Timing Behavior of the Magnetically Active Rotation-Powered Pulsar in the Supernova Remnant Kesteven 75

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ABSTRACT

We report a large spin-up glitch in PSR J1846−0258 which coincided with the onset of magnetar-like behavior on 2006 May 31. We show that the pulsar experienced an unusually large glitch recovery, with a recovery fraction of $Q = 5.9 \pm 0.3$, resulting in a net decrease of the pulse frequency. Such a glitch recovery has never before been observed in a rotation-powered pulsar, however, similar but smaller glitch over-recovery has been recently reported in the magnetar AXP 4U 0142+61 and may have occurred in the SGR 1900+14. We discuss the implications of the unusual timing behavior in PSR J1846−0258 on its status as the first identified magnetically active rotation-powered pulsar.

Subject headings: pulsars: general—pulsars: individual (PSR J1846−0258)—X-rays: stars

1. Introduction

PSR J1846−0258 is a young (∼800 yr), 326 ms pulsar, discovered in 2000 with the *Rossi X-ray Timing Explorer* (*RXTE*; Gotthelf et al. 2000). No radio pulsations have been

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detected despite deep searches (Kaspi et al. 1996; Archibald et al. 2008). PSR J1846−0258 has a large inferred magnetic field of $B \simeq 5 \times 10^{13}$ G, above the quantum critical limit, and a braking index of $n = 2.65 \pm 0.01$ (Livingstone et al. 2006, hereafter LKGK06). The pulsar was therefore believed to be simply a high-magnetic field rotation-powered pulsar (RPP), with radio pulsations that do not cross our line of sight. However, in 2006 May, the source experienced a series of X-ray bursts and a sudden increase in X-ray flux, which point to magnetic activity in the source (Gavriil et al. 2008; Kumar & Safi-Harb 2008; Ng et al. 2008).

A magnetar is a neutron star whose magnetic energy powers the bulk of its emission (Thompson & Duncan 1995), while a RPP produces radiation that is powered via the loss of rotational kinetic energy (e.g. Manchester & Taylor 1977). PSR J1846−0258 is a unique transition object between these two source classes. The X-ray luminosity of PSR J1846−0258 can be entirely accounted for by the spin-down power of the pulsar, however, the observed X-ray bursts and flux flare are phenomena only seen thus far from magnetars (Gavriil et al. 2008).

Neutron star glitches are defined as a sudden, usually unresolved, increase in spin frequency, ν. Glitches are often accompanied by an increase in the frequency derivative, $\dot{\nu}$, and are sometimes followed by an exponential decay on timescale τ_d, where some of the initial jump in ν is recovered. In general, a glitch at time t_g can be modeled as:

$$\nu(t) = \nu_0(t) + \Delta\nu_p + \Delta\nu_d e^{-(t-t_g)/\tau_d} + \Delta\dot{\nu}(t - t_g), \tag{1}$$

where $\nu_0(t)$ is the frequency of the pulsar prior to the glitch and $\Delta\nu$ is the initial frequency jump, which can be decomposed into the part of the glitch that is permanent, $\Delta\nu_p$, and that which decays, $\Delta\nu_d$. The recovery fraction is defined as $Q \equiv \Delta\nu_d/\Delta\nu$. The variety of observed pulsar glitches is interesting. The fractional magnitude of the observed change in ν ranges over 5 orders of magnitude from $10^{-11} < \Delta\nu/\nu < 10^{-5}$ (Lyne et al. 2000; Janssen & Stappers 2006; Hobbs et al. 2002). Some glitches are characterized only by a ν increase (e.g. PSR B1758−23; Shemar & Lyne 1996), while some glitches (typically in young pulsars) are dominated by a change in $\dot{\nu}$. Some glitches decay on timescales of ∼days (e.g. Flanagan 1990), while others display very long decay time scales (∼ hundreds of days; Wang et al. 2000). The fraction of the glitch that decays is also highly variable. In older pulsars the amount of glitch recovery is typically small ($Q << 1$, Shemar & Lyne 1996) while in the Crab pulsar the recovery can be nearly complete (e.g. $Q \sim 0.96$, Lohsen 1981). However, in many glitches, no recovery is detected.

