PROCEEDINGS OF SCIENCE

Two new transient radio phenomena: RRATs and Intermittent Pulsars

A. G. Lyne[*]
University of Manchester, Jodrell Bank Observatory, Macclesfield, SK11 9DL, UK
E-mail: `andrew.lyne@manchester.ac.uk`

In this paper we describe the recent discovery of two new pulsar-related transient phenomena, both of which will provide important information on the physical processes occurring in neutron star magnetospheres. Rotating RAdio Transients (RRATs) are a recently identified class of transient radio sources which were discovered in the largest-scale search ever performed for transient radio sources (McLaughlin et al 2006). Eleven of these new sources have been found and are characterized by isolated dispersed radio bursts with durations between 2 and 30 ms, peak flux densities at 1400MHz of between 0.1 and 3.6 Jy and average intervals between bursts ranging from 4 minutes to 3 hours. So far, no periodicities have been detected in their emission using standard search techniques, although, through an arrival-time analysis of the bursts, we have identified periodicities in the range of 0.4 to 7 s in 10 of the 11 objects. Period derivatives have been measured for three RRATs; one with a spin period of 4.3 s has an inferred surface dipole magnetic field strength of 0.5×10^{14} G, perhaps indicating a close relationship between this source and the high-energy magnetars (Woods & Thompson 2004). Why these ephemeral objects emit for a total of only perhaps 0.1 second during a day is not clear. The second class of object is that of the Intermittent Pulsars, exemplified by PSR B1931+24, whose emission switches ON and OFF on timescales of weeks and greater (Kramer et al. 2006). This Intermittent Pulsar shows a slowdown rate which is ~1.5 times greater when ON than OFF, showing for the first time that magnetospheric particle currents play a significant role in both the slowdown and emission processes. Four other Intermittent Pulsars have been identified and are being studied and, as a class, offer a possible new window on neutron star magnetospheric physics.

Bursts, Pulses and Flickering:Wide-field monitoring of the dynamic radio sky June 12-15 2007
Kerastari, Tripolis, Greece

PoS(Dynamic2007)001

---

[*] Speaker.

1. Introduction

Transient phenomena are usually difficult to find and characterise, particularly if they spend much of their time in a null state. This is true of two recently discovered types of transient radio source on which I report in this paper. Both spend much of their time invisible in quite different ways, and both have underlying periodicities which are attributable to rotating magnetic neutron stars. In these circumstances, they also represent the small tips of much larger populations which may cause us to revise our views of what "normal" neutron star behaviour is.

2. RRATs - Repeating Radio Transients

RRATs were discovered recently in the Parkes Multibeam Pulsar Survey (PMPS) during a search for transient phenomena in the data. Pulsar searches are usually conducted by performing a Fourier analysis of dedispersed time-sequence data, revealing pulsars through the highly periodic nature of the pulses which results in discrete frequency features and their harmonics in the spectra. Such searches have resulted in the discovery of over 750 new pulsars (Manchester et al. 2001, Morris et al. 2002, Kramer et al. 2003, Hobbs et al. 2004, Faulkner et al. 2004). In parallel with such searches, we performed a search for single, dispersed transient events. Fig.1 shows two typical pulses which display the characteristic dispersed tracks through the channels of the receiver filterbank.

We found 11 14-arcmin-diameter patches of sky from which occasional single, dispersed bursts of radiation were received. Upon reobserving each of these patches, more single bursts were seen, having the same Dispersion Measure (DM) as the original survey detection. Each burst was an isolated pulse of emission of duration between 1 and 20 milliseconds, the next one occurring after an interval which ranged in duration from about 4 minutes to a few hours. Fig.2 shows the events during 35-minute observations of each of three patches. Standard Fourier analysis failed to find the periodic signature of any normal pulsar, as did fast-folding techniques.

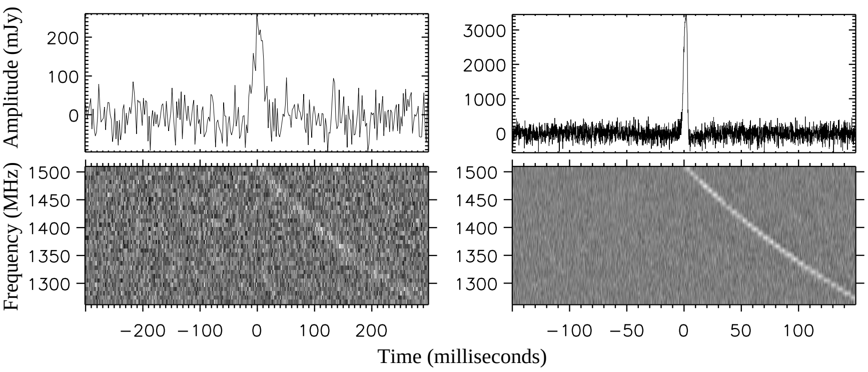

Figure 1: Examples of dispersed pulses from two of the new transient sources: (left) J1443–60 and (right) J1819–1458. The lower panel shows the dispersed nature of the bursts detected in the individual frequency channels. The upper panel shows the dedispersed time series, obtained by summing outputs of the individual receiver channels after appropriate delays for the optimum value of the DM.

