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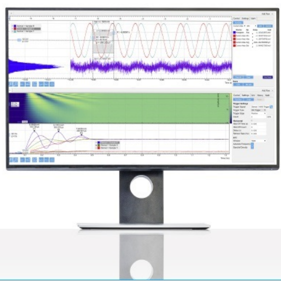

Post-outburst timing of the magnetically active pulsar J1846−0258

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Abstract.
The ∼800 yr-old pulsar PSR J1846-0258 in the supernova remnant Kes 75 is a unique transition object between rotation-powered pulsars and magnetars. While it typically behaves as a rotation-powered pulsar, in 2006 it exhibited a distinctly magnetar-like outburst accompanied by a large glitch with an unusual over-recovery. We present X-ray timing observations taken with the *Rossi X-ray Timing Explorer* after the X-ray outburst and accompanying glitch had recovered. We observe that the braking index of the pulsar, previously measured to be $n = 2.65 \pm 0.01$ has decreased by $18 \pm 5\%$. We also note a persistent increase in the timing noise relative to the pre-outburst level, reminiscent of behavior previously observed from some magnetars.

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INTRODUCTION

PSR J1846−0258 is a 326 ms, $\sim$ 800 yr-old X-ray pulsar [1] that usually exhibits properties common to rotation powered-pulsars, including powering a pulsar wind nebula (PWN). The pulsar has a large magnetic field of $B = 5 \times 10^{13}$ G, and is one of the few with a measured braking index [$n \equiv \nu\ddot{\nu}/\dot{\nu}^2 = 2.65 \pm 0.01$, where ν is the spin-frequency, and $\dot{\nu}$ and $\ddot{\nu}$ its derivatives; 2]. Measured braking indices fall in the range $1.4 < n < 2.84$ [3, 4, 5, 6], all less than $n = 3$ as predicted for vacuum magnetic dipole radiation [e.g. 7]. Possible explanations for $n < 3$ include an increasing magnetic moment [e.g. 8] or the effects of magnetospheric plasma [e.g. 9]. Timing observations of PSR J1846−0258 over 7 yr showed largely steady rotation (allowing for the measurement of n) and one small glitch [2]. Thus, other than lacking radio pulsations [typically assumed to be due to beaming 10] and its large B-field, PSR J1846−0258 behaved similar to other young, Crab-like pulsars.

Unexpectedly, in May 2006 PSR J1846−0258 experienced distinctly magnetar-like behavior: it displayed 5 X-ray bursts, a sudden increase in X-ray flux and the appearance of a blackbody component [11, 12, 13]. Coincident with the radiative outburst was a large glitch [$\Delta\nu/\nu \sim 4 \times 10^{-6}$, 14], followed by a unique over-recovery of the spin-up by a factor of ∼9, resulting in a net spin-down of the pulsar [15].

Because PSR J1846−0258 has a measurable braking index and magnetic activity, it

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presents the first opportunity to explore the relationship between magnetar-like behavior and deterministic spin-down in neutron stars.

OBSERVATIONS AND ANALYSIS

PSR J1846−0258 has been observed with the proportional counter array aboard the *Rossi X-ray Timing Explorer* (*RXTE*) since 1999. Photons in the 2–20 keV energy range are folded and resulting profiles are cross-correlated with a template to produce times of arrival. These are fitted phase-coherently with a timing model using the timing package `TEMPO`[1]. Full analysis details are given in [16] and references therein.

For all data between 2000 and 2010, we created short phase-coherent timing solutions fitting for only ν and $\dot{\nu}$. Figure 1 (left panel) shows the resulting $\dot{\nu}$ measurements. From 2000-2006 May, $\dot{\nu}$ increased regularly, except at the small glitch in 2001, which was not accompanied by detectable recovery or change in slope [implying constant $n = 2.65$ across the event 2]. The large glitch (visible as a dramatic decrease in $\dot{\nu}$ in the left panel of Fig. 1), followed by a non-monotonic recovery throughout 2007. The increase in timing noise and glitch relaxation had largely recovered by the beginning of 2008, as shown in the Figure.

In order to examine the relationship between spin down and the outburst, we aimed to measure n in the post-outburst era. In order to minimize the effect of the glitch recovery on a measurement of n, we discarded timing data before 2008, where the glitch recovery and timing noise dominate (see Fig.1, left). We performed a weighted least-squares fit to 16 $\dot{\nu}$ measurements spanning 2008 January – 2010 April, shown in the inset of Figure 1 (left). Given the scatter in the post-burst $\dot{\nu}$ measurements and the known effects of timing noise, it is likely that the formal uncertainties underestimate the true values. Thus, to better estimate the uncertainty on $\ddot{\nu}$, we used a bootstrap error analysis [17]. This results in $\ddot{\nu} = 3.13(19) \times 10^{-21}\,\mathrm{s}^{-3}$, corresponding to $n = 2.16 \pm 0.13$. This is smaller than the pre-outburst value of $n = 2.65 \pm 0.01$ at the 3.8σ level. Thus, the braking index decreased by $\Delta n = -0.49 \pm 0.13$, following the period of magnetar-like activity in 2006, implying the first significant measurement of a variable braking index. Other measurements of n thus far are comparatively steady, e.g. the Crab pulsar varies by about 5% over 30 yr of observations [3].