Glitches are now known to be ubiquitous in magnetars as well as rotation-powered pulsars (Kaspi et al. 2000; Kaspi & Gavriil 2003; Dall'Osso et al. 2003; Dib et al. 2008a; Gavriil et al. 2009). What remains to be seen is whether glitches have the same physical origin in both types of objects, or if the super-critical magnetic fields of magnetars are responsible for different glitch origins and evolutions. While some magnetar glitches are indistinguishable from those observed in RPPs, others occur contemporaneously with radiative changes such as bursts, flux enhancements and spectral or pulse profile variations, such as in the Anomalous X-ray Pulsar (AXP) 1E 2259+586 (Kaspi et al. 2003). No radiative changes have been observed with RPP glitches (e.g. Helfand et al. 2001). RPP glitches are believed to arise from a sudden unpinning of vortices in the superfluid interior crust of the pulsar (e.g. Alpar et al. 1993). Magnetar glitches, on the other hand, may be triggered by strong internal magnetic fields as the crust is deformed, either plastically or cracked violently (Thompson & Duncan 1996).

In this paper, we discuss the timing behavior of PSR J1846−0258 prior to, during, and following the period of magnetic activity observed in 2006. We show that a large glitch occurred contemporaneous with the X-ray bursts and onset of the flux flare. We also show that the glitch recovery is very unusual for a RPP but is reminiscent of timing behavior observed from magnetars and is further evidence of magnetic activity in PSR J1846−0258.

2. *RXTE* Observations and Analysis

Observations of PSR J1846−0258 were made using the Proportional Counter Array (PCA; Jahoda et al. 1996; Jahoda et al. 2006) on board *RXTE*. The PCA consists of an array of five collimated xenon/methane multi-anode proportional counter units (PCUs) operating in the 2 – 60 keV range, with a total effective area of approximately 6500 cm^2 and a field of view of $\sim 1^\circ$ FWHM.

Our entire *RXTE* data set spans 9.7 yr from 1999 April 18 through 2008 December 10 (MJD 51286 – 54810). Data from 2000 January 31 - 2005 July 27 (MJD 51574 – 53578) were reduced and analyzed previously and details can be found in LKGK06. Eleven observations taken in 1999 April 18-21 are of limited use for the current analysis since they cannot be unambiguously phase connected to the rest of the data. Analysis of data spanning 2005 July 27 - 2008 December 10 (MJD 53578 – 54810) is presented here. Data were collected in "GoodXenon" mode, which records the arrival time (with 1-μs resolution) and energy (256 channel resolution) of every unrejected event. Typically, 2-3 PCUs were operational during an observation. We used all 3 layers of each operational PCU in the 2–60 keV range, as this maximizes the signal-to-noise-ratio for this source.

Observations were downloaded from the HEASARC archive[2] and data from each active PCU were merged and binned at (1/1024) s resolution. Photon arrival times were converted to barycentric dynamical time (TDB) at the solar system barycenter using the J2000 source position RA = $18^{\rm h}46^{\rm m}24\overset{\rm s}{.}94 \pm 0\overset{\rm s}{.}01$, Dec = $-02°58'30.1'' \pm 0.2''$ (Helfand et al. 2003) and the JPL DE200 solar system ephemeris.

The known ephemeris from LKGK06 was used to fold each time series with 16 phase bins. Resulting profiles were cross-correlated in the Fourier domain with a high signal-to-noise ratio template created by adding phase-aligned profiles from all observations. The cross-correlation process assumes that the pulse profile is stable; indeed, we found no evidence for variability that could bias TOA measurement, as shown in Figure 1, and confirmed by Kuiper & Hermsen (2009). The figure shows average profiles from before, after, and throughout the outburst and unusual timing behavior. For each observation, the cross-correlation yielded the time of arrival (TOA) of phase-zero of the average pulse profile at the fold epoch. The TOAs were fitted to a timing model (see §3) using the pulsar timing software package TEMPO[3]. After phase-connecting the data, we merged observations occurring on a single day and used the ephemeris to re-fold the data in order to obtain more precise TOAs. This process produced 178 TOAs with a typical uncertainty ~9 ms (~2.7% of the pulse period). Further details of the observation and analysis are given in LKGK06.