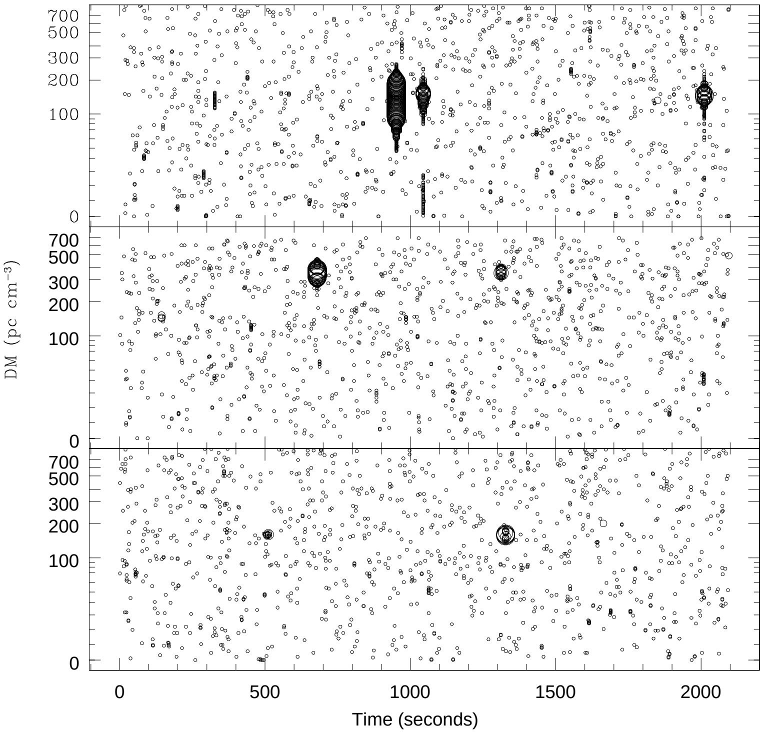

Figure 2: 35-minute observations of the 3 RRATs, J1317−5759 (top), J1443−60 and J1826−1429 (bottom). In these plots, the areas of the symbols are proportional to signal-to-noise ratio of events as a funtion of time and dispersion measure. Between 1 and 3 significant events can be seen during each observation, occurring at repeating values of dispersion measure (DM).

All sources have been reobserved at least nine times at intervals of between one and six months. All have shown a number of bursts, with between four and 229 events in total from each object (see Table 1). As far as we can tell from the limited statistics, the density of sources on the sky appears to be greater towards the Galactic plane. While the survey covered latitudes up to $\pm 5^\circ$, as many as eight of the 11 sources have $|b| < 2^\circ$. In general, the spatial distribution of the bursting sources is consistent with that of the young pulsars detected in the PMPS (e.g. Kramer et al. 2003).

Although no periodicities were detected in any of the sources using standard Fourier or folding methods, for ten of the sources we were able to identify a periodicity from the arrival times of the individual bursts. The period was identified as being the smallest common denominator of the differences between the burst arrival times (see Table 2). The 0.4 to 7 s range of these periodicities indicates that these sources are probably rotating neutron stars. In general, most of the periods are quite long for normal radio pulsars; five of the ten sources have periods exceeding four seconds, compared with less than 1% of the known radio pulsar population which have such long periods. The extremely sporadic nature of the bursts makes localization of the sources difficult, with most positions known only to within one Parkes 1400-MHz 14-arcminute beam. However, for three sources we have been able to determine more accurate positions through the application of standard pulsar timing techniques to the individual burst times (Table 1). For these pulsars, we have also been able to measure period derivatives, which are all positive (Table 2), like those of radio pulsars

