GHz (*35*). The cross marks the position of the young pulsar PSR J1119-6127.

In the past 5 years we have seen substantial advances in the science of pulsars. The two most important contributors to this progress are the great success of the Parkes multibeam pulsar surveys (which have more than doubled the number of known pulsars) and the advances made possible by multiwavelength studies, especially those using data from the Chandra X-ray Observatory. The latter have been particularly important in elucidating the relationship between pulsars and SNRs. Future work will build on these advances. Pulsar timing and polarization studies of the enlarged sample will be critical in a wide range of investigations, from understanding the pulse emission mechanism to detecting gravity waves. Future x-ray and gamma-ray observations will also have impacts on a wide range of topics. In particular, they will be vital in reaching an understanding of the relationship between normal pulsars and magnetars and in improving our understanding of pulsar birth properties and pulsar electrodynamics.

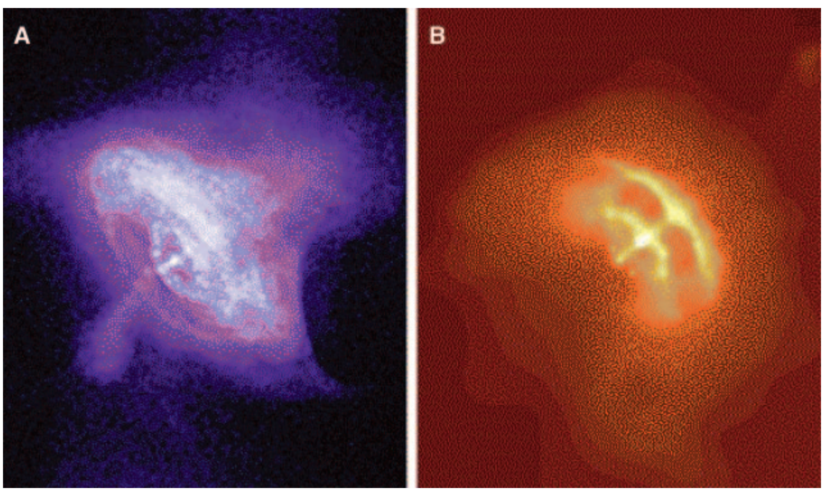

Fig. 5. Chandra x-ray images of the PWNs surrounding the (**A**) Crab and (**B**) Vela pulsars (*36*, *37*). [Credit: NASA/CXC/Smithsonian Astrophysical Observatory, NASA/Pennsylvania State University, and G. Pavlov]

References and Notes

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