THE DOUBLE PULSAR SYSTEM J0737−3039: MODULATION OF THE RADIO EMISSION FROM B BY RADIATION FROM A

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ABSTRACT

We have analyzed single pulses from PSR J0737−3039B, the 2.8 s pulsar in the recently discovered double pulsar system, using data taken with the Green Bank Telescope at 820 and 1400 MHz. We report the detection of features similar to drifting subpulses, detectable over only a fraction of the pulse window, with a fluctuation frequency of 0.196 cycles per period. This is exactly the beat frequency between the periods of the two pulsars. In addition, the drifting features have a separation within a given pulse of 23 ms, equal to the pulse period of A. These features are therefore due to the direct influence of J0737−3039A's 44 Hz electromagnetic radiation on J0737−3039B's magnetosphere. We only detect them over a small range of orbital phases, when the radiation from the recycled pulsar J0737−3039A meets our line of sight to J0737−3039B from the side.

Subject headings: binaries: general — pulsars: general —
pulsars: individual (PSR J0737−3039A, PSR J0737−3039B) —
radiation mechanisms: nonthermal

1. INTRODUCTION

The discovery of the first double pulsar binary system, J0737−3039 (Burgay et al. 2003; Lyne et al. 2004), presents us with a unique opportunity to study new aspects of relativistic gravity and relativistic plasma physics. The two pulsars in this system, J0737−3039A and J0737−3039B (hereafter simply "A" and "B") have periods of $P_A = 23$ ms and $P_B = 2.8$ s and are in a 2.4 hr mildly eccentric orbit. Of particular interest here is the fact that, because the rate of spin-down energy loss from A is ∼3600 times greater than that from B, the radiation from A is expected to have a significant impact on B. In fact, at the light cylinder radius of B, the energy density of the 44 Hz radiation from A is about 2 orders of magnitude greater than that of the 0.36 Hz radiation from B.

Aside from an ∼30 s duration eclipse (Lyne et al. 2004; Kaspi et al. 2004), the emission from the more energetic pulsar A is very steady and is consistent with that seen from other recycled pulsars. The emission from pulsar B, however, exhibits extreme variations in its flux density over a single orbit. At two orbital phases near the inferior conjunction of B (i.e., when B is closest to Earth), bright single pulses are detectable and can be studied in detail while at some other orbital phases, no radio emission is detectable at all. To explain these variations, Jenet & Ransom (2004) proposed a geometric model in which B is stimulated to emit when it is illuminated by A's hollow-

coned radio beam. Zhang & Loeb (2004) suggest that this occurs as pairs from A's wind flow into the open field line region of B and emit curvature radiation. Alternatively, it seems possible that the charges in A's wind short out the currents in the magnetosphere of B at certain orbital phases. While these models are plausible, no direct proof of an interaction between the two pulsars has so far been found.

In this Letter, we present the first direct observational evidence for the impact of A's electromagnetic radiation on B from an analysis of single pulses from B. This has revealed a phenomenon similar to the drifting subpulses detected from many radio pulsars (e.g., Drake & Craft 1968; Backer 1973; Taylor et al. 1975). However, in this case, the features are only detected at certain orbital phases. In § 2, we describe our observations and analysis and characterize the drifting behavior. In § 3, we show that this phenomenon is due to the direct influence of A's electromagnetic radiation on B's magnetosphere and explain why these features are only seen at certain orbital phases.

2. OBSERVATIONS AND ANALYSIS

We have analyzed the now publicly available exploratory-time observations of the double pulsar system obtained with the 100 m Green Bank Telescope (GBT) in 2003 December and 2004 January and using receivers at 427, 820, and 1400 MHz. The 427 and 820 MHz data discussed here were acquired with the GBT Spectrometer SPIGOT card with sampling times of 81.92 and 40.96 μs at those two frequencies, respectively. At both frequencies, 1024 synthesized frequency channels covered a 50 MHz bandwidth. The 1400 MHz data were acquired using the Berkeley-Caltech Pulsar Machine (BCPM) using a sampling interval of 72 μs on each of 96 channels covering a 96 MHz bandwidth. For further details of the data acquisition systems, see Ransom et al. (2004) and references therein.

