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Intensive X-ray Monitoring of the 16ms Crab-like Pulsar PSR J0537−6910

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Abstract. The recently discovered pulsar PSR J0537-6910 is the most rapidly rotating young pulsar known. This latest example of a Crab-like pulsar, located in the supernova remnant N157B in the Large Magellanic Cloud, is rotating twice as fast as the Crab pulsar. With a characteristic age of 5000 years, it is also the oldest known example of a Crab-like pulsar and was likely rotating close to the maximum rate for a neutron star when it was born. Here we report preliminary results from an intensive monitoring campaign of X-ray observations acquired with the Rossi X-ray Timing Explorer that began in January 1999. These observation have revealed a large glitch event in the pulse timing during the first six month of our campaign, consistent with those suggested by sparse observations dating back to 1993. The current evolution of the rotation rate of PSR J0537-6910 provides a unique probe of the internal structure of neutron stars and constraints on possible pulsar emission mechanisms.

1. Introduction

The X-ray pulsar PSR J0537-6910 was discovered during RXTE observations of the Large Magellanic Cloud and was subsequently identified with the young supernova remnant N157B in the 30 Doradus star formation region (Marshall et al. 1998). Of the five known Crab-like pulsars in plerionic radio nebulae, PSR J0537-6910 is quite unusual. Its rotation rate is twice that of the Crab pulsar, making it the most rapidly spinning young pulsar known. Furthermore,

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its spin-down rate is also the slowest of the Crab-like pulsars with a characteristic age of $\tau = P/(2\dot{P}) = 5 \times 10^3$ yrs, consistent with the estimated age for the remnant itself (Wang & Gotthelf 1998a). For reasonable values of the braking index, the initial rotation rate is faster than that estimated for any other pulsar. Initial study of the spin-history of PSR J0537-6910 suggested several episodes of timing irregularity, or "glitches", a poorly understood phenomena associated with young pulsars. Here, we concentrate on new observations of PSR J0537-6910 which reveal a large timing glitch in its period evolution and discuss its implication.

Crab-like pulsars, like other rotationally powered pulsars, slowly convert their rotational energy into electro-magnetic radiation and energetic particles. For some of these pulsars this gradual slowing down is occasionally interrupted by a sudden increase ("glitch") in its rotation rate. Such glitches are rare and have been seen only in a few per cent of the known pulsars (e.g., Shemar & Lyne 1996). The largest glitches have relative amplitudes ($\Delta\nu/\nu$) of several parts per million (ppm), but the range of amplitudes covers many orders of magnitude. Often there is a partial recovery back toward the pre-glitch rotation rate on a time scale of $\sim$ 100 days. In addition, these glitches occasionally lead to a permanent change in the spin-down rate.

Glitches are most commonly seen in pulsars with characteristic ages of $1 - 5 \times 10^4$ years, while younger and older pulsars typically exhibit small glitches or none at all (Lyne 1995). At the extreme end is the pulsar PSR J1740-3015 which has been observed to glitches about once per year (McKenna & Lyne 1990).

The physical cause(s) of the glitch phenomenon is not understood. They may be be due either to sudden changes in the crust configuration ("starquakes"), to the sudden unpinning of vortices in the superfluid neutrons in the inner part of the crust (e.g., Link et al. 1998 and references therein), or to abrupt changes in the magnetic field. If the glitches are due to the unpinning of vortices, the amplitude of the glitch provides an estimate of the fractional part of the moment of inertia carried by superfluid neutrons (Lyne et al. 1996).

The amount of recovery in the rotation rate depends inversely on the characteristic age of the pulsar (Lyne 1995). This suggests that the vortices become more strongly pinned as the star cools. For the Crab and two other pulsars (Link et al. 1998 and references therein), the glitches are accompanied by a persistent increase in the spin-down rate with a relative amplitude of a few $\times 10^{-4}$. This increase may be caused by changes in the alignment of the magnetic field because of starquakes (Allen & Horvath 1998; Link et al. 1998). These changes may also occur in other pulsars and may explain the unusually low value of braking index for Vela (Link & Epstein 1997). With an age of 5000 years, PSR J0537-6910 appears to be at a transition stage between young neutron stars in which vortices move relatively easily and the older stars in which movement is difficult.