3. Timing Analysis and Results

Phase-coherent timing is a powerful method for obtaining accurate pulsar parameters, but can only be used when timing noise and glitches are relatively small (e.g. Livingstone et al. 2005). To obtain a phase-coherent timing solution, each turn of the pulsar is accounted for by fitting TOAs with a Taylor expansion of the pulse phase (Lyne & Smith 2005).

Phase-coherent timing for PSR J1846−0258 spanning 2000 January 1 – 2005 July 27 (MJD 51574–53578) is discussed in LKGK06. Phase coherence was maintained for the next 308 days without incident. Phase coherence was lost with the observation occurring on 2006 May 31 (MJD 53886) which contained 4 X-ray bursts and a pulse flux increase (Gavriil et al. 2008). For the following 32 observations spanning 192 days, no unambiguous phase coherent timing solution was possible. Instead, we performed periodograms to determine the pulse frequency. Uncertainties were determined from a Monte Carlo simulation, where noise was

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[2] http://heasarc.gsfc.nasa.gov/docs/archive.html

[3] http://www.atnf.csiro.au/research/pulsar/tempo

added to simulated sinusoidal pulses and the frequency for each trial was determined in the same way as for the real data. Phase coherence was once again obtained starting 2007 January 26 (MJD 54126) with closely spaced bootstrapping observations after the source reappeared from behind the Sun after 48 days. A single phase coherent timing solution was obtained spanning 2007 January 26 – 2008 December 10 (MJD 54126–54810). This timing solution is severely contaminated by long-term glitch recovery and timing noise, so the fitted parameters for the global solution are of limited value.

To analyze the long-term rotational behavior of the pulsar, we created short phase-coherent timing solutions from 2000 until the onset of bursts, and from 2007 and 2008. Each timing solution included only ν and $\dot{\nu}$, and included as much data as possible while requiring the reduced χ^2 value of the fit to be $\sim$1. This resulted in 10 measurements of ν and $\dot{\nu}$ pre-glitch and 11 measurements post-glitch. In order to better utilize the available data in the post-glitch period, we created overlapping short data sets, each of which used approximately half the data from two of the above described short data sets, and has the same fitted parameters and χ^2 requirements. This can be useful because the short coherent data sets result in parameter fits that are dominated by the end points, which can be problematic when ν is varying rapidly from glitch recovery as in this case, or when timing noise is a significant effect. This produces an additional 9 post-glitch measurements of ν and $\dot{\nu}$. Coherent frequency measurements (crosses), overlapping frequency measurements (filled circles) and frequency measurements obtained via periodograms (open circles), are plotted in the top panel of Figure 2, with the pre-burst ν, $\dot{\nu}$ and $\ddot{\nu}$ removed. The middle panel of Figure 2 shows measurements of $\dot{\nu}$ from the short coherent timing solutions as crosses, with the overlapping $\dot{\nu}$ measurements in filled circles. In addition, three measurements of $\dot{\nu}$ are calculated from weighted least-squares fits of five periodogram measurements in open circles.

A sudden frequency increase is apparent in the frequency residual plot (top panel, Fig. 2), indicating that a glitch occurred (also noted by Kuiper & Hermsen 2009). A sudden increase in the magnitude of $\dot{\nu}$ is also apparent (middle panel). Following the frequency increase, we note a remarkable period of strongly enhanced spin-down, visible both as a rapid decrease in ν, and increase in $\dot{\nu}$ (top and middle panels, Fig. 2).