The GBT data were dedispersed and folded using freely available software tools (Lorimer 2001) assuming the nominal dispersion measure (48.9 cm^{-3} pc; Burgay et al. 2003) and using an ephemeris for pulsar B from Lyne et al. (2004). As reported in that paper, and in Ramachandran et al. (2004), we find that the B pulsar is brightest at orbital phases 195°–230°

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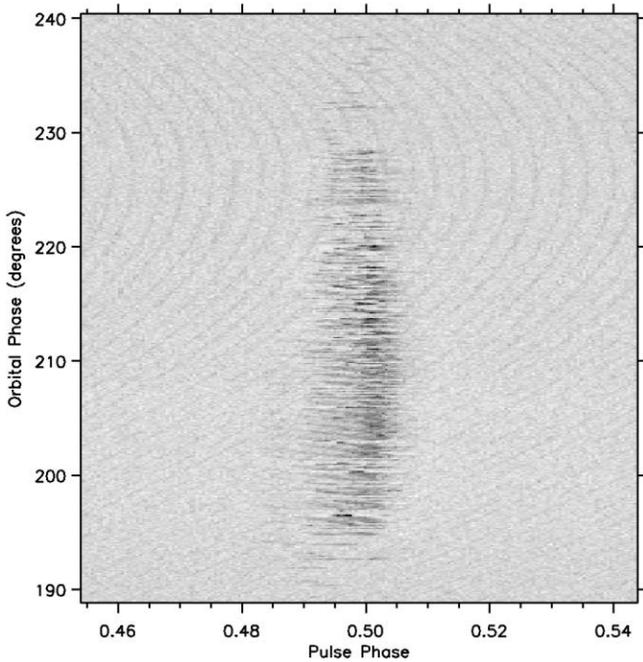[8] Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu km 0.7, 09042 Monserrato, Italy.

Fig. 1.—Single pulses of B at 820 MHz for orbital phases 190°–240° (i.e., 403 pulses) on MJD 52,997. Only 10% of the pulse period of B is shown. Drifting features are present through most of these data but are particularly obvious from orbital phases ∼195° to 210°. Single pulses from both components of A may also be seen in the background, most clearly at orbital phase ∼225°, where differential Doppler shifts from the orbital motion result in harmonically related apparent pulse periods. An expanded view of the drifting region is provided in Fig. 5.

and 260°–300°, where we define orbital phase as the longitude from ascending node (i.e., the sum of the longitude of periastron and the true anomaly). In Figure 1, we present a sequence of single pulses from B at 820 MHz between orbital phases 190° and 240°. At these orbital phases, the pulses of B are characterized by a strong trailing pulse component with a weaker leading component. In Figure 1, single pulses from A are also apparent. The single pulses from A at these orbital phases are very stable in flux, show no obvious drifting behavior, and are typical of those seen in other recycled pulsars (e.g., Jenet et al. 2001; Edwards & Stappers 2003), although the number of millisecond pulsars from which single pulses have been detected is quite small.

A striking effect seen in Figure 1, which was not reported in an earlier analysis of these data by Ramachandran et al. (2004), is a drifting phenomenon occurring in the single pulses of B in the orbital phase range ∼195°–215°. The drifting features are confined to the leading component of the pulse profile and are quite narrow, with a width of ∼$0.001P_B$. In Figure 2, we present a longitude-resolved fluctuation spectrum, calculated as described in Backer (1973), for this pulse sequence. These spectra reveal the frequencies at which the intensity of a pulsar signal fluctuates for a range of pulse longitudes. Because of the short amount of time over which the single pulses from B are detectable, only 384 pulses were used for this analysis. The fluctuation spectrum was calculated using two overlapping spectra of 256-pulse sequences, for a spectral resolution of ($1/256P_B$). We detect a strong feature at $0.196^{+0.005}_{-0.002}$ cycles per period (i.e., a modulation period $P_3 = 5.10P_B$). The subpulse separation within a given pulse, $P_2 = 23 \pm 1$ ms, is equal, within the uncertainties, to the period of pulsar A. We see similar drifting behavior at the same orbital phases and with
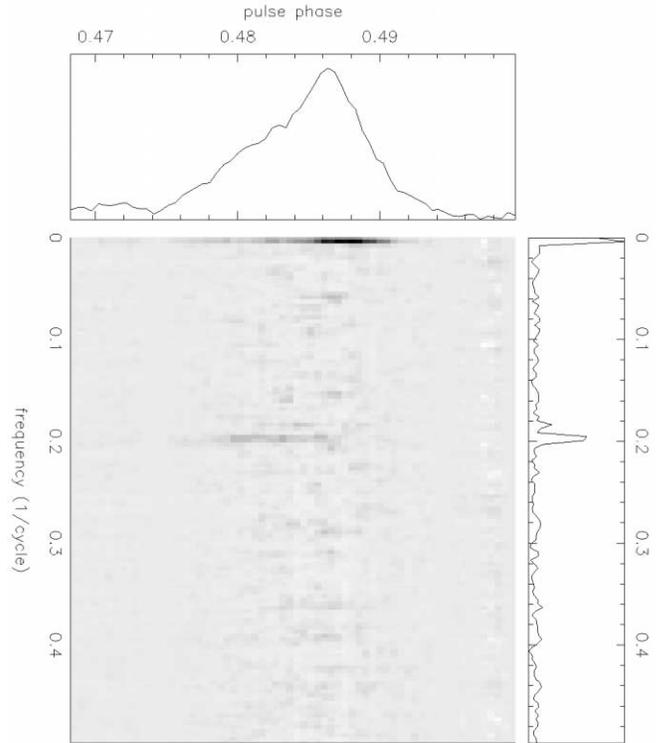

