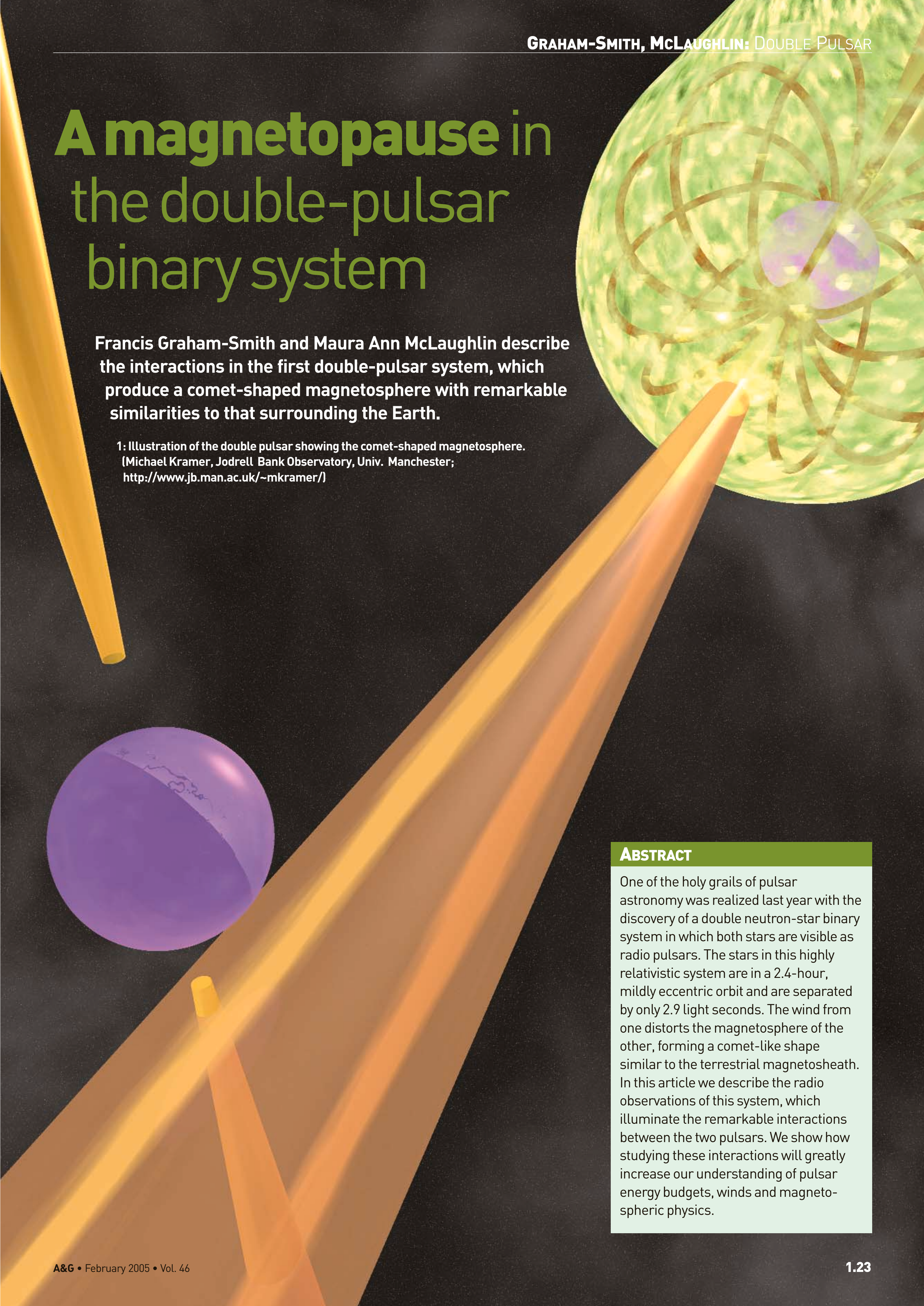
A magnetopause in the double-pulsar binary system

Francis Graham-Smith and Maura Ann McLaughlin describe the interactions in the first double-pulsar system, which produce a comet-shaped magnetosphere with remarkable similarities to that surrounding the Earth.



