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D. R. Lorimer
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M. Kramer
G. G. Pavlov

See next page for additional authors
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D. R. Lorimer1,2, A. G. Lyne3, M. A. McLaughlin1,2, M. Kramer4,5, G. G. Pavlov5,6, and C. Chang5

1 Department of Physics, West Virginia University, White Hall, Morgantown, WV 26506, USA
2 National Radio Astronomy Observatory, Green Bank, WV 24944, USA
3 Jodrell Bank Centre for Astrophysics, The University of Manchester, Alan Turing Building, Manchester M13 9PL, UK
4 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
5 Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab., University Park, PA 16802, USA
6 St.-Petersburg State Polytechnical University, Polytekhnicheskaya ul. 29, St.-Petersburg 195251, Russia

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ABSTRACT

We report on radio and X-ray observations of PSR J1832+0029, a 533 ms radio pulsar discovered in the Parkes Multibeam Pulsar Survey. From radio observations taken with the Parkes, Lovell, and Arecibo telescopes, we show that this pulsar exhibits two spin-down states akin to PSRs B1931+24 reported by Kramer et al. and J1841−0500 reported by Camilo et al. Unlike PSR B1931+24, which switches between “on” and “off” states on a 30–40 day timescale, PSR J1832+0029 is similar to PSR J1841−0500 in that it spends a much longer period of time in the off-state. So far, we have fully sampled two off-states. The first one lasted between 560 and 640 days and the second one lasted between 810 and 835 days. From our radio timing observations, the ratio of on/off spin-down rates is 1.77 ± 0.03. Chandra observations carried out during both the on- and off-states of this pulsar failed to detect any emission. Our results challenge but do not rule out models involving accretion onto the neutron star from a low-mass stellar companion. In spite of the small number of intermittent pulsars currently known, difficulties in discovering them and in quantifying their behavior imply that their total population could be substantial.

Key word: pulsars: individual (B1931+24, PSR 1832+0029, PSR J1841−0500)

Online-only material: color figure

1. INTRODUCTION

It is well established that not all radio pulsars emit radiation during each rotation. Backer (1970) first observed this phenomenon and demonstrated that some pulsars exist in a “null state” for several pulse periods before switching back on again. Pulsar nulling has been investigated extensively over the years (e.g., Ritchings 1976; Rankin 1986; Biggs 1992). From a study of pulsars in the Parkes Multibeam Pulsar Survey (PMPS; Manchester et al. 2001), Wang et al. (2007) confirmed earlier evidence (Ritchings 1976) that the fraction of nulling pulses generally increases with increasing characteristic age.

In addition to the nulling phenomenon, it has become apparent that a new class of intermittent pulsars exist where no radiation is observed over much longer timescales. In a single-pulse analysis of archival PMPS data, McLaughlin et al. (2006) discovered a new class of neutron stars (Rotating Radio Transients) from which radio emission is detectable, on average, only 1 s per day in an apparently random fashion. In the same year, Kramer et al. (2006) reported the discovery of a more deterministic type of intermittency in PSR B1931+24, which appears to be the prototype of a large population of pulsars that have so far been difficult to detect. As Kramer et al. demonstrated, PSR B1931+24 shows a quasi-periodic on/off cycle with a period of 30–40 days in which the spin-down rate increases by ~50% when the pulsar is in its on-state compared to the off-state. In this paper, we report observations characterizing intermittent behavior in PSR J1832+0029 an apparently ordinary 533 ms pulsar with a characteristic age of 5.6 Myr which was discovered as part of the PMPS (Lorimer et al. 2006). Earlier accounts of this work we presented by Kramer (2008) and Lyne (2009).

Very recently, Camilo et al. (2012) announced the discovery of PSR J1841−0500, a 912 ms pulsar which has so far shown one off-state lasting 580 days. Like B1931+24, the spin-down rate in the on-state is higher than the off-state. For J1841−0500 the increase is approximately 150%! These pulsars are dramatic examples of a newly recognized and large group of pulsars that show changes in their emission properties and period derivatives (Lyne et al. 2010) which are correlated and often quasi-periodic. Understanding pulsar intermittency will shed new insights into neutron star physics and populations.