Name	RA (J2000) h m s	Dec (J2000) ° ′ ″	DM pc cm^{-3}	D kpc	w_{50} ms	S_{1400} mJy	N_p/T_{obs} hr^{-1}
J0848–43	08:48(1)	–43:16(7)	293(19)	5.5	30	100	27/19
J1317–5759	13:17:46.31(7)	–57:59:30.2(6)	145.4(3)	3.2	10	1100	108/24
J1443–60	14:43(1)	–60:32(7)	369(8)	5.5	20	280	32/41
J1754–30	17:54(1)	–30:11(7)	98(6)	2.2	16	160	18/30
J1819–1458	18:19:33.0(5)	–14:58:16(32)	196(3)	3.6	3	3600	229/13
J1826–1429	18:26:47.28(7)	–14:29:06(6)	159(1)	3.3	2	600	11/16
J1839–01	18:39(1)	–01:36(7)	307(10)	6.5	15	100	8/13
J1846–02	18:46(1)	–02:56(7)	239(10)	5.2	16	250	11/10
J1848–12	18:48(1)	–12:47(7)	88(2)	2.4	2	450	10/8
J1911+00	19:11(1)	+00:37(7)	100(3)	3.3	5	250	4/13
J1913+1333	19:13:17.69(6)	+13:33:20.1(7)	175.8(3)	5.7	2	650	66/14

Table 1: Measured and derived parameters for the 11 RRATs. For each, we give the Right Ascension, the Declination, the DM, the inferred distance, the average burst duration at 50% of the maximum, the peak 1400-MHz flux density of brightest detected burst and the rate of occurrence, which is the ratio of the total number of bursts detected to the total observation time. Estimated 1-σ errors are given in parentheses where relevant and refer to the least-significant quoted digit.

as they spin down.

It seems therefore that the new sources represent a previously unknown population of bursting neutron stars, which we call Rotating RAdio Transients (RRATs). In Figure 3, we show the relationship of these sources to other neutron star populations. The inferred surface dipolar magnetic field of J1819–1458 of 0.5×10^{14} G is greater than the magnetic field of all but four of the 1700 known radio pulsars and is comparable to those of the high-energy magnetars (McLaughlin et al. 2003; Woods & Thompson 2004). This pulsar is young, with a characteristic age of 117 kyr, which is smaller than those of 94% of all currently known radio pulsars. The magnetic fields and ages of the other two sources are, however, fairly typical of "normal" radio pulsars. None of the objects lie in the region of the period-period derivative diagram beyond which pair production, and hence radio emission, is expected to cease (Zhang et al. 2000). The RRATs for which we have measured period derivatives show no evidence for binary motion. Likewise, we see no evidence for glitches or other timing abnormalities, although continued timing is necessary to gauge the regularity of spin-down rates. In the future, radio polarization data may enable us to constrain the emission mechanisms.

The discovery of this population of RRATs results in substantially increased estimates of the total number of active radio-emitting neutron stars in the Galaxy. For instance, we have detected, on average, one single burst for every three hours of observation time for J1911+00. The chance of detecting this source within the single 35-min PMPS observation was therefore less than 20%, implying that there should be roughly five times the number of similar sources in the same searched volume of the Galaxy. Applying a similar analysis to all of the bursting RRATs shows that we

Name	P s	Epoch MJD	$\dot{P}$ 10^{-15} s s^{-1}	B 10^{12} G	Age Myr	$\dot{E}$ 10^{31} erg s^{-1}
J0848–43	5.97748(2)	53492	–	–	–	–
J1317–5759	2.6421979742(3)	53346	12.6(7)	5.83(2)	3.33(2)	2.69(1)
J1443–60	4.758565(5)	53410	–	–	–	–
J1754–30	0.422617(4)	53189	–	–	–	–
J1819–1458	4.263159894(6)	53265	576(1)	50.16(6)	0.1172(3)	249.4(5)
J1826–14	0.6603545503(1)	53372	–	–	–	–
J1839–01	0.93190(1)	51038	–	–	–	–
J1846–02	4.476739(3)	53492	–	–	–	–
J1848–12	6.7953(5)	53158	–	–	–	–
J1913+1333	0.9233885242(1)	53264	7.87(2)	2.727(4)	1.860(6)	39.4(1)

Table 2: Measured and derived parameters of the 10 sources for which periods have been determined. For each source, we give the J2000 source name, the period and, if measurable, the period derivative. Assuming that the objects are indeed rotating neutron stars, the inferred surface dipole magnetic field is calculated as $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G, the characteristic age as $\tau_c = P/2\dot{P}$ and the spin-down luminosity as $4\pi^2 I\dot{P}P^{-3}$, where I, the neutron star moment of inertia, is assumed to be 10^{45} g cm^2 (see Lorimer & Kramer 2005).

expect there to be twice as many RRATs as we have detected at a similar sensitivity level and sky coverage as for the PMPS. However, this number may be a gross underestimate. Firstly, it is very difficult to identify such sources in the many observations which are contaminated with large amounts of impulsive radio-frequency interference. We estimate that there may be at least twice as many similar sources that were missed due to this effect. Secondly, we are only extrapolating to the area covered by the PMPS, and the true distribution of RRATs is not known. In addition, because our sensitivity in this search was diminished for burst durations greater than 32 ms, there may be many more sources with longer bursts that fell below our detection threshold. Furthermore, previous surveys with observations times of a few minutes had little chance of detecting such events and most did not include searches for them.