We fitted the measured frequencies of PSR J1846−0258 with an exponential recovery glitch model (Eq. 1), the results of which are shown in Figure 3. The top panel of the Figure shows frequency measurements with pre-glitch ν, $\dot{\nu}$, $\ddot{\nu}$ removed (as in Figure 2), while the bottom panel shows residuals from the glitch fit. The uncertainties from the periodogram measurements of ν are $\sim$ 2 orders of magnitude larger than those from short coherent fits to the data and thus contribute minimally to the overall χ^2 value. Thus the glitch residuals (bottom panel, Fig. 3) are shown to highlight the deviation of the coherent frequencies from the fit which dominate the χ^2. The fitted value of the initial fractional frequency increase is $\Delta\nu/\nu = 6.2(3) \times 10^{-6}$, very large for such a young pulsar. More remarkable yet, however, is the amount by which the frequency recovers. We find $Q = 5.9(3)$. All fitted glitch parameters are given in Table 1. Significant deviations from the fit can be seen during the period of glitch recovery, giving rise to the large reduced χ^2 value of ~ 326 for 47 degrees of freedom for the best fit (bottom panel, Fig. 3). Quoted uncertainties on the glitch parameters are from $\Delta\chi^2 = 1$ contours, but should be understood as approximations because the fitted model is not a satisfactory description of the data, as indicated by the very large value of ${\chi^2}_\nu$. While the deviation from the exponential fit is very significant for several months, the overall evolution after the glitch is dominated by the exponential recovery: the deviation from the fit is ~2 orders of magnitude smaller than the overall post-glitch decrease in ν. The deviation from exponential recovery may well have been larger in the period just following the glitch, however, the large uncertainties on the periodogram measurements of ν ($\sim 10^{-6}$ Hz) prevent any firm conclusion. However, since the corresponding pulse TOAs cannot be unambiguously phase-connected, it is likely that large variations in ν and $\dot{\nu}$ occurred during the 240-day period between the glitch epoch and when we regained phase-coherence. It is also possible that a second, smaller glitch ($\Delta\nu/\nu < 10^{-7}$) occurred during this period. The observed deviation from the exponential recovery decreases as the glitch recovers. Thus, in the closing months of 2008, the pulsar was rotating very regularly again, similar to its pre-glitch behavior.

Figure 4 shows post-glitch phase-coherent measurements of $\dot{\nu}$ (a subset of the $\dot{\nu}$ measurements shown in the middle panel of Figure 2). The pre-glitch measurements are excluded here for clarity. The solid line is the derivative of the glitch model fitted to the ν measurements, clearly showing that there is significant deviation. The overall effect of the glitch recovery on $\dot{\nu}$ is clear, however, from MJD 54100-54300 the $\dot{\nu}$ measurements deviate from the exponential recovery by $\sim 0.15\%$. The effect of this anomalous change in $\dot{\nu}$ is not directly evident in the measurements of ν (which are dominated by the exponential recovery) but does help explain why the exponential glitch fit is not a satisfactory description of the data, and is clear in the residuals of the glitch fit in the bottom panel of Figure 2.

4. Bursts and pulsed flux

The glitch during PSR J1846−0258's outburst was accompanied by a major pulsed flux enhancement (Gavriil et al. 2008). In order to quantify the radiative properties of the source during the glitch recovery, we extracted its pulsed flux using all available *RXTE* observations. First, we generated separate event lists for each PCU in FITS[4] format using the standard `FTOOLS`[5]. We then filtered our event lists such that we only preserved photons in the 2–60 keV band and from all Xenon layers alone. The photon arrival times were then barycented using the source's position and the JPL DE200 solar system ephemeris. We folded our filtered barycented photon arrival times using the ephemeris determined in our phase-coherent timing analysis using 16 phase bins. Using the folded profiles, we calculated the RMS pulsed flux in each PCU using the Fourier method described by Woods et al. (2004) keeping only the contribution from the 1st harmonic given the source's sinusoidal profile. Not all the observations were pointed at PSR J1846−0258, therefore we corrected for the reduced efficiency in each PCU due to the offset pointing using the collimator response of each PCU and the instrument attitude files. Finally, we averaged the pulsed flux in each PCU weighted by the fractional exposure of each PCU. We excluded the contribution PCU 0 because of the loss of its propane layer and of the numerous amounts of detector breakdown events. Our pulsed flux time series is presented in the bottom panel of Figure 2. The event lists for each PCU created for the pulsed flux analysis were binned into 31.25 ms lightcurves and were searched for bursts using the burst search algorithm introduced in Gavriil et al. (2002). No additional bursts were found other than the 5 reported in Gavriil et al. (2008).