The long off-states of intermittent pulsars are in stark contrast to the longest known quiescence times of nulling pulsars, i.e., they exceed the typical nulling timescale by about five orders of magnitude. In addition, the observed increase in spin-down rate points to a significant increase in the magnetospheric particle outflow when the pulsar switches on, indicating that a pulsar wind plays a significant role in neutron star spin evolution. As described by Kramer et al. (2006) and discussed later in this paper, the spin-down rate changes allow us to estimate the current density associated with the radio emission.

The difficulties in detecting and identifying intermittent pulsars imply that the few we currently observe represent a potentially substantial population of similar objects in the Galaxy. To better understand this population, it is therefore important to establish the related timescales for the non-emitting state. Here we detail our observations of intermittent behavior in PSR J1832+0029. In Section 2, we describe the radio observations we have carried out to characterize its intermittency. In Section 3, we describe the Chandra X-ray observations which constrain the high-energy emission from the pulsar. In Section 4, we discuss the implications of our results.

2. RADIO OBSERVATIONS OF PSR J1832+0029

PSR J1832+0029 was first detected during the PMPS in an observation made on 2000 November 23. Following its confirmation observation in 2003 September as part of...
follow-up observations for the survey (Lorimer et al. 2006). PSR J1832+0029 has been observed regularly by both the Parkes 64 m and Lovell 76 m radio telescopes. Parkes observations span the period from 2003 September until 2008 September. Lovell observations began in 2006 March and continue to be made. To date, a total of 422 individual detections of the pulsar have been collected (331 of these with the Lovell telescope). The initial Parkes observations provided routine detections of the pulsar at 1374 MHz in five minute pointings until 2004 May. Despite 27 observations of the pulsar between 2004 June 26 and 2006 January 7, the pulsar was not detected. By 2005 March, the Parkes observation times had increased to 20 minutes. The non-detections mean that the flux density of PSR J1832+0029 must have been less than 70 \( \mu \)Jy during the period 2004 May to 2005 February for the 5 minute observations and below 40 \( \mu \)Jy for the 20 minute observations carried out between 2005 March and 2006 January. The pulsar was finally detected again on 2006 March 3 in a 20 minute observation at 1374 MHz. It was subsequently routinely detectable, primarily with the Lovell telescope, until 2010 April 7, after which it became undetectable until 2012 July 20 when it resumed its regular behavior.

In all of the observations in which the pulsar was detected, we find no evidence for any variation in the pulse width (7.1 ms FWHM) or flux density (140 \( \mu \)Jy) as originally presented in Lorimer et al. (2006). Currently, our Parkes and Lovell observations provide only modest constraints on the degree of polarization in PSR J1832+0029 and indicate that it is less than 20\% linearly polarized. As we discuss later (Section 4.2), sensitive observations of this pulsar’s polarimetric properties could be valuable in helping to discriminate between various proposed models.