With these caveats in mind, we have carried out a Monte Carlo simulation to provide a first-order estimate of the size of the Galactic population of these RRATs. The implied size of the Galactic population of RRATs is $N \sim 4 \times 10^5 (L_{\rm min}/10\,{\rm mJy\ kpc}^2)^{-1} \times (0.5/f_{\rm on}) \times (0.5/f_{\rm int}) \times (0.1/f_b)$, where $f_{\rm on}$ is the fraction of sources with bursts visible within our 35-min observation, $f_{\rm int}$ is the fraction of bursts not missed due to interference and f_b is the fraction of RRATs whose bursts are beamed towards the Earth. Note that the average beaming fraction for pulsars is roughly 10%, and this decreases for longer period pulsars (Tauris & Manchester 1998). Assuming that the total Galactic population of active radio pulsars is of order 10^5 (e.g. Vranesevic et al. 2004), the discovery of RRATs increases the current Galactic population estimates of neutron stars by at least several times.

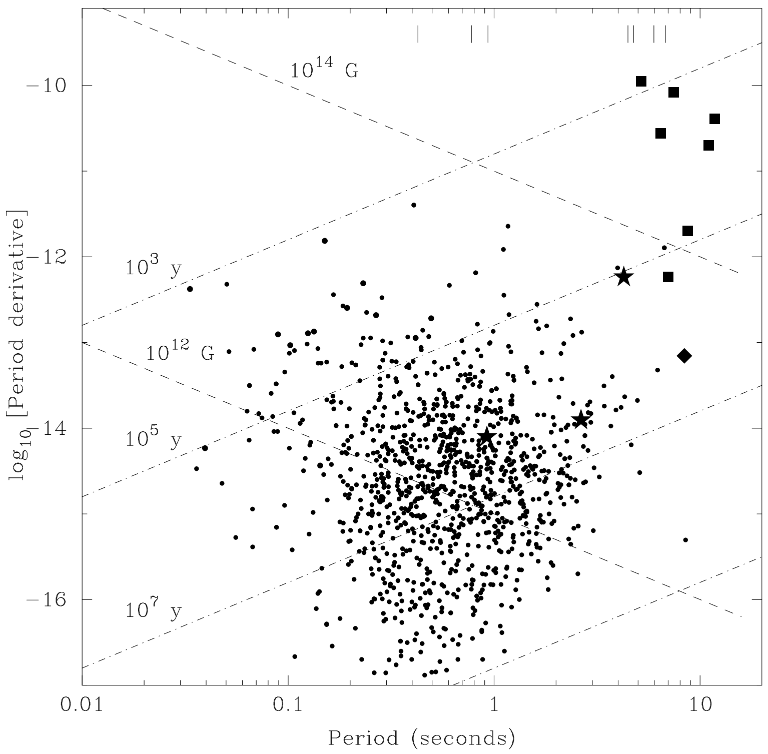

Figure 3: The P-Pdot diagram for pulsars (small symbols), magnetars (filled rectangles) and an isolated dim X-ray neutron star (diamond), with the positions of the 3 RRATs (stars) for which period derivatives have been determined from coherent timing solutions. The periods of the remaining 7 RRATs for which only periods have been determined are shown as vertical bars below the upper axis.

3. PSR B1931+24 and Intermittent Pulsars

PSR B1931+24 has been observed for many years in the timing programme using the 76-m Lovell Telescope at Jodrell Bank and initially seemed to be an ordinary pulsar, with a spin period of 813 ms (Stokes et al. 1985). It had a typical rotational frequency derivative of $\dot{\nu} = -12.2 \times 10^{-15}$ Hz s^{-1} (Table 1, Hobbs et al. 2004). It was noted that it exhibits considerable short-term rotational instabilities intrinsic to the pulsar, known as timing noise, but shows no evidence for the presence of any stellar companion. It became clear a few years ago that the pulsar was not detected in many of the regular observations and that the flux density distribution was bimodal, the pulsar being either ON or OFF (Kramer et al. 2006). Figure 4a shows the best sampled data span which covers a 20-month period between 1999 and 2001 and demonstrates the quasi-periodic fashion of the ON-OFF sequences. The pulsar is typically ON for a week and completely OFF for the following month. The power spectrum of the data reveals a strong $\sim$ 35-d periodicity with two further harmonics, which reflect the duty-cycle of the switching pattern (Fig. 4b). Studying a much longer time-series from 1998 to 2005, including some intervals of less densely sampled data, we find that the periodicities are persistent but slowly varying with time in a range from 30 to 40 days. No other known pulsar behaves this way.