Qualitatively, the timing noise in the 2.2-yr period used to obtain the post-burst measurement of n is larger than that observed prior to the outburst, though much smaller than in the initial aftermath of the outburst, when no phase-coherent timing solution was possible.

In order to quantify this, we used an analog to the well-known measure of timing noise, the Δ_8 parameter, defined as the contribution to the rotational phase of the pulsar from a measurement of $\ddot{\nu}$ over a period of 10^8 s, assuming that $\ddot{\nu}$ is entirely dominated by timing noise [18]. This parameter is uninteresting when $\ddot{\nu}$ is dominated by secular spin-down, e.g. due to magnetic braking. To quantify the change in timing noise observed in PSR J1846−0258, we define an analogous parameter which quantifies the contribution

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

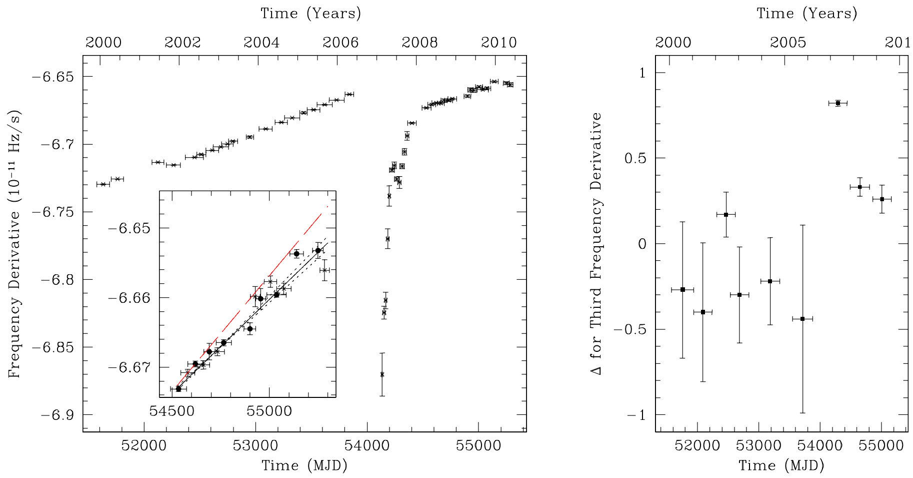

FIGURE 1. Left: Frequency derivative over $\sim 10\,\mathrm{yr}$ of *RXTE* observations. The effect of the two glitches in 2001 and 2006 are visible (see [2] and [15]). The inset shows $\dot{\nu}$ in 2008 – 2010. The result of a least-squares fit is shown as the solid line, with 1σ uncertainties shown as dotted lines, corresponding to $n = 2.16 \pm 0.13$. The expected slope from the pre-outburst $n = 2.65$ is shown as a dashed line. Right: A quantification of the timing noise in PSR J1846−0258 over 10 yr. Each point is a measurement of the $\Delta_{\dddot{\nu}}$ parameter. It shows a dramatic increase after the large glitch observed in 2006, followed by some recovery, but not reaching the pre-burst level.

to the spin phase from the third frequency derivative, $\dddot{\nu}$, over $\sim 2.5 \times 10^7$ s. We measured the $\Delta_{\dddot{\nu}}$ parameter for nine segments of data, and show the results in the right panel of the Figure. The value of $\Delta_{\dddot{\nu}}$ increased dramatically with the 2006 outburst, after which it decays initially, but by 2010 has not returned to the pre-outburst quiescent level.

DISCUSSION AND CONCLUSIONS

The observed change in n after the magnetar-like outburst in PSR J1846−0258, if shown to be steady via ongoing timing observations, has important implications for the physics of neutron star spin-down.

Most descriptions of a changing n require a persistent change in radiative behavior, while neither pulse profile or persistent flux variability are observed in PSR J1846−0258 [16]. An increase in wind losses relative to dipole losses does not provide a good description of $\Delta n < 0$ here because of the lack of a persistent increase in PWN luminosity [9]. However, variability in magnetospheric plasma remains a promising avenue for future consideration, given the detection of variable spin-down rates correlated with radio pulse shape changes in some pulsars [19]. While no variability in the X-ray pulse profile is detected in PSR J1846−0258, short time scale variability would not be detectable in the current data.

Other explanations for $\Delta n < 0$ include an increasing B or counter-alignment of α. While both scenarios can also describe a constant value of $n < 3$, an observation of $\Delta n < 0$ implies an increased rate of growth of B. For example, $n = 2.65$ implies a timescale of growth for B of $\sim 8000\,\mathrm{yr}$, while $n = 2.16$ implies a timescale of 3500 yr. Thus the smaller n could indicate that currents shielding a larger internal B are in the process of dissipating [20].

An alternate explanation of $\Delta n < 0$ is that the true n is constant but masked by timing noise and/or ongoing glitch recovery. Four years after outburst, the timing noise remains at a higher level than in pre-outburst quiescence. Interestingly, the observed timing noise is similar to that observed in other young pulsars, however the sudden and persistent change in the level of timing noise is noteworthy. In fact, such long-term variability in timing noise is a property of some magnetars [e.g. 21]. The observed increase in timing noise might arise from changes to the superfluid interior brought on by the unusual 2006 glitch or magnetosphere variability after the outburst.

The observed decrease in n and increase in timing noise may or may not be permanent. Regular monitoring observations beyond the *RXTE* era will help to answer this question, as well as to search for future magnetar-like X-ray outbursts and glitches from PSR J1846−0258.

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