Fig. 2.—*Upper panel*: Integrated pulse profile of B for orbital phases 190°–240°. Only 64 of 2048 original phase bins are shown. *Middle panel*: Grayscale plot of the fluctuation spectrum of B, with the *x*-axis corresponding to pulse longitude and the *y*-axis to fluctuation frequency. Overlapping spectra of 256-pulse sequences have been computed. A feature with frequency of 0.196 cycles per period near the front half of the pulse profile is obvious. The low-frequency feature is due to the large change in the flux of B over this orbital phase range. *Right panel*: Spectrum summed over pulse phases 0.478–0.486, where the feature at 0.196 cycles per period is brightest.

exactly the same fluctuation frequency one orbit later in the same 820 MHz data set and in data taken with the BCPM at 1400 MHz 2 weeks prior to the 820 MHz data set. We also detect the same drifting in 427 MHz data taken with the SPIGOT card, but the lower signal-to-noise ratio of single pulses (partly due to the large amount of radio frequency interference) does not allow us to compute sensitive fluctuation spectra. We detect the same drifting features very weakly in data taken with the Parkes 64 m telescope in 2003, but the signal-to-noise ratio of those data is too poor to permit any detailed analysis.

In Figure 3, we show single pulses of B at orbital phases 260°–300°. The pulses in this orbital phase range are somewhat weaker than those shown in Figure 1. The profile is generally broader, with a stronger leading component. No drifting is seen at these orbital phases. In Figure 4, we show a fluctuation spectrum for the single-pulse sequence shown in Figure 3. Because of the shorter amount of time that single pulses are detectable in this phase range, only 192 pulses were used for the analysis, with overlapping 128-pulse spectra computed. No features indicative of drifting are obvious for this range of orbital phases, although there is a larger modulation index on the outer edges of the pulse.

3. DISCUSSION

At first sight, the drifting we see in the single pulses of pulsar B is similar to the drifting subpulses that have been detected from a number of "normal" radio pulsars. In the fol-
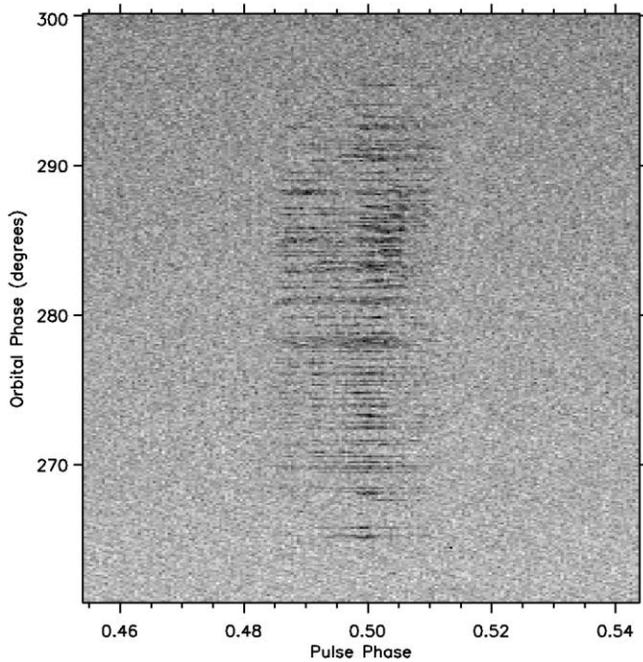
FIG. 3.—Single pulses of B at 820 MHz for orbital phases 260°–300° (i.e., 296 pulses) on MJD 52,997. As in Fig. 1, only 10% of the pulse period of B is shown. No drifting features are obvious, although the single pulses do show ordered structure, which may be influenced in some way by A. Further studies of the single pulses in this orbital phase range are underway.

lowing discussion, however, we demonstrate that, rather than being intrinsic to B's emission process, the drifting features are a direct result of the impact of A's 44 Hz electromagnetic radiation on B.