To make the most stringent constraints of PSR J1832+0029 during its off-state, on 2011 March 8 and 9 we carried out two 1 hr observations using the 305 m William E. Gordon Arecibo radio telescope. Both observations were conducted using the L-band wide receiver\(^7\) and the Wideband Arecibo Pulsar Processors (WAPPs; Dowd et al. 2000). Four WAPPs were used to measure three-level autocorrelation functions every 128 \( \mu \)s in each of four 100 MHz sub-bands spanning 1100–1500 MHz. The data from each WAPP were Fourier transformed using the\(^8\) filterbank program within the SIGPRO software package to synthesize a filterbank with 512 frequency channels, each of width 781.25 kHz. These channelized data were then de-dispersed at the pulsar’s dispersion measure (DM) of 28.3 cm\(^{-3}\) pc and folded over a range of trial periods around the nominal value predicted by our timing model using SIGPRO’s fold program. A blind periodicity search was also carried out using SIGPRO’s seek program down to a signal-to-noise ratio (S/N) of 6. PSR J1832+0029 was not detected in either of these analyses. Assuming an average gain of 8.5 K Jy\(^{-1}\), which is appropriate for the large zenith angles during the observation (17–20 deg), these S/N limits in the searching and folding analyses translate to an upper limit on the flux of 2–3 \( \mu \)Jy in each observation. Folding the data coherently across both days also resulted in no detection, with a corresponding upper limit of 1.6 \( \mu \)Jy. At its nominal on-state flux density of 140 \( \mu \)Jy, the pulsar would have been detected with S/N of approximately 440. We can therefore constrain any emission in the off-state to be less than one part in 440 of the flux density in the on-state. At the distance \( d = 1.3 \) kpc inferred from the pulsar’s dispersion measure and the Cordes & Lazio (2002) free electron distribution model, the upper limit on the 1400 MHz luminosity from these observations is 2.7 \( \mu \)Jy kpc\(^2\). This limit is a factor of 16 lower than that inferred for the off-state of PSR B1931+24 (Kramer et al. 2006) and an order of magnitude below the faintest pulsar currently known (PSR J2144–3933; Manchester et al. 1996).

3. X-RAY OBSERVATIONS OF PSR J1832+0029

PSR J1832+0029 was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra on October 19 (observation ID 9145) and 2011 March 28 (observation ID 12256), when the pulsar was in on- and off-states, respectively. In both observations, the target was imaged near the optical axis on the S3 chip in Timer Exposure mode with a frame time of 3.24 s. Other activated chips were I2, I3, S1, S2, and S4. The data were telemetered in Very Faint format, optimal for distinguishing between X-ray events and events associated with cosmic rays. The useful effective exposure times (livetimes) were 19.87 ks and 22.75 ks for the first and second observations, respectively.

Table 1 Observed and Derived Parameters for PSR J1832+0029

<table>
<thead>
<tr>
<th>Timing model parameters for first “on” period</th>
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<tbody>
<tr>
<td>Data span (MJD)</td>
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<tr>
<td>Rotation frequency, ( \nu ) (Hz)</td>
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<tr>
<td>Frequency derivative, ( \dot{\nu} ) (10(^{-15}) s(^{-2}))</td>
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<td>Reference epoch (MJD)</td>
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<tr>
<th>Timing model parameters for second “on” period</th>
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<tbody>
<tr>
<td>Data span (MJD)</td>
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<tr>
<td>Right ascension, ( \alpha ) (J2000)</td>
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<tr>
<td>Declination, ( \delta ) (J2000)</td>
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<tr>
<td>Rotation frequency, ( \nu ) (Hz)</td>
</tr>
<tr>
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<td>Reference epoch (MJD)</td>
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<th>Timing model parameters for third “on” period</th>
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<tr>
<td>Data span (MJD)</td>
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<td>Reference epoch (MJD)</td>
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<th>Derived parameters for on-state</th>
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<tr>
<td>Spin-down energy loss rate, ( E \propto \dot{\nu}^2 )</td>
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<tr>
<td>Characteristic age, ( t_c = \nu/(2\dot{\nu}) )</td>
</tr>
<tr>
<td>Surface magnetic field, ( B \propto \sqrt{\nu/\dot{\nu}} )</td>
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Notes. Parentheses indicate 1\( \sigma \) uncertainties on the last digit(s) as reported by TEMPO2.

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\(^7\) http://www.naic.edu/~astro/RXstatus/Lwide/Lwide.shtml

\(^8\) http://sigproc.sourceforge.net

\(^9\) http://cxc.harvard.edu/ciao/threads/reproject_aspect
2MASS sources with likely X-ray counterparts on the S3 chip (separations $<1.2$) for each of the observations, which resulted in $0.3$ and $0.2$ corrections in the pulsar’s position for the first and second observations, respectively (i.e., less than the size of the ACIS pixel, $0.492$). The corrected images are shown in Figure 1.