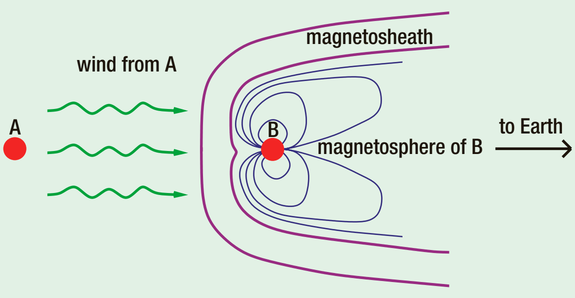
1: Illustration of the double pulsar showing the comet-shaped magnetosphere. (Michael Kramer, Jodrell Bank Observatory, Univ. Manchester; http://www.jb.man.ac.uk/~mkramer/)

ABSTRACT

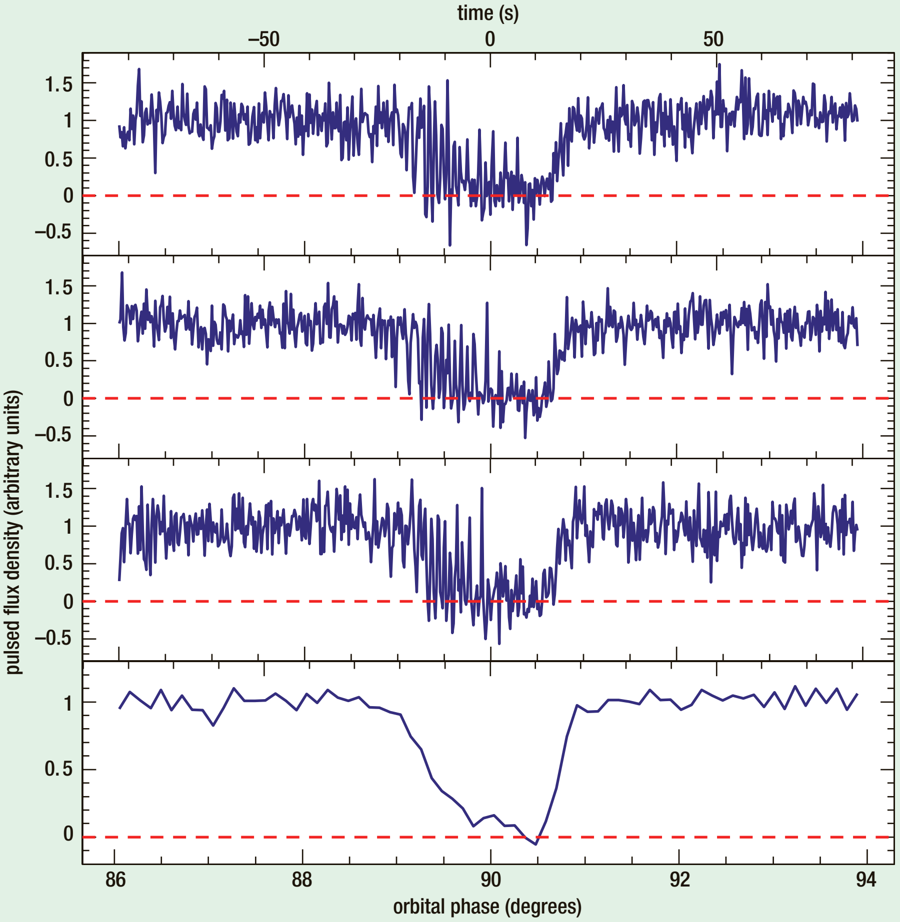
One of the holy grails of pulsar astronomy was realized last year with the discovery of a double neutron-star binary system in which both stars are visible as radio pulsars. The stars in this highly relativistic system are in a 2.4-hour, mildly eccentric orbit and are separated by only 2.9 light seconds. The wind from one distorts the magnetosphere of the other, forming a comet-like shape similar to the terrestrial magnetosheath. In this article we describe the radio observations of this system, which illuminate the remarkable interactions between the two pulsars. We show how studying these interactions will greatly increase our understanding of pulsar energy budgets, winds and magnetospheric physics.