Despite the switches between the ON and OFF states being rare events, we have been able to observe one switch from ON to OFF which occurred within 10 seconds, the time resolution being

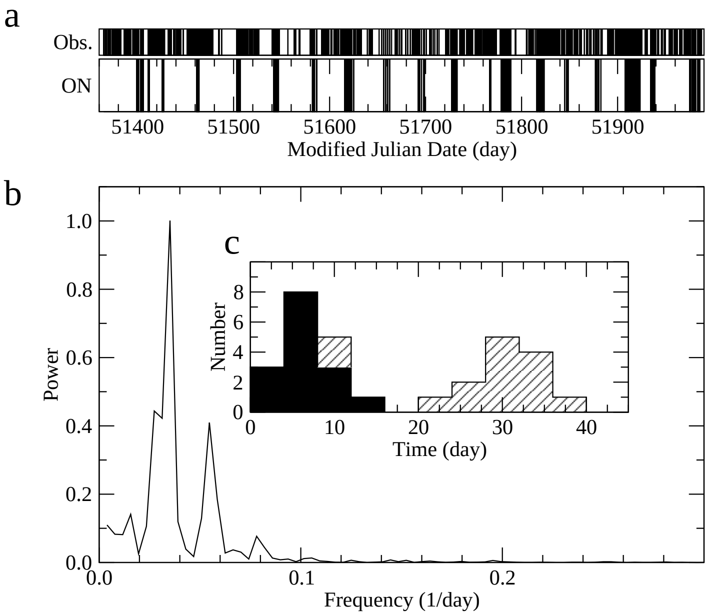

Figure 4: The intermittent nature of the radiation from PSR B1931+24 (Kramer et al. 2006). a) The vertical bars in the upper diagram show the location of good observations of the pulsar during a 600-day period. The lower diagram shows vertical bars for those observations in which the pulsar was detected (ON). b) The spectrum of the time sequence in a), obtained from the fourier transform of its autocorrelation function. Inset are histograms of the lengths of the 'ON' (filled area) and 'OFF' (hatched area) intervals.

limited by the signal-to-noise ratio of the observations.

We have examined the rotation rate of the pulsar over a 160-day period during which the sampling of the data was particularly dense (Fig. 5, top). The variation is dominated by a decrease in rotational frequency which is typical for pulsars. However, inspection of the longer sequences of the available ON data reveals that the rate of decrease is even more rapid during these phases, indicating greater values of rotational frequency first derivative than the average value. This suggests a simple model in which the frequency derivative has different values during the OFF and ON phases. Such a model accurately describes the short-term timing variations seen relative to a simple long-term slow-down model (Fig. 5, bottom). Over the 160-day period shown, the pulsar was monitored almost daily, so that the switching times are defined to within a fraction of a day, and a model could be fitted to the data with good precision. The addition of a single extra parameter (i.e. two values of frequency derivative rather than one) reduces the timing residuals by a factor of 20 and provides an entirely satisfactory description of the data. A similar fitting procedure has been applied to other well-sampled sections of data and produces consistent model parameters, giving values for the rotational frequency derivatives of $\dot{\nu}_{\rm OFF} = -10.8(2) \times 10^{-15}$ Hz s^{-1} and $\dot{\nu}_{\rm ON} = -16.3(4) \times 10^{-15}$ Hz s^{-1}. These values indicate that there is a $\sim$50% increase in the magnitude of the spin-down rate of the neutron star when the pulsar is ON.

We have searched our databases carefully for other pulsars which may exhibit this phenomenon. Four other candidates have been identified and are being studied now. One of these is PSR J1832+0029 which shows the same basic phenomenon on an even longer timescale. Fig. 6 shows the variation