We analyzed the data in the ACIS energy range of $0.3$–$8$ keV, conservatively choosing $r = 3''$ circles around the radio pulsar position for the source region, which includes $99\%$ of all source counts, for a typical pulsar spectrum. We measured the background, $N_b = 1140$ and $1062$ counts for the first and second observations, respectively, in the $80''$ radius circle around the pulsar position, excluding the $r = 10''$ circle around the pulsar and $r = 5''$ circle around the faint (and variable) field source $\approx 20''$ south of the pulsar (i.e., the area of background aperture is $A_b = 19,713$ arcsec$^2$). With the background surface densities $N_b/A_b = 0.058 \pm 0.002$ and $0.054 \pm 0.002$ counts arcsec$^{-2}$, we expect $n_b = 1.64 \pm 0.05$ and $1.54 \pm 0.05$ background counts in the $r = 3''$ source apertures for the first and second observations, respectively.

The detected numbers of source and background counts in the source aperture are $n = 0$ and $3$, for the first and second observations, respectively (the same as in the uncorrected images). This means that the pulsar was not detected in our observations, and we can only put upper limits on its count rate and flux. Assuming Poisson statistics, the upper limit $n_u$ on the total number of counts in the detection area at confidence level $C$ can be estimated (see, e.g., Gehrels 1986) as follows:

$$C = 1 - \sum_{m=0}^{n} \frac{n_u^m \exp(-n_u)}{m!}, \quad (1)$$

which leads to the upper limit $n_{s,u} = n_u - n_b$ on the number of source counts. For the first observation ($n = 0$), $n_u = -\ln(1 - C)$ and $n_{s,u} = 2.97$ counts for $C = 0.99$. For the second observation ($n = 3$), the corresponding upper limit for $C = 0.99$ is $10.05$ counts (see Table 1 in Gehrels 1986), and $n_{s,u} = 8.51$ counts. The source count rate upper limits at the $99\%$ confidence level are therefore $R_{s,u} = 1.5 \times 10^{-4}$ counts s$^{-1}$ for the first observation and $R_{s,u} = 3.7 \times 10^{-4}$ counts s$^{-1}$ for the second observation.

The radio observations reported above suggest long-term intermittent behavior in PSR J1832+0029, while the X-ray observations failed to detect any difference in the high-energy emission between the on- and off-states. We now discuss the implications of these observations.

4. DISCUSSION

The radio observations reported above suggest long-term intermittent behavior in PSR J1832+0029, while the X-ray observations failed to detect any difference in the high-energy emission between the on- and off-states. We now discuss the implications of these observations.

4.1. Spin-down Behavior in the Two States

To track the variation in spin frequency ($\nu$) of PSR J1832+0029 we used the tempo2 software package (Hobbs et al. 2006) and its stridefit plugin to carry out measurements of $\nu$ based on timing model fits to short (30 day time span) segments of data in which the position was fixed at the nominal values found by Lorimer et al. (2006) and the spin frequency derivative $\dot{\nu}$ was assumed to be zero. As shown in Figure 2, this analysis reveals a clear discontinuity in the spin-down behavior during the off-states. Two explanations could account for this: (1) the pulsar suffered a period glitch during the off-states and
(2) The spin-down rate was different during the off-states, as
is observed for PSRs B1931+24 and J1841–0500. Although
it is possible to fit across the 2004–2005 period, resulting in
Δν/ν = (5.34 ± 0.07) × 10⁻⁸ for the putative glitch, no exo-
"Figure 3. Timing model residuals for PSR J1832+0029 obtained from
ernential recovery is observed and the abrupt turn-off observed
our TEMPO2 analysis of the second on-state using the ephemeris quoted in
in emission is inconsistent with other observations of glitching
Table 1. The root-mean-square of the data shown here is 4.37 ms. These
data, and all other pulse arrival times collected so far, are freely available at