We checked for a correlation between torque and pulsed flux by plotting the pulsed flux against the spin frequency derivative in log-log space, as shown in Figure 5. All measurements of $\dot{\nu}$ before and after the glitch and bursts are shown, including those made from weighted least squares fits of periodogram measurements of the frequency. The plot shows that there is a correlation between flux and torque while both parameters are extreme. Fitting a power law to the data gives a power law index of 7.4 ± 0.7. However, excluding the 3 $\dot{\nu}$ measurements made from periodogram measurements with relatively large uncertainties, and considering only the much more precise $\dot{\nu}$ meausurements made from phase-coherent timing, no correlation between flux and $\dot{\nu}$ is found. The observed variations in $\dot{\nu}$ during the phase connected period, however, are only at the $\sim 3\%$ level, while the variation in $\dot{\nu}$ immediately following the glitch are at the $\sim 15\%$ level. Correspondingly small fluctuations in pulsed flux are not detectable in these data.

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[4] http://fits.gsfc.nasa.gov

[5] http://heasarc.gsfc.nasa.gov/docs/software/ftools/

5. Discussion

5.1. Glitch properties

Four X-ray bursts in PSR J1846−0258 coincided with the onset of a flux flare on 2006 May 31 (MJD 53886). The pulsed flux decayed over ∼2 months and reached quiescence around the time of the fifth burst on 2006 July 27 (MJD 53943) (Gavriil et al. 2008). Significant spectral changes also occurred (Gavriil et al. 2008; Kumar & Safi-Harb 2008; Kuiper & Hermsen 2009) and flux enhancement up to 300 keV was observed (Kuiper & Hermsen 2009). Contemporaneous with the sudden change in the X-ray emission from PSR J1846−0258, we observed a large glitch with an initial frequency increase of $\nu = 1.9(1) \times 10^{-5}$. The glitch decayed over 117(1) days, with a recovery fraction of $Q = 5.9(3)$, resulting in a net decrease of the pulse frequency of $\Delta\nu = 9.392(7) \times 10^{-5}$ Hz. Furthermore, the timing behavior during the period of recovery is not well modeled by a simple exponential function and measurements of $\dot{\nu}$ in particular are suggestive of a high level of timing noise for several hundred days following the glitch.

This glitch and subsequent recovery reinforces that PSR J1846−0258 underwent a period of magnetic activity in 2006. This glitch is entirely different from the previous glitch in this source, which was radiatively silent, small in magnitude ($\Delta\nu/\nu = 2.5(2) \times 10^{-9}$), dominated by a change in $\dot{\nu}$ ($\Delta\dot{\nu}/\dot{\nu} = 9.3(1) \times 10^{-4}$), and had no measurable recovery (LKGK06). This small glitch is very similar to those observed in the Crab pulsar (e.g. Wong et al. 2001) and other very young rotation-powered pulsars such as PSR B0540−69 (Livingstone et al. 2005). It is unusual to have two such disparate initial $\Delta\nu$ magnitudes in the same source, particularly in such a young pulsar, though this has been seen in some older pulsars such as PSR B1737−30, which has glitch magnitudes spanning four orders of magnitude (Lyne et al. 2000; Janssen & Stappers 2006). In fact, this is the largest glitch ever observed in any of the pulsars with characteristic ages less than ~ 2 kyr (the Crab pulsar, B0540−69, B1509−59, and J1119−6127), none of which have experienced glitches with fractional magnitudes larger than $\Delta\nu/\nu \sim 10^{-8}$.