The recently discovered pair of pulsars bound together in a tight binary system is already famous for providing the most accurate observational tests of Einstein's Theory of General Relativity. Also, there is a remarkable interaction between the radio emissions of the two, which provides the most striking example of magnetospheric physics apart from the terrestrial magnetosphere itself. A powerful wind from one pulsar distorts the magnetosphere of the other, forming a comet-like shape closely resembling the terrestrial magnetosheath and with many of its characteristics.

The first of the two pulsars, now known as PSR J0737-3039A, was discovered at the Parkes Radio Telescope in Australia, in a large-scale survey at a wavelength of 21 cm. The survey was designed by Andrew Lyne of Jodrell Bank Observatory, UK, and Dick Manchester of the Australia National Telescope Facility, with collaborators in Australia, the USA, India and Italy. This pulsar, known as A, has a short spin period of 23 milliseconds, with large Doppler shifts showing it is in a mildly eccentric 2.4-hour orbit (eccentricity $e \sim 0.09$). Relativistic precession of the orbit was soon detected, at the phenomenal rate of 17° per year, more than four times greater than that of any other pulsar binary system and 10^5 times greater than the relativistic precession of Mercury. The precession rate is proportional to the sum of the masses of the binary pair, while the two Doppler shifts give the ratio, allowing the masses of A (1.34 solar masses) and its unseen companion (1.25 solar masses) to be determined. The companion was almost certainly another neutron star and very small, as the whole orbit would fit inside a star like the Sun. Several other pulsar–neutron star pairs were known; this one was distinguished by its orbital period, the shortest so far observed.



2: Diagram (not to scale) showing the interaction between the relativistic wind from pulsar A and the magnetosphere of pulsar B. The collision of A's wind and B's magnetosphere creates a magnetosheath of hot, magnetized plasma surrounding the magnetosphere of B. The rotation of B inside this sheath modulates A's eclipse, as shown in figure 2.



3: The pulsed flux density of A versus time (with respect to superior conjunction) and orbital phase. The top three panels show individual eclipse light curves for three 820 MHz observations with the Green Bank Telescope; every 12 A pulses have been summed. The eclipse of A is modulated at eclipse ingress with half of the period of B. The lower panel shows the composite light curve (i.e. all three eclipses summed) with every 100 A pulses averaged. Eclipse ingress takes roughly four times longer than egress; this arises from the direction of rotation of B with respect to the orbital velocity.

Five-minute search

Pulsars are usually discovered by recognizing a precisely periodic signal in a noisy background, using data strings of several minutes to hours. In Parkes surveys the analysis is shared among observing teams who are continually developing and sharing new computational techniques. Pulsar A was discovered in a five-minute search observation by Marta Burgay of Bologna in April 2003 (Burgay *et al.* 2003). It seemed worth exploring the possibility that A's companion might also be a pulsar, but at first nothing was found. A deeper search was proposed, with a longer integration time, but then pulsar B was found, almost by accident.

It turned out that pulsar B is strong but variable and detectable only for a part of the orbit not covered by the data used by Burgay. The luck of the discovery fell instead to Duncan Lorimer from the Jodrell Bank Observatory. He was at Parkes in October 2003 testing a search technique for binary pulsars on some recorded data sets, including some of the J0737-3039 recordings, when he found a strong pulsar signal with the long spin period of 2.8 seconds. The Doppler shifts of the 2.4-hour orbit were present; this was indeed the first double-pulsar binary (Lyne *et al.* 2004). We now have two accurate clocks orbiting at 0.1%c, displaying dramatic effects of General Relativity, such as orbital precession, the Shapiro delay and spin-orbit coupling. Table 1 summarizes relevant spin and orbital parameters of the system.