details are summarized in Table 1. The pulsar’s DM was not constrained by
these analyses and was therefore held fixed at the value reported
by Lorimer et al. (2006; DM = 28.3 cm⁻³ pc). The shorter
timing baseline (~270 days) for the first on-state compared to
the second one (~4 yr) means that the timing parameters
obtained from it are less precise and subject to covariances.
So far, we have only sampled ~1 month in the current (third)
on-state. To minimize these covariances, we held the position
in the first on-state fit fixed at the position derived from
the second on-state. While the post-fit residuals for the first on-state
are approximately white, a significant amount of timing noise
is present in the residuals from the second on-state shown in
Figure 3. This behavior can be removed by fitting multiple
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Using TEMPO2, we obtained independent timing solutions in
each of the three on-states. The results of these analyses are
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Hobbs et al. 2004). To check the effect on the measured
parameters in Table 1, we carried out such an analysis using
the fitwaver plugin to TEMPO2. The residuals can be whitened by
removing six harmonically related sinusoids and the result fit
parameters are all within 1σ of the values presented in Table 1.
We therefore adopt the parameters from the second on-state as
being our most precise measurements of the pulsar to date and,

hence, \( \dot{\nu}_{\text{on}} = -(5.44505 \pm 0.00007) \times 10^{-15} \text{ s}^{-2} \).

To measure \( \dot{\nu}_{\text{off}} \), we accounted for the uncertainties in off/on
switching epochs in the following way. We first assumed that
the nominal switch-off epoch (\( T_{\text{off}} \)) of the pulsar occurred midway
between the date of the last detection during the second on-
phase (\( T_3 = \text{MJD 55293.33} \)) and the first non-detection (\( T_2 = \text{MJD 53301.99} \)). Similarly, for the nominal switch-on epoch
\( T_{\text{on}} \), we adopt the midpoint between the last non-detection
(\( T_4 = \text{MJD 56110.85} \)) and the first re-detection of the third
on-phase (\( T_4 = \text{MJD 56128.78} \)). Using TEMPO2, we computed
\( \nu(T_{\text{off}}) \) and \( \nu(T_{\text{on}}) \) — the nominal pulse frequencies at both \( T_{\text{off}} \)
and \( T_{\text{on}} \) as predicted by the second and third on-state timing
models, respectively. The off-state spin-down rate

\( \dot{\nu}_{\text{off}} = \frac{\nu(T_{\text{off}}) - \nu(T_{\text{on}})}{T_{\text{on}} - T_{\text{off}}} = -(3.08 \pm 0.05) \times 10^{-15} \text{ s}^{-2} . \)

Here, the uncertainty in \( \dot{\nu}_{\text{off}} \) is dominated by the uncertainty in
\( T_{\text{on}} - T_{\text{off}} \) which we estimated to be the mean of the two time
windows of interest here (i.e., \( (T_3 - T_1 + T_2 - T_1)/2 ) \)). A similar analysis for the first off-state yields \( \dot{\nu}_{\text{off}} = -(3.2 \pm 0.2) \times 10^{-15} \text{ s}^{-2} \). These results imply that the ratio of on/off spin-down rates \( R = \dot{\nu}_{\text{on}}/\dot{\nu}_{\text{off}} \) is therefore 1.77 ± 0.03, i.e., slightly higher
than PSR B1931+24 but below PSR J1841–0500.