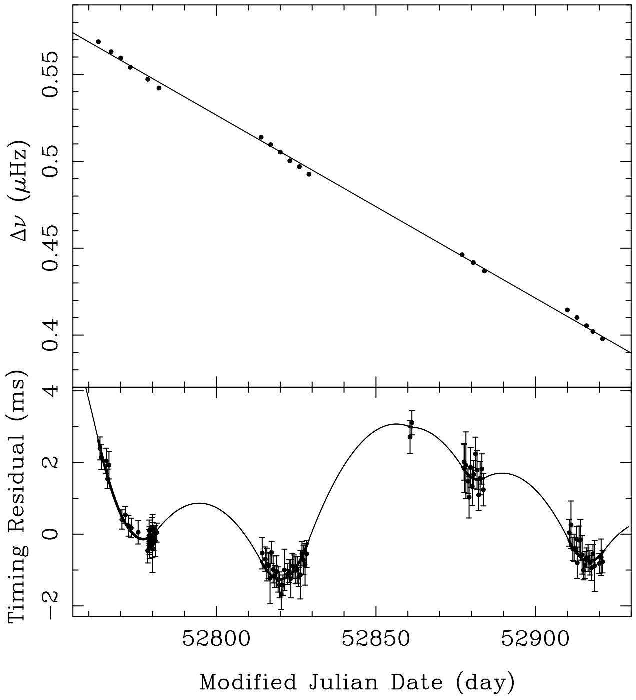

Figure 5: Top panel: The variation of the rotational frequency ν of PSR B1931+24 over a period of 160 days (Kramer et al. 2006). The increase in steepness of the slope during the 'ON' periods compared with the mean slope can be seen clearly, indicating an increase in slowdown rate. Bottom panel: Timing residuals relative to a simple slowdown model over the same period. The line shows a fitted model which includes a single extra parameter, an increase in frequency derivative during the 'ON' phase, and provides an excellent description of the data.

in its rotational frequency, showing a similar increase in slow-down rate during the ON periods.

The observed quasi-periodicity in PSR B1931+24's activity and its time-scale have never seen before as a pulsar emission phenomenon and are accompanied by massive changes in the rotational slow-down rate. This raises a number of questions. Why does the emission switch ON and OFF? Why is the activity quasi-periodic? Why is the pulsar spinning down faster when it is ON?

On the shortest, pulse-to-pulse time scales, intrinsic flux density variations are often observed in pulsar radio emission. The most extreme case is displayed by a small group of pulsars, which are known to exhibit nulls in their emission, i.e. the random onset of a sudden obvious lack of pulsar emission, typically for between one and a few dozen pulsar rotation periods (Backer 1970). An acceptable explanation for such "nulling", which appears to be the complete failure of the radiation mechanism, is still missing. This nulling represented the longest known time scales for an intrinsic disappearance of pulsar emission. Although the OFF periods in PSR B1931+24 last five orders of magnitude longer than typical nulling and the activity pattern is quasi-periodic, this may well be the same basic phenomenon as nulling.

The approximate 35-day period might be attributed to free precession, although we find no

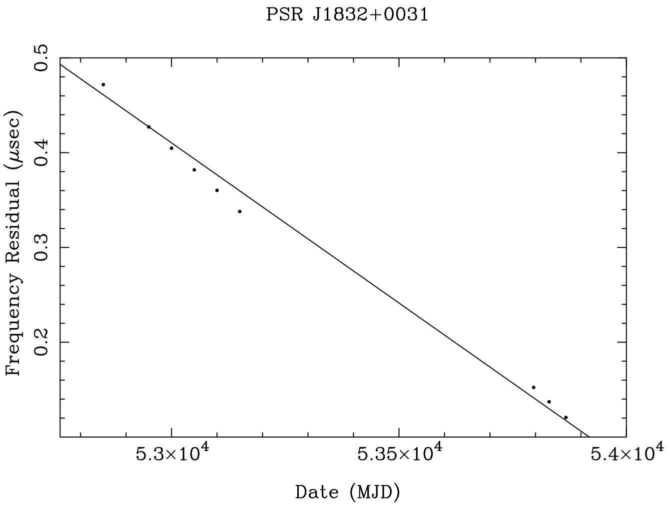

Figure 6: The variation of the rotational frequency ν of PSR J1832+0029 over about 4 years. The pulsar was OFF for the gap of ~600 days between the two ON periods. Note the increased magnitude of frequency derivative during the 'ON' periods.

evidence of expected profile changes (e.g. Stairs et al. 2000). The sudden changes between the two states, occurring within 10 seconds, and the imperfect constancy of the periodicity point toward a relaxation oscillation of unknown nature within the pulsar system, rather than precession.

What can cause the radio emission to cut off so quickly? The energy associated with the radio emission from pulsars accounts for only a very small fraction of the pulsar's slow-down energy which may suggest that the disappearance of radiation is simply due to the failure of the coherence condition in the emission process (Michel 1991). However, in this case, the long timescales of millions of pulsar rotations are hard to understand.