2. Observations

X-ray pulsations have been detected from PSR J0537-6910 in observations with several instruments dating back to 1993 (Marshall et al. 1998; Wang & Gotthelf 1998b). Prior to 1999, the source was observed infrequently, limiting our ability

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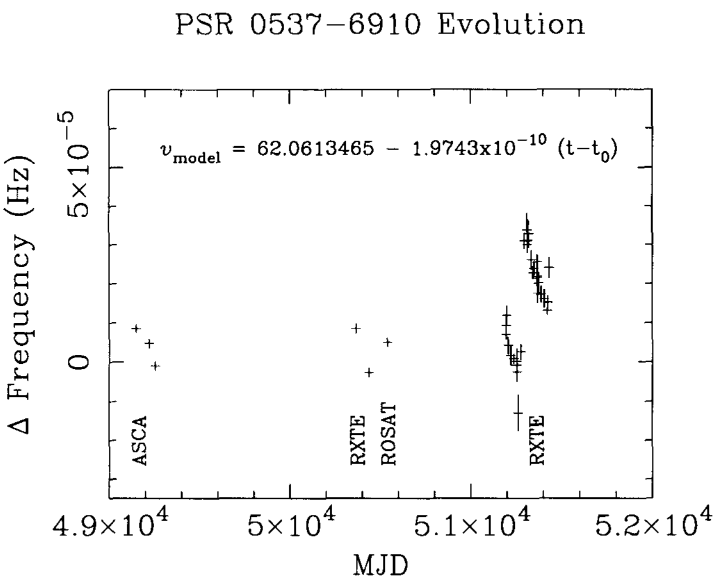

Figure 1. The evolution of the rotation rate of PSR J0537-6910 plotted as residuals from a model assuming a constant linear spin-down trend. t_0 is MJD 50000.

to characterize variations in the rotation rate. Beginning in February 1999, the pulsar has been routinely monitored with the Proportional Counter Array on Rossi X-ray Timing Explorer (RXTE; Bradt et al. 1993). The observing program consists of a series of seven logarithmically spaced observations over a 60-day interval. The series is then repeated every 60 days. The spacing is chosen so that phase can be maintained if the pulsar rotation rate evolves smoothly. The results reported here are based on quick-look data; there may be minor changes when the final ("production") data set is available.

The PCA observations used the Good Xenon data mode, which tags each photon with 0.9 μs timing resolution. For the current analysis, the absolute timing uncertainty is $\sim$ 100 μs (Rots et al. 1998). Moderate spectral information is available in the 2 – 60 keV energy range with a resolution of $\sim$ 16% at 6 keV. Although RXTE lacks imaging capabilities, its high time resolution and large effective area ($\sim$ 6500 cm^2 at 10 keV) make it a powerful instrument for studying rapidly pulsating sources.

3. Timing Results

The measured rotation rate for PSR J0537-6910 from the current RXTE monitoring campaign and earlier observations is shown in Fig. 1. The rotation frequencies are plotted as residuals to a simple linear model whose parameters are chosen to match the long-term average frequency change between the 1993 ASCA observations and the 1996 RXTE observations (Marshall et al. 1998).

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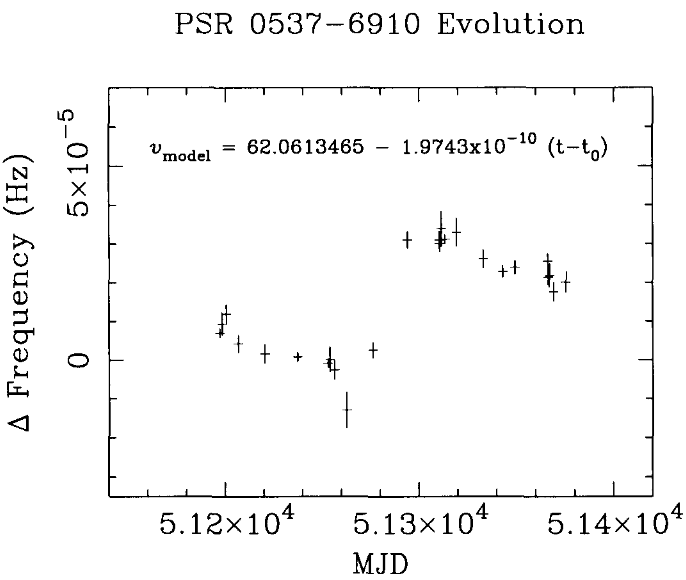

Figure 2. The pulsar rotation rate during the 1999 RXTE observations plotted as residuals from a model assuming a constant linear spin-down trend.