4.2. Charge Density in the Pulsar Magnetosphere

To estimate the implied current flow in the pulsar magnetos-
sphere for both the on and off-states, we follow Kramer et al.
(2006) and consider the simplest possible emission model. We
assume that, in the off-state, the pulsar spins down by a mecha-
anism that does not involve a substantial particle ejection (e.g.,
it would be magnetic dipole radiation if the pulsar were in vac-
uum), while the rate in the on-state is enhanced by a torque
from the current of an additional plasma outflow. Assuming
that the spin-down energy loss rate in the on-state, \( \dot{E}_{\text{on}} \),
can be written as the sum of the energy loss rate in the off-state,
\( \dot{E}_{\text{off}} \), and the energy loss due to the additional plasma,
\( \dot{E}_{\text{plasma}} \), the corresponding charge density (in cgs units) in the plasma

\( \rho_{\text{plasma}} = \frac{3I(\dot{\nu}_{\text{off}} - \dot{\nu}_{\text{on}})}{R_{\text{pc}}^3 B_{\text{off}}} . \)

Here, \( I \) is the moment of inertia of the neutron star,

\( R_{\text{pc}} = \sqrt{\frac{2\pi \nu R_{\text{NS}}^3}{c}} \)

is the polar cap radius, \( B_{\text{off}} \) is the dipole surface magnetic field
strength calculated from the spin frequency and spin-down rate
in the off-state, and \( c \) is the speed of light. For a canonical
neutron star of radius \( R_{\text{NS}} = 10^6 \text{ cm} \) and moment of inertia
\( I = 10^{45} \text{ gm cm}^2 \), we find \( \rho_{\text{plasma}} \approx 62 \text{ esu cm}^{-3} \). This is
slightly higher than the so-called Goldreich–Julian density

\( \rho_{\text{GJ}} = \frac{B_{\text{off}}}{P_c} \approx 44 \text{ esu cm}^{-3} \),

which is the charge density required to radiate along the open
magnetic field lines in the idealized pulsar magnetosphere model

For PSR B1931+24, Kramer et al. (2006) found that \( \rho_{\text{GJ}} \approx \rho_{\text{plasma}} \approx 100 \text{ esu cm}^{-3} \). Taking the corresponding values for
PSR J1841–0500 from Camilo et al. (2012), we find for this
pulsar that the plasma density \( \rho_{\text{plasma}} \approx 400 \text{ esu cm}^{-3} \) is
significantly larger than \( \rho_{\text{GJ}} \approx 130 \text{ esu cm}^{-3} \). The fact that
these inferred densities all equal or exceed \( \rho_{\text{GJ}} \) at least implies
that the basic conditions for radiation by the Goldreich & Julian
(1969) model are being met.

For simplicity, the above calculations make the assumption
that the pulsar is an orthogonal rotator. In reality, of course, the
increment angle between the spin and magnetic axes \( \alpha < 90^\circ \). More recent and realistic modeling of the pulsar magnetosphere by Li et al. (2012) and Kalapotharakos et al. (2012) consider force-free electrodynamic and resistive solutions which can account for the different spin-down rates observed in these three intermittent pulsars. Based on our measurement of the on/off spin-down ratio, \( R \), and the results presented in Figure 3 of Li et al. (2012), the prediction for PSR J1832+0029 is that \( \alpha \sim 60^\circ \). A future Arecibo observing campaign on this pulsar during its next on-state will be undertaken to obtain high-quality polarimetric data with the aim of constraining \( \alpha \). As discussed by Beskin & Nokhrina (2007) and Kalapotharakos et al. (2012), further discoveries of intermittent pulsars with different values of \( R \) than observed so far would greatly help to constrain these models.

In the context of models for pulsar intermittency involving the neutron star’s emission mechanism, it should also be noted that Zhang et al. (2007) proposed that intermittent pulsars are old isolated neutron stars which have entered the so-called death valley in the \( P-P \) diagram (Chen & Ruderman 1993) where the voltage across the neutron star polar cap is no longer sufficient for pair production in the neutron star magnetosphere, and the radio emission becomes sporadic. Zhang et al. suggest that non-dipolar magnetic field configurations, similar to the sunspot phenomenon, may be effective in such neutron stars and temporarily rejuvenate their radio emission. It is not clear, however, how the quasi-periodic nature seen in PSR B1931+24 can be explained quantitatively in this scenario, or indeed whether it applies to PSR J1832+0029 or PSR J1841−0500, since (as noted by Camilo et al. 2012) none of these pulsars are in the death valley region.