An alternative explanation is that there is a more global failure of charged particle currents in the magnetosphere. Intriguingly, the large changes in slow-down rate that accompany the changes in radio emission can also be explained by the presence or absence of a plasma whose current flow provides an additional braking torque on the neutron star. In this model, the open field lines above the magnetic pole become depleted of charged radiating particles during the OFF phases and the rotational slow-down, $\dot{\nu}_{\rm OFF}$, is caused by a torque dominated by magnetic dipole radiation (Pacini 1967; Gunn & Ostriker 1969). When the pulsar is ON, the decrease in rotational frequency, $\dot{\nu}_{\rm ON}$, is enhanced by an additional torque provided by the outflowing plasma, $T \sim \frac{2}{3c} I_{pc} B_0 R_{pc}^2$, where B_0 is the dipole magnetic field at the neutron star surface and $I_{pc} \sim \pi R_{pc}^2 \rho c$ which is the electric current along the field lines crossing the polar cap, having radius of R_{pc} (e.g. Harding et al. 1999).[1] The charge density of the current can be estimated from the difference in loss in rotational energy during the ON and OFF phases. When the pulsar is ON, the observed energy loss, $\dot{E}_{\rm ON} = 4\pi^2 I \nu \dot{\nu}_{\rm ON}$, is the result of the sum of the magnetic dipole braking as seen during the OFF phases, $\dot{E}_{\rm OFF} = 4\pi^2 I \nu \dot{\nu}_{\rm OFF}$, and the energy loss caused by the outflowing current, $\dot{E}_{\rm wind} = 2\pi T \nu$, i.e. $\dot{E}_{\rm ON} = \dot{E}_{\rm OFF} + \dot{E}_{\rm wind}$ where I is the moment of inertia of the neutron star. From the difference

---

[1] In order to be consistent with existing literature e.g. Harding et al. 1999, we quote formulae in cgs-units but refer to numerical values in SI units.

in spin-down rates between OFF and ON phases, $\Delta\dot{\nu} = \dot{\nu}_{\rm OFF} - \dot{\nu}_{\rm ON}$, we can therefore calculate the charge density $\rho = 3I\Delta\dot{\nu}/R_{pc}^4 B_0$ by computing the magnetic field $B_0 = 3.2 \times 10^{15}\sqrt{-\dot{\nu}_{\rm OFF}/\nu^3}$ Tesla and the polar cap radius $R_{pc} = \sqrt{2\pi R^3 \nu/c}$ for a neutron star with radius $R = 10$ km and a moment of inertia of $I = 10^{38}$ kg m^2 (Lorimer & Kramer 2005). We find that the plasma current that is associated with radio emission carries a charge density of $\rho = 0.034$ C m^{-3}. This is remarkably close to the charge density $\rho_{\rm GJ} = B_0\nu/c$ in the Goldreich-Julian model of a pulsar magnetosphere (Goldreich & Julian 1969), i.e. $\rho_{\rm GJ} = 0.033$ C m^{-3}.

Such current is sufficient to explain the change in the neutron star torque, but it is not clear what determines the long timescales or what could be responsible for changing the plasma flow in the magnetosphere. In that respect, understanding the cessation of radiation that we see in PSR B1931+24, may ultimately help us to also understand ordinary nulling. Whatever the cause is, it is conceivable that the onset of pulsar emission may be a violent event which may be revealed with high-energy observations. While an archival search for X-ray or γ-ray counterparts for PSR B1931+24 has not been successful, the relatively large distance of the pulsar ($\sim$ 4.6 kpc) and arbitrary viewing epochs may make such a detection unlikely. The relationship between the presence of pulsar emission via radiating particles and the increased spin-down rate of the neutron star provides strong evidence that a pulsar wind plays a significant role in the pulsar braking mechanism. While this has been suggested in the past (e.g. Spitkovsky 2004), direct observational evidence has hitherto been missing. We note that, as a consequence of the wind contribution to the pulsar spin-down, the surface magnetic fields estimated for normal pulsars from their observed spin-down are likely to be overestimated.

The behaviour of PSR B1931+24 suggests that many more such objects exist in the Galaxy but have been overlooked so far because they were not active during either the search or confirmation observations. The periodic transient source serendipitously found recently in the direction of the Galactic centre (Hyman et al. 2005) may turn out to be a short-timescale version of PSR B1931+24 and hence to be a radio pulsar. In general, the timescales involved in the observed activity patterns of these sources pose challenges for observations scheduled with current telescopes. Instead, future telescopes with multi-beaming capabilities, like the Square Kilometre Array (SKA) or the Low Frequency Array LOFAR), which will provide continuous monitoring of such sources, are needed to probe such timescales which are still almost completely unexplored in most areas of astronomy.

References

[1] M. A. McLaughlin, A. G. Lyne, D. R. Lorimer, M. Kramer, A. J. Faulkner, R. N. Manchester, J. M. Cordes, F. Camilo, A. Possenti, I. H. Stairs, G. Hobbs, N. D'Amico, M. Burgay, J. T. O'Brien, *Nature* **439** 817–820 (2006).