The glitch reported here has a recovery fraction of $Q = 5.9 \pm 0.3$. $Q > 1$ implies that the net frequency change after the glitch recovery is negative, as shown in Figure 2. A similar effect was recently observed in the AXP 4U 0142+61, though with much smaller magnitude of $Q = 1.07 \pm 0.02$ (Gavriil et al. 2009). The negative change in ν resulting from the over-recovery of the PSR J1846−0258 glitch is similar in magnitude to the unresolved timing event seen in the magnetar SGR 1900+14, contemporaneous with the giant flare in 1998 (Woods et al. 1999). In that case, an enhanced spin-down of the magnetar was observed over 4 months. Well spaced timing observations around the time of the giant flare were not available, so no glitch could be resolved, if indeed one occurred. They attribute the observed behavior to one of two possibilities. The first is an increase in the magnitude of $\dot{\nu}$ by a factor of ~ 2.3, persisting for ~ 80 days. The second is that a negative glitch, that is, a sudden spin-down occurred, with magnitude $\Delta\nu/\nu \simeq 1 \times 10^{-4}$ (Thompson et al. 2000). However, a timing event similar to that observed in PSR J1846−0258 provides an equally good description of the data. It is curious, however, that such similar fractional changes in ν should occur in two sources that experienced such disparate radiative changes, with the energy output from SGR 1900+14 several orders of magnitude larger than from PSR J1846−0258.

AXP 1E 2259+586 experienced a glitch contemporaneous with 80 X-ray bursts, a flux flare and pulse profile changes in 2002 (Kaspi et al. 2003; Woods et al. 2004). The observed glitch was not well described by a single exponential, as is the case for PSR J1846−0258. The addition of an exponential growth component was required to adequately describe the data. However, the addition of a similar term to the glitch fit for PSR J1846−0258 does not provide a significant improvement to our fit. Interestingly, the flux enhancement observed in 1E 2259+586 lasted much longer (> 2 yr; Zhu et al. 2008) than the glitch recovery time scale ($\tau_d \sim 16$ days), whereas the reverse is true for PSR J1846−0258, with $\tau_d = 117$ days and a flux decay timescale of 55.5 ± 5.7 days (Gavriil et al. 2008). The 1E 2259+586 event can also be distinguished from the PSR J1846−0258 glitch in that its recovery fraction is much smaller, with $Q \simeq 0.19$. In 2001, the AXP 1RXS J170849.0−400910 also experienced a glitch with recovery that was not well described by a simple exponential, and not improved with the addition of a second exponential term (Kaspi & Gavriil 2003; Dall'Osso et al. 2003; Dib et al. 2008a). Woods et al. (2004) argued that it is unlikely that 1RXS J170849.0−400910 experienced bursts or a pulsed flux flare associated with this glitch because a flux flare would have had to decay on a time scale less than the glitch decay time scale. However, this is exactly the behavior observed from PSR J1846−0258, albeit with a much longer glitch decay time scale. Long-term spectral changes and flux variations have been claimed in 1RXS J170849.0−400910 (Rea et al. 2005; Campana et al. 2007; Israel et al. 2007b).

An interesting characteristic of some AXP glitches is a period of enhanced spin-down immediately following the glitch, as observed in 1E 1841−045, 1RXS J170849.0−400910, and 1E 2259+586 (Kaspi & Gavriil 2003; Dib et al. 2008a). The instantaneous spin-down at the time of the glitch can be quantified as $\dot{\nu}_{\rm inst} = \Delta\nu_d/\tau_d$ (found by taking one derivative of Eq. 1 and setting $t = 0$). For the 1E 2259+586 glitch, this is $\dot{\nu}_{\rm inst} = (8.2 \pm 0.6)\dot{\nu}$, while a typical value for a RPP is $\sim 0.005\dot{\nu}$ (Peralta 2006, catalog). For PSR J1846−0258 the instantaneous spin-down is $\dot{\nu}_{\rm inst} = 0.14\dot{\nu}$, larger than for any RPP glitch, but not as large as those measured for AXPs. It should be noted, however, that an enhanced spin-down is not observed in every AXP glitch.

In PSR J1846−0258, there is evidence for a ~200-day interval where $\dot{\nu}$ deviates significantly from an exponential glitch recovery, and it is possible that further significant deviation occurred during the 240-day period of unconnected data directly following the glitch. Perhaps $\dot{\nu}$ is varying in a stochastic fashion similar to that observed in the AXP 1E 1048.1−5937 (Gavriil & Kaspi 2004; Dib et al. 2008b). In this AXP, a ~year-long period of rapid $\dot{\nu}$ variations followed a large pulsed flux flare and a possible glitch in 2002. Another glitch in 2007 coincided with the onset of a pulsed-flux flare, again followed by stochastic variations in $\dot{\nu}$. Another similarity between these sources is that the flux enhancement decayed away long before the timing variations subsided. Alternatively, perhaps the variations are more simply attributed to timing noise, as is seen in many young RPPs. The behavior remains unusual however, since this is qualitatively very different from the mild timing noise observed in PSR J1846−0258 prior to magnetic activity, and such a large change in timing noise behavior is unprecedented among RPPs.