The ratio of the intrinsic barycentric rotation period of B to that of A is 122.182. Because the periods are incommensurate, any influence of A's electromagnetic radiation on B's magnetosphere will manifest itself as a drifting behavior caused by the beating of the two periodicities. Using the intrinsic periods of the two pulsars and their orbital elements, we can accurately predict the frequency of A's pulsed radiation as seen by B. We simply compute the apparent period of A as seen by B given the barycentric period of A and the changing propagation time of A's pulses due to the varying separation of the two pulsars, arising from the orbital eccentricity. We assume that the signal travels at the velocity of light. At orbital phases 195°–210°, where the drifting is most obvious, the beat frequency between A and B varies from 0.200 to 0.196 cycles per period, exactly matching the detected feature at $0.196^{+0.005}_{-0.002}$ cycles per period. Indeed, in Figure 5 we show an expanded view of the single pulses from Figure 1 for the range of orbital phases of interest with the predicted phases at the center of mass of B of a signal with A's periodicity. It is clear that the drifting pattern closely follows the predicted variation in phase. This, and the fact that the separation of successive features within a given pulse is equal to P_A, makes a convincing case that the drifting is due to the direct influence of a signal with A's periodicity on the B pulse emission mechanism. The fact that the observed modulation is at 44 Hz with only a single pulse in each 23 ms period suggests that it is not the beamed radiation from A, which has two pulses per period, that excites the B emission. On these as well as energetic grounds, we conclude that the observed modulation is due to the influence of the 44 Hz magnetic dipole radiation on the magnetosphere of B. Furthermore, the modulation is caused by the electromagnetic field itself,
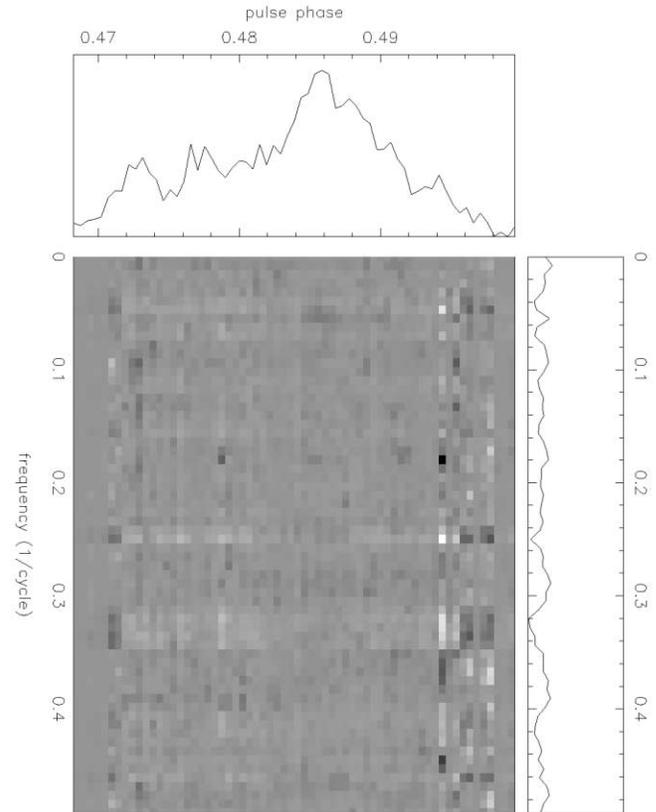

FIG. 4.—Same as Fig. 2, but for orbital phases 260°–300°. No features indicative of drifting behavior are seen in the fluctuation spectrum. Because the flux of B is more stable at these orbital phases, there are no obvious low-frequency features. Given the model discussed in § 3, fluctuation frequencies of 0.180–0.166 cycles per period would be expected.

rather than its intensity or pressure, which have an 88 Hz periodicity.[9] We note that this result provides observational support to the idea that, close to the pulsar, most of the spin-down energy is carried by the Poynting flux of the magnetic dipole radiation rather than by energetic particles (e.g., Michel 1982).