The long-term average frequency derivative of -1.9743×10^{-10} Hz s^{-1} provides a qualitative description of the frequency evolution, but there are obvious deviations from this simple model.

A major glitch was seen during the 1999 RXTE observations at approximately MJD 51285 (Figure 2). The amplitude of the glitch was $\sim 4.2 \times 10^{-5}$ Hz or a relative amplitude of $\sim 0.7 \times 10^{-6}$.

Fitting the observed frequencies for $\sim$ 80 days before and after the glitch shows no evidence for a change in the frequency derivative. Since the observations just before and just after the glitch are separated by 18 days, it is not possible to search for short-lived transient behavior immediately after the glitch. The best-fit derivatives are consistent with the measured derivatives during the 1993 ASCA observations and the 1996 RXTE observations. The best-fit "local" values clearly differ from the long-term average. Table 1 gives best-fit values for the local frequency derivatives using our our preliminary data.

The data in Table 2 show that there are frequent glitches in the rotation rate of PSR J0537-6910. At least one glitch occurred between the group of ASCA observations in 1993, the group of RXTE observations in 1996, the ROSAT observation in 1996, and the RXTE observing campaign in 1999. An additional glitch occurred between the first and second ASCA observation in 1993, and another during the 1999 RXTE campaign. At least one glitch occurred in three separate intervals of less than 200 days. Since the observations were sparse before 1999, it is usually not possible to tell how many glitches occurred during each interval. There are also four intervals with durations between 34 and 81 days in which there is no evidence of large glitches. The data suggest that the

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Table 1. Local Rate of Change in the Rotation Rate

Observation	MJD	Time Span (Days)	Freq. Derivative (pHz/s)
ASCA 1993[a]	49,200	34	-199.4 ± 0.1
RXTE 1996	50,400	69	-199.4 ± 0.1
RXTE (pre-glitch)	51,220	65	-199.1 ± 0.4
RXTE (post-glitch)	51,350	81	-199.5 ± 0.4
Long-Term Average			-197.4

[a]Using 2nd and 3rd observing intervals.

pulsar has a major glitch every ~ 100 days and between the major glitches the pulsar maintains a relatively constant spin-down rate of -1.992×10^{-10}Hz s^{-1}. There may also be glitches with smaller amplitudes, but glitches smaller than $\sim 1 \times 10^{-5}$ Hz would not be obvious in Figure 2. The sum of all glitches changes the rotation rate by ~ 0.9 ppm yr^{-1}.

Table 2. PSR J0537-6910 Glitches

Observation	MJD	No.	Time Span (Days)	$\Delta\nu$ (μHz)	$\Delta\nu/\nu$ (ppm)
ASCA 1993[a]	$\sim 49,180$	?	68	7	0.1
ASCA-RXTE	$\sim 49,700$	?	1114	180	2.9
RXTE-ROSAT	$\sim 50,500$	?	103	24	0.4
ROSAT-RXTE	$\sim 50,850$	?	657	104	1.7
RXTE 1999	51,285	1	179	42	0.7

[a]Between 1st and 2nd observing intervals.

4. Discussion

Using data from the first 6 months of our RXTE monitoring campaign we have clearly found a major glitch with an amplitude of 0.7 ppm. The historical record shows the existence of four other intervals containing at least one glitch. The data are consistent with a model in which a large glitch occurs every every few months, and these large glitches dominate the frequency changes due to all glitches. The frequency and size of the glitches are comparable to the extreme values for any pulsar. The pulsars exhibiting the largest known rates of glitches are PSR J1740-3015, for which nine glitches have been observed in 8 years (Shemar & Lyne 1996), and PSR J1341-6220, for which 8 glitches have been seen in 4.7 years (Wang et al. these proceedings). Most of these glitches were relatively small, however, with amplitudes of $< 1 \times 10^{-7}$. The Vela pulsar has had nine major glitches in 25 years (Lyne et al. 1996). The behavior of PSR J0537-6910 is even more remarkable since glitches are uncommon for pulsars younger than

$\sim 10^4$ years. Unlike the phenomena seen in many pulsars, there is no compelling evidence for partial recovery from glitch or a permanent change in the spin-down rate after the glitch.

The RXTE monitoring of PSR J0537-6910 is continuing. It should provide improved information about the frequency of glitches, their amplitude distribution, and any transient behavior related to glitches. With a long baseline, it will be possible to examine variations in the rotation rate between bursts and attempt to determine the braking index.

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