### 4.3. Constraints from the X-Ray Non-detections

The X-ray count rate upper limits can be used to estimate upper limits on energy flux, which, however, depend on assumed spectrum. We know from observations of old pulsars that their X-ray spectra can be approximated by an absorbed power-law model with a photon index \( \Gamma \approx 2 \)–4 (e.g., Kargaltsev et al. 2006; Pavlov et al. 2009). The hydrogen column density toward the pulsar, \( N_{\text{H}} \approx 1 \times 10^{21} \text{ cm}^{-2} \), can be estimated from the DM assuming a 10% average degree of ionization of the interstellar medium. Using the Chandra PIMMS tool,\(^\text{10}\) we obtain the following absorbed and unabsorbed energy fluxes for a given source count rate \( R_x \) in the first observation:

\[
F_{\text{abs}}^{0.3-8\text{keV}} = 0.63, \quad 0.47 \quad \text{and} \quad 0.48, \quad F_{\text{unabs}}^{0.3-8\text{keV}} = 0.82, \quad 0.90 \quad \text{and} \quad 1.33, \quad \text{in units of} \quad 10^{-15} (R_x / 10^{-4} \text{ counts s}^{-1}) \text{ cm}^{-2} \text{ s}^{-1}, \quad \text{for} \quad \Gamma = 2, \quad 3 \quad \text{and} \quad 4, \quad \text{respectively}. \quad \text{For the second observation, the corresponding fluxes are} \quad F_{\text{abs}}^{0.3-8\text{keV}} = 0.70, \quad 0.55 \quad \text{and} \quad 0.59, \quad F_{\text{unabs}}^{0.3-8\text{keV}} = 0.91, \quad 1.04 \quad \text{and} \quad 1.64, \quad \text{in the same units. Note that the same count rates correspond to higher fluxes in the second observation because the ACIS effective area became smaller. Using these relations and the count rate upper limits estimated above, we can estimate the flux upper limits at a given confidence level. For instance, for} \quad \Gamma = 3 \quad \text{and} \quad C = 0.99, \quad \text{we obtain} \quad F_{\text{abs}}^{0.3-8\text{keV}} < 0.7 \quad \text{and} \quad < 2.0, \quad F_{\text{unabs}}^{0.3-8\text{keV}} < 1.3 \quad \text{and} \quad < 3.8, \quad \text{for the first and second observations, respectively, in units of} \quad 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad \text{From these upper limits, one can estimate upper limits on X-ray luminosity,} \quad L_x = 4\pi d^2 \frac{F_x}{c^2} \quad \text{and efficiency,} \quad \eta_x = L_x / \dot{E}. \quad \text{For the on-state (where} \quad \dot{E} = 4.0 \times 10^{32} \text{ erg s}^{-1}, \quad \text{assuming} \quad \Gamma = 3, \quad \text{we obtain} \quad L_{0.3-8\text{keV}} < 2.6 \times 10^{35} \text{ergs s}^{-1}, \quad \eta_{0.3-8\text{keV}} < 6.5 \times 10^{-4}(d/1.3 \text{kpc})^2, \quad \text{at} \quad C = 0.99. \quad \text{Making the same assumptions for the off-state (where} \quad \dot{E} = 2.4 \times 10^{33} \text{ erg s}^{-1}, \quad \text{we obtain} \quad L_{0.3-8\text{keV}} < 7.7 \times 10^{29} \text{(d/1.3 kpc)}^2 \quad \text{erg s}^{-1}, \quad \eta_{0.3-8\text{keV}} < 3.0 \times 10^{-5} \text{(d/1.3 kpc)}^2, \quad \text{at} \quad C = 0.99. \quad \text{These limits are consistent with the non-thermal efficiencies observed in other non-recycled pulsars (Possenti et al. 2002; Zavlin & Pavlov 2004).}

### 4.4. Implications for Other Intermittent Models

Our discussion so far has focused on pulsar intermittency as being due to processes that are internal to the neutron star magnetosphere. At least two alternative scenarios, which we discuss below, have been made to explain the phenomenon as being due to the influence of material emanating from outside the magnetosphere.