We can think of two different ways in which the electromagnetic radiation from A could influence the processes in B's magnetosphere. It is possible that the electric component of A's radiation field accelerates the radiating particles in the magnetosphere of B. Alternatively, the magnetic component of A's radiation field could modulate the magnetic field of B. The latter would lead to an oscillation at 44 Hz in the radio beam direction, due to effects either in the emission region or during propagation out of the magnetosphere, taking the beam in and out of our line of sight.

The predicted beat frequency varies from 0.160 to 0.205 cycles per period over the orbit. However, the fact that we only see this drifting phenomenon at certain orbital phases can be understood given the geometry of the system. The energy and momentum from the 44 Hz electromagnetic radiation distort B's magnetosphere into a cometary shape. When B is between us and A (i.e., the orbital phase range plotted in Fig. 3), the B pulses propagate through the cometary tail and are relatively undisturbed. However, for the orbital phase range plotted in Figure 1, the radiation from A is more transverse to the field lines in the emission and propagation zones, allowing the modulation process to be effective (see Fig. 4 in Lyne et al. 2004).

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[9] The power in the fluctuation spectrum at 0.392 cycles per period is a factor of ~4 smaller than the power at 0.196 cycles per period.
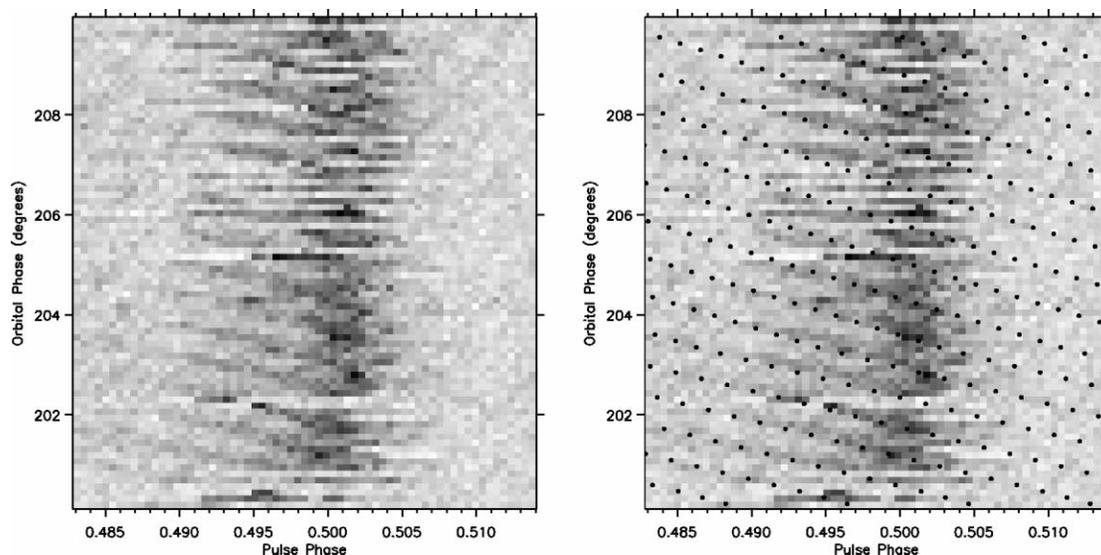
FIG. 5.—*Left*: An expanded view of Fig. 1 from orbital phases 200°–210°. *Right*: Filled circles denote the arrival at the center of B of emission from an arbitrary rotational phase of A, retarded by the propagation time across the orbit.

We would expect to see this modulation at other orbital phases where the direction of A's radiation is transverse to the direction of B's emission. Unfortunately, however, at other orbital phases the emission from B is too weak for these effects to be detectable. It is not likely that this interaction is itself responsible for the overall orbital modulation of the B-pulse emission (i.e., the large changes in flux density and pulse profile across the orbit), although this must also be due to the effect of A's radiation on the B magnetosphere.

In summary, we have detected drifting features in the radiation from the 2.8 s B pulsar of the double pulsar system. This effect is only detectable at orbital phases when the electromagnetic radiation from A meets the beam of B from the side. We have shown that this phenomenon is due to the *direct influence* of the magnetic dipole radiation from A on B. This is clear evidence for an interaction between these two pulsars and is extremely important for understanding not only the unique emission processes in this system but also pulsar radio

emission in general. Further detailed studies of this drifting behavior may enable us to significantly improve our knowledge of the geometry of and physics responsible for B's emission beam.

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