An estimate of the change in rotational kinetic energy of the pulsar from the glitch can be obtained by treating the star as a solid rotating body. Assuming a typical moment of inertia of $10^{45}\,\mathrm{g\,cm^2}$, the energy deposited in the crust at the time of the glitch due to the increase in ν is $\sim 2 \times 10^{42}$ ergs, while the energy lost due to the over-recovery of ν in the glitch aftermath is $\sim 1 \times 10^{43}$ ergs, both of which are larger than the energy estimated to have been released in the bursts and flux flare of $(3.8-4.8) \times 10^{41} (d/6\mathrm{kpc})^2$ ergs (2–60 keV). A new estimate of the distance to pulsar of ~10 kpc (Su et al. 2009) increases the amount of energy contained in the radiative outburst to $(1.1-1.3) \times 10^{42} (d/10\mathrm{kpc})^2$ ergs (2–60 keV). For either distance however, this stands in contrast to the bursts and glitch from 1E 2259+586, for which the energy contained in the glitch was ~2 orders of magnitude less than the energy contained in the bursts and flux flare.

5.2. Physical models for ‘magnetic glitches’

Rotation-powered pulsar glitches are thought to arise from differential rotation in the neutron star, where the crust contains superfluid neutrons rotating more rapidly than the surrounding matter (e.g. Alpar et al. 1984; Alpar & Pines 1993). The angular momentum of a rotating superfluid is quantized in vortices which are thought to be become pinned to nuclei in the star's crust. The vortex lines are therefore under extreme stresses due to the differential rotation between the crust and the superfluid. It is thought that the vortex lines experience sudden unpinning, resulting in the transfer of angular momentum to the crust, observed as an increase in the spin-frequency of the neutron star. Magnetar glitches may instead be triggered by strong internal magnetic fields as the crust is deformed, either plastically or cracked violently (Thompson & Duncan 1996). This idea is supported by the large number of glitches now observed to occur at the same epoch as magnetically powered radiative events, such as bursts and flares (e.g. Kaspi et al. 2003; Dib et al. 2008b; Israel et al. 2007a).

The physics underlying glitches with $Q > 1$ is unclear. The classical glitch model of vortex unpinning in the superfluid crust of the neutron star does not readily produce such dramatic glitch recoveries. One possibility is that some parts of the superfluid are in fact rotating more slowly than the crust. Then the initial ν increase would be from a transfer of angular momentum from a more rapidly rotating region of the superfluid to the crust, which is then followed by a transfer of angular momentum from the crust to the more sluggish region of the superfluid. This is the explanation put forward by Thompson et al. (2000) to explain the net spin-down event in SGR 1900+14. They argue that regions of slowly rotating superfluid can occur in magnetars because vortex motion is dominated by advection across the neutron star surface by the deforming crust and that gradual plastic deformation of the neutron star crust will cause the superfluid to rotate more slowly than the crust. However, it is not clear whether such behavior is expected in a neutron star with a magnetic field of $\sim 5 \times 10^{13}$ G, spinning relatively rapidly compared to the magnetars.

That the recovery of the PSR J1846−0258 glitch so far overshoots the initial frequency increase is suggestive of an external torque following the glitch. Previous evidence for an external torque includes the large fraction of the moment of inertia implied to have decoupled in the 1E 2259+586 glitch. However, this may also be explained with a core glitch, that is, where the core of the pulsar (and thus a large fraction of I) decouples temporarily from the crust (Kaspi & Gavriil 2003; Woods et al. 2004). In PSR J1846−0258, however, the post-glitch relaxation amplitude is much greater than the initial glitch amplitude, strongly supporting the idea that the post-glitch spin-down behavior results from an external source.