The diameter of the orbit, determined through radio timing, is 2.9 light-seconds, and the orbital plane lies very nearly in the line of sight; the timing-derived dynamics give an inclination within 2° of 90°, while observations of interstellar scintillation by Coles *et al.* (2004) give an inclination of roughly 0.3° from 90°. The line of sight to each pulsar therefore passes within 3000 km of its partner. Although the radius of a neutron star is only 10 km, every pulsar is surrounded by a co-rotating, ionized and very energetic magnetosphere, which for an isolated pulsar extends to the velocity-of-light cylinder radius where co-rotation would require a velocity of *c*. The magnetosphere of the millisecond pulsar, A, extends to a radius of 1084 km, while that of the long-period pulsar, B, should reach 132 000 km,

Table 1: Relevant parameters of PSRs J0737-3039A and B

Pulsar	**A**	**B**
Pulse period (ms)	22.699	2773.5
Projected semi-major axis (lt-sec)	1.4	1.5
Characteristic age (My)	210	50
Surface magnetic field strength (Gauss)	6×10^{9}	2×10^{12}
Rate of energy loss due to spin-down (erg/s)	5800×10^{30}	2×10^{30}
Stellar mass (solar masses)	1.34	1.25
Orbital inclination (deg)	~90	
Orbital period (hours)	2.45	
Eccentricity	0.088	
Orbital inclination (deg)	90	
Advance of periastron (deg/yr)	16.9	

Comparison between this pulsar magnetopause and the terrestrial magnetopause, where the field is several magnitudes smaller, should provide some interesting plasma physics

well past the line of sight to A at superior conjunction. A should therefore be eclipsed by B for several minutes. An eclipse is indeed seen, but it lasts only 30 seconds, corresponding to an 18 000 km movement (Lyne *et al.* 2004). This was the first observation of the magnetosphere of any pulsar, but at only 9000 km radius it was much smaller than expected.

Catching the detail of this eclipse required the most sensitive telescope available. As soon as the discovery was announced, observations were made at the 100 m Green Bank Telescope (GBT) in West. Virginia by a joint US/Canadian team, using arrangements for urgent observing time (Kaspi *et al.* 2004). They found that the duration of eclipse was only slightly dependent on radio frequency, showing that the line of sight had encountered a sharply defined boundary: the magnetosphere of B, compressed by the outflow of wind and radiation from A. The outer edge of the magnetosphere was recognized as a magnetopause (Arons *et al.* 2004). Pulsar B, with its strong dipolar field and its magnetosphere, is rotating within the magnetosheath, as shown in figure 2. This rotation was expected to modulate the shape of the eclipse. No such effect was initially noticed; however, when six months later the recorded data became available, a new analysis showed that the light curve of the eclipse contained in some astonishing detail the expected modulation at half the rotation period of B, as shown in figure 3 (McLaughlin *et al.* 2004a).

We therefore see a strong influence of pulsar A on pulsar B, distorting its magnetosphere and preventing us from seeing its pulses over much of its orbit, while B's distorted magnetosphere obstructs the line of sight to A at superior conjunction. A's magnetosphere is smaller and does not cross the line of sight; it appears to be unaffected by the proximity of B. This is not surprising; A is the more powerful of the two, since its energy loss by spin down is 3000 times greater. The detailed mechanism of energy loss from pulsars has been under discussion for many years. Originally it was thought to be simple magnetic dipole radiation at the rotation period, together with an approximately equal energy density in particles flowing out from the magnetic poles. However, observations of energetic nebulae near some pulsars, notably the Crab pulsar, can be explained only as the result of a pulsar wind streaming along the rotation axis. The outflow changes character at some distance from the pulsar, but up to now its composition close to the pulsar has been unobservable. The double-pulsar binary offers the first opportunity of observing the outflow near a pulsar.