[2] Lorimer, D. R. and Kramer, M., Handbook of Pulsar Astronomy, Cambridge University Press, 2005.

[3] P. M. Woods, C. Thompson, Soft gamma repeaters and anomalous x-ray pulsars: Magnetar candidates, in: W. H. G. Lewin, M. van der Klis (Eds.), Compact Stellar X-ray Sources, CUP, Cambridge, 2004, (astro-ph/0406133).

[4] M. Kramer, A. G. Lyne, J. T. O'Brien, C. A. Jordan, D. R. Lorimer, *Science* **312** 549–551 (2006).

[5] R. N. Manchester, A. G. Lyne, F. Camilo, J. F. Bell, V. M. Kaspi, N. D'Amico, N. P. F. McKay, F. Crawford, I. H. Stairs, A. Possenti, D. J. Morris, D. C. Sheppard, *MNRAS* **328** 17–35 (2001).

[6] D. J. Morris, G. Hobbs, A. G. Lyne, I. H. Stairs, F. Camilo, R. N. Manchester, A. Possenti, J. F. Bell, V. M. Kaspi, N. D. Amico, N. P. F. McKay, F. Crawford, M. Kramer, *MNRAS* **335** 275–290 (2002).

[7] M. Kramer, J. F. Bell, R. N. Manchester, A. G. Lyne, F. Camilo, I. H. Stairs, N. D'Amico, V. M. Kaspi, G. Hobbs, D. J. Morris, F. Crawford, A. Possenti, B. C. Joshi, M. A. McLaughlin, D. R. Lorimer, A. J. Faulkner, *MNRAS* **342** 1299–1324 (2003).

[8] G. Hobbs, A. Faulkner, I. H. Stairs, F. Camilo, R. N. Manchester, A. G. Lyne, M. Kramer, N. D'Amico, V. M. Kaspi, A. Possenti, M. A. McLaughlin, D. R. Lorimer, M. Burgay, B. C. Joshi, F. Crawford, *MNRAS* **352** 1439–1472 (2004).

[9] A. J. Faulkner, I. H. Stairs, M. Kramer, A. G. Lyne, G. Hobbs, A. Possenti, D. R. Lorimer, R. N. Manchester, M. A. McLaughlin, N. D'Amico, F. Camilo, M. Burgay, *MNRAS* **355** 147–158 (2004).

[10] M. A. McLaughlin, I. H. Stairs, V. M. Kaspi, D. R. Lorimer, M. Kramer, A. G. Lyne, R. N. Manchester, F. Camilo, G. Hobbs, A. Possenti, N. D'Amico, A. J. Faulkner, *ApJ* **591** L135–L138 (2003).

[11] B. Zhang, A. K. Harding, A. G. Muslimov, *ApJ* **531** L135–L138 (2000).

[12] T. M. Tauris, R. N. Manchester, *MNRAS* **298** 625–636 (1998).

[13] N. Vranesevic, R. N. Manchester, D. R. Lorimer, G. B. Hobbs, A. G. Lyne, M. Kramer, F. Camilo, I. H. Stairs, V. M. Kaspi, N. D'Amico, A. Possenti, F. Crawford, A. J. Faulkner, M. A. McLaughlin, *ApJ* **617** L139–L142 (2004).

[14] G. H. Stokes, J. H. Taylor, J. M. Weisberg, R. J. Dewey, *Nature* **317** 787–788 (1985).

[15] G. Hobbs, A. G. Lyne, M. Kramer, C. E. Martin, C. Jordan, *MNRAS* **353** 1311–1344 (2004).

[16] D. C. Backer, *Nature* **228** 42–43 (1970).

[17] I. H. Stairs, A. G. Lyne, S. Shemar, *Nature* **406** 484–486 (2000).

[18] F. C. Michel, Theory of Neutron Star Magnetospheres, University of Chicago Press, Chicago, 1991.

[19] F. Pacini, *Nature* **216** 567–568 (1967).

[20] J. E. Gunn, J. P. Ostriker, *Nature* **221** 454–+ (1969).

[21] A. K. Harding, I. Contopoulos, D. Kazanas, *ApJ* **525** L125–L128 (1999).

[22] P. Goldreich, W. H. Julian, *ApJ* **157** 869–880 (1969).

[23] A. Spitkovsky, Electrodynamics of pulsar magnetospheres, pp. 357–364.

[24] S. D. Hyman, T. J. W. Lazio, N. E. Kassim, P. S. Ray, C. B. Markwardt, F. Yusef-Zadeh, *Nature* **434** 50–52 (2005).