Cordes & Shannon (2008) investigated the consequences of debris disks around neutron stars, i.e., metal-rich leftover material from the supernova explosion that has aggregated into a disk of circumpulsar material. They propose a scenario in which the behavior seen in PSR B1931+24 is produced by an asteroid in an eccentric 40 day orbit which deflects material from the debris disk into the neutron star magnetosphere. Such a process could temporarily halt the electron–positron pair production thought to be responsible for the radio emission. Unfortunately, the infall rates required by this model translate to completely undetectable X-ray fluxes. In addition, given that sufficiently high-precision timing is not possible for pulsars such as PSR J1832+0029, any periodic signatures from such small bodies would not be detectable in its timing residuals (Figure 3).

Rea et al. (2008) suggested that accretion onto the neutron star from a low-mass stellar companion in an eccentric orbit close to periastron could halt pair production. In this case, the heating of the infalling matter would produce additional X-rays in the off-state. While no signatures indicative of a binary companion exist in our radio timing residuals, such an orbit would not be detectable if it were close to face-on. Rea et al. attempted to test this hypothesis for PSR B1931+24 via a Chandra ACIS observation in 2006. Unfortunately, the pulsar switched on unexpectedly before their observations. To test this model in our observations of PSR J1832+0029, following the discussion in Section 5.2 from Rea et al. (2008), we assume that the radio emission is quenched when the neutron star’s Alfvén radius is less than its light cylinder radius. This corresponds to \( L_x \gtrsim 10^{30} \text{ erg s}^{-1} \), and is right at the boundary of detectability in our off-state observation given the upper limit \( L_{0.3-8\text{keV}} \lesssim 7.7 \times 10^{29} \text{(d/1.3 kpc)}^2 \text{ erg s}^{-1} \), found in Section 4.3. However, since the distance estimate to PSR J1832+0029 made using the Cordes & Lazio (2002) electron density model can be uncertain by factors of two or more (see, e.g., Deller et al. 2009), we cannot therefore conclusively reject this scenario as an explanation for the behavior observed in PSR J1832+0029.

### 4.5. How Common are Intermittent Pulsars?

Regardless of the form of the mechanism for pulsar intermittency, its recognition and characterization through the three pulsars so far poses interesting questions as to the size of the likely population of similar objects in the Galaxy. From our sampling of PSR J1832+0029 so far, it appears to spend approximately 50% of the time in the off-state. Similar considerations for PSRs B1931+24 and J1841−0500 imply similar off-state duty cycles. Because these and similar pulsars are less likely to be on during pulsar search and confirmation observations, as noted by Kramer et al. (2006), they could represent a substantial population that has so far evaded detection. PSR J1841−0500, for

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\(^{10}\) http://asc.harvard.edu/toolkit/pimms.jsp
example, was in an off-state during the closest PMPS observation, and was only discovered serendipitously during a search of a magnetar in the same telescope beam (Camilo et al. 2012). In addition to intermittent pulsars evading discovery in large-scale surveys, since a significant fraction of the ~1700 non-recycled pulsars currently known are not subject to long-term timing programs, it is currently unclear as to what fraction of these could exhibit intermittency on long timescales. Even the prototypical object B1931+24 evaded characterization for almost 20 years after its discovery (Stokes et al. 1985). For PSR J1832+0029, had the initial Parkes timing observations spanned a period of a year and no off-state seen, it is possible that the intermittent behavior would have evaded detection. Perhaps the majority of normal pulsars exhibit some form of intermittent behavior, if they are studied long enough. If that is the case, then current estimates of the pulsar birthrate would need to be upwardly revised by a factor of two. The impact of the discovery of intermittent pulsars on our understanding of the neutron star birth rate (see, e.g., Keane & Kramer 2008) is a currently unsolved problem which merits further investigation.

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