A familiar geometry

The geometry shown in figure 2 might apply equally well (with some changes in parameters) to the terrestrial magnetosphere. This cometary tail points away from A, so that our line of sight to B passes through the compressed head when it is furthest away from us, and through the tail when it is closest. B is observable between these two positions, when it is seen from either side of the tail. At eclipse, pulses from A are blocked by the nose and the front half of the "comet". This means that this part of the magnetosheath is opaque to radio waves, probably through synchrotron absorption. The shape seems to be well represented as a comet, although rotation of B within the magnetosheath distorts the surface, creating cusps like those in the terrestrial magnetosheath, and giving the complex variations of absorption seen during the eclipse of A.

For most pulsars the rotational slowdown gives a good measurement of the magnetic dipole field. For millisecond pulsars such as A the field at the surface is of order 10^{8-9} Gauss (10^{4-5} Tesla); for slow pulsars such as B it is usually of order 10^{12} Gauss. Using this value, and the known rate of momentum loss from A, Arons *et al.* (2004) calculated the distance of the magnetopause from B to be of order 50 000 km, smaller than the velocity-of-light cylinder limit and considerably larger than the 18 000 km observed in eclipse. However, the magnetic field of B cannot be deduced from its slowdown rate in the usual way: the impact of the momentum stream from A on B's magnetosphere accounts for some of the observed slowdown. The surface dipole magnetic field of B may also be only 10^{11} Gauss, low among the slow pulsars, accounting for most of the discrepancy.

Arons *et al.* (2004) and Lyutikov (2004) suggest that the pressure on B's magnetosphere from A's energy outflow is mainly due to a weakly magnetized wind of particles originating as pairs within A's magnetosphere, with only mildly relativistic energy. This is difficult to check but, surprisingly, yet another observation of the interaction between A and B at least restricts the range of possibilities. McLaughlin *et al.* (2004b) showed a modulation of B's pulsed emission at the 23 ms period of A. The stream of momentum from A will take 2.9 light seconds to reach B if it is electromagnetic radiation; if it is a stream of particles it will be slower, and a spread of energies might smooth out the 23 ms modulation. Particles that could preserve the modulation without a guiding electromagnetic field would have to have relativistic energies, with the relativistic factor γ greater than about 30. The observed modulation indicates that the stream contains a strong electromagnetic field with period 23 ms (44 Hz). The ratio σ, of the energies in the electromagnetic (Poynting) flux and the particle flux, is low when the stream reaches a distant nebula, as seen in the Crab nebula. Close to a typical pulsar, such as A, σ may be much higher, possibly greater than unity. Evolution of the ratio as the stream progresses has been suggested by Coroniti (1990).

Before pulsars were discovered it seemed unlikely that such a small cold object as a neutron star could ever be observed; it turns out that their powerful lighthouses have illuminated a whole new population of fascinating stars. Similarly, the wind of radiation and particles streaming from pulsars is usually invisible; in PSR J0737-3039A and B we can see its direct effects. Comparison between this pulsar magnetopause, where the magnetic field is of order 10 Gauss, and the terrestrial magnetopause where the field is several magnitudes smaller, should provide some interesting plasma physics and aid our understanding of both systems. ●

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References

Arons J *et al.* 2004 Proceedings of the 2004 Aspen Winter Conf. on Astrophysics *Binary Radio Pulsars* ASP Conf. Series, eds F Rasio and I Stairs (astro-ph/0404159).

Burgay M *et al.* 2003 *Nature* **426** 531.

Coles W A *et al.* *ApJ* in press.

Coroniti F V 1990 *ApJ* **349** 538.

Kaspi V M *et al.* 2004 *ApJ* **613** 137.

Lyne A G *et al.* 2004 *Science* **303** 1153.

Lyutikov M 2004 *MNRAS* **353** 1095.

McLaughlin M A *et al.* 2004a *ApJ* **613** 57.

McLaughlin M A *et al.* 2004b *ApJ* **616** 131.