One possibility is that a magnetic field twist responsible for the X-ray bursts and flux enhancement also affects the spin-down of the pulsar. In this case the observed recovery is driven by the propagation of magnetic field untwisting (similar to a shock wave) through the magnetosphere. During this process, the spin-down of the star may increase because the effective magnetic field has increased. When the 'shock' reaches the light cylinder, which can take place on few month time scales, the spin-down should return to its pre-burst value (Beloborodov 2008). This theory also allows for non-monotonic behavior in the spin-down after an event, as observed in both AXP 1E 1048.1−5937 (Gavriil & Kaspi 2004; Dib et al. 2008b) and PSR J1846−0258. This model allows for a delay between flux variations and the onset of timing variability, as was observed in 1E 1048.1−5937, though not observed in PSR J1846−0258. However, as in the model of variably rotating superfluid, it is not immediately clear how the more rapid rotation and smaller magnetic field affect the relevance of this model.

Alternatively, it has been proposed that fallback disks from the supernova explosion creating the neutron star could be interacting with magnetars and be responsible for some of the observed emission (e.g. Chatterjee et al. 2000; Alpar 2001). In this case, the initial X-ray bursts could irradiate a fossil disk commencing a period of disk activity. The interaction between the neutron star and a disk could cause the enhanced spin-down, which would decay as the disk cooled. However, in the framework of this model, it is difficult to understand how accretion causing variations in the spin-down rate could continue for so much longer than the pulsed-flux enhancement.

5.3. Magnetar and High-B Radio Pulsar Properties

Another RPP, PSR J1119−6127, has very similar properties to PSR J1846−0258. Its P, $\dot{E}$, and τ_c are all similar, and notably, it has a similarly large magnetic field of $B = 4.1\times10^{13}$ G (Camilo et al. 2000). This pulsar has shown some indication of unusual X-ray emission (Gonzalez et al. 2005). No magnetospheric X-ray emission is detected, but thermal pulsations with a $\sim$ 75% pulsed fraction and a large surface temperature are detected. No direct evidence of magnetic activity (i.e. bursts or flux enhancements) is present in this pulsar. Given the similarities between PSR J1119−6127 and PSR J1846−0258, both, as well as other high B-field RPPs should be monitored for similar magnetic activity. Currently, such a monitoring program in ongoing with *RXTE*.

PSR J1846−0258 may be related to the transient AXPs (TAXPs). PSR J1846−0258 appears to be a typical RPP for $\geq$ 95% of the time, with brief periods of magnetic activity occurring approximately once a decade. The TAXP XTE J1810−197 increased in brightness by a factor of $\sim$ 100 and was subsequently visible for several years as a pulsed X-ray source (Ibrahim et al. 2004; Halpern & Gotthelf 2005). Another TAXP, 1E 1547−5408 was detected as a pulsed radio source after an X-ray outburst in which the flux increased by at least a factor of 16 (Camilo et al. 2007). Interestingly, both XTE J1810−197 and 1E 1547−5408, two *bona fide* TAXPs, are the only two magnetars with detected radio pulsations. By contrast, no radio pulsations have been detected from PSR J1846−0258 despite extensive searches both before and after the magnetic activity (Kaspi et al. 1996; Archibald et al. 2008).

6. Conclusions

In *RXTE* observations of PSR J1846−0258, we have observed a large glitch with an unusual quasi-exponential over-recovery of ν and substantial timing noise contemporaneous with X-ray bursts and a flux increase. These observations strengthen the tie between magnetic activity in neutron stars and unusual glitch activity, as has been previously noted (e.g., Dib et al. 2008a). A glitch with recovery fraction $Q > 1$ has never before been observed from a rotation-powered pulsar and is not compatible with the standard model of pulsar glitches. This unusual glitch recovery, taken together with radiative changes contemporaneous with this, and some AXP glitches, provides the best evidence that there are physical differences between typical RPP glitches and some glitches observed in magnetars.

Ongoing timing observations of PSR J1846−0258 are required to obtain a deterministic post-outburst braking index measurement that is uncontaminated by long-term glitch recovery. A measurement of the braking index for this source after outburst is of considerable interest as a change would strongly suggest that a magnetic reconfiguation occurred at the time of the outburst.

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