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The Crab Pulsar Observed by RXTE: Monitoring the X-ray to Radio Delay for 16 Years

Reply to Attn of:

Arnold Rots[1] & Keith Jahoda[2]

[1]*Smithsonian Astrophysical Observatory/CXC*
[2]*NASA/Goddard Space Flight Center*

Summary

In 2004 we published the results of 8 years of monitoring the Crab pulsar by RXTE (Rots, Jahoda, & Lyne 2004, ApJ 605, L129). At that time we determined that the primary pulse of the pulsar at X-ray energies precedes its radio counterpart by about 0.01 period in phase, or approximately 330 μs. However, we could not establish unambiguously whether the delay is in phase or due to a difference in pathlength.
At this time we have twice the time baseline that we had in 2004 and we present the same analysis, but now over a period of 16 years - which will represent almost the full mission and the best that will be available from RXTE.
The full dataset shows that the phase delay has been decreasing faster than the pulse frequency over the 16-year baseline and that there are variations in the delay on a variety of timescales.

Observations and Analysis

We have analyzed 349 RXTE/PCA observations of the Crab pulsar, spanning a period of 5,756 days from MJD 50129 until 55885. All observations were analyzed with a private version of the program faseBin, using the Crab radio timing ephemerides provided by the University of Manchester/Jodrell Bank, and selecting the energy range 2-16 keV.
The phase of the primary pulse was determined by fitting either a parabola or a Lorentzian to the peak.

Results

The measured phase of the primary pulse in the energy range 2-16 keV (relative to its radio counterpart) for all observations is shown in Fig. 1. We have identified certain groups of observations by color:

- Black: regular, good data (though some points are clearly less reliable than others)
- Red: observations prior to MJD 50600; from that date onward the radio observation were performed differently, resulting in a more reliable value for the dispersion measure and, hence, higher-quality timing ephemerides
- Magenta: observations made during "troubled" periods; for instance, the period immediately preceding MJD 50870, as well as September 2011, were plaged by anomalies in dispersion measure, while the period MJD 55000-55400 is not yet understood

The pulsar's glitches are indicated by vertical tick marks near the top of the plot: minor glitches in parentheses, major ones marked with a asterisk(*), very large ones with two asterisks (**). The numbering follows the table by Espinoza et al. (2010, MNRAS 414, 1679) and on http://www.jb.man.ac.uk/~pulsar/glitches/gTable.html.
The general slope of the pulse phase is about 5×10^{-7} period/day, faster than needed for a constant pathlength difference. It results in the values for the extremes of the range given in Table 1.

Table 1:

MJD	φ	ν (Hz)	Delay (μs)	Pathlength (km)
51000	0.988868	29.8638	373	112
56000	0.991308	29.7030	293	88

Our interpretation is that the height at which the X-ray photons are being generated has been gradually decreasing over the past 16 years. Considering that Fig. 1 shows systematic variations over timescales of months that exceed the estimated errors, we also conclude that these are indicative of real variations in that height at various timescales. These variations explain why different values for the delay have been reported in the literature.
We investigated how well the timing of the Crab pulsar can be modeled with a single timing ephemeris between glitches. For this we selected the periods between glitches 23, 24, and 25. We only fitted a third order polynomial, using ν and its first and second derivatives; see Table 2.

Table 2:

Start MJD	End MJD	Epoch	ν	dν/dt	$d^2\nu/dt^2$
53970	54580	54998	29.73478491986286	$-3.7161352574\cdot10^{-10}$	$1.174106\cdot10^{-20}$
54580	55875	54998	29.73478474389909	$-3.7162023261\cdot10^{-10}$	$1.174224\cdot10^{-20}$

The resulting pulse phases (with an arbitrary zero point) are shown in Fig. 2. It is clear that extended periods (at least up to four years) between glitches can coherently be described by a single timing ephemeris that includes no more than the second derivative. It may appear that the timing noise during the second era in Fig. 2 is much larger than in the first. However, when one considers that the second era (1300 days) is more than twice the length of the first (600 days), it becomes clear that one would be able to reduce the excursion considerably by splitting the second one into two and fitting separate ephemerides to the two halves. The main effect would appear to be an increase in the second derivative for the first half and a decrease for the second half. Nevertheless, the single cubic timing ephemeris maintains coherence over 3.3 billion pulses in the second era.

Encore: PSR B1509-58

We ran all 205 RXTE observations of PSR B1509-58, using a single timing ephemeris record that was derived from the one published by Livingstone & Kaspi (2011, ApJ 742, 31) as a starting point, containing ν and its first, second, and third derivatives; see Table 3. The resulting phase of the pulse peak is presented in Fig. 3. The phase varies by up to 0.25 period. Clearly, we can with this single ephemeris record keep track of individual pulses over 5777 days, or 3.3 billion pulses.

Table 3:

Start MJD	End MJD	Epoch	ν	dν/dt	$d^2\nu/dt^2$	$d^3\nu/dt^3$
50000	56000	52384	6.6115186502914	$-6.6943826310\cdot10^{-11}$	$1.91868721\cdot10^{-21}$	$-0.8711\cdot10^{-31}$

It turns out that the curve can be fit quite well with three or four harmonic sine functions with period ratios 3:4:2:1 and respective amplitude ratios of approximately 20:7:4:1. The period of the dominant harmonic is about 1900 days.
Whether there is any real physical significance to this fit remains to be seen.

arots@head.cfa.harvard.edu

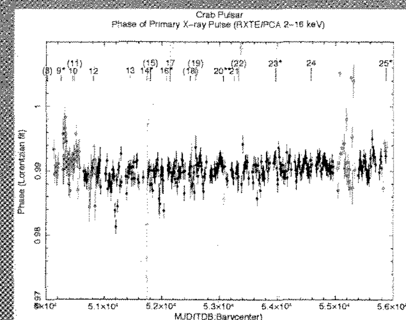

Fig. 1

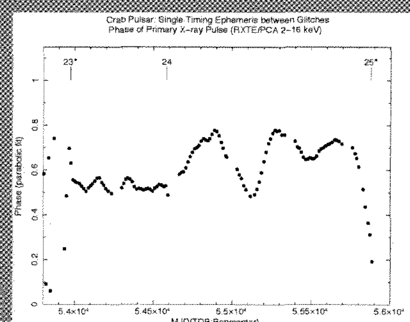

Fig. 2

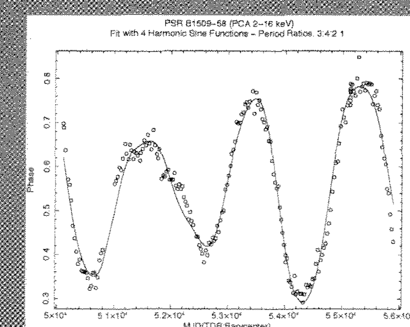

Fig. 3

Acknowledgments

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The Crab radio timing ephemerides were obtained from http://www.jb.man.ac.uk/~pulsar/crab.html; see: Lyne, Pritchard, & Graham-Smith (1993, MNRAS, 265, 1003).
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