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Absolute Timing of the Crab Pulsar with RXTE

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ABSTRACT

We have monitored the phase of the main X-ray pulse of the Crab pulsar with the Rossi X-ray Timing Explorer (RXTE) for almost eight years, since the start of the mission in January 1996. The absolute time of RXTE's clock is sufficiently accurate to allow this phase to be compared directly with the radio profile.

Our monitoring observations of the pulsar took place bi-weekly (during the periods when it was at least 30 degrees from the Sun) and we correlated the data with radio timing ephemerides derived from observations made at Jodrell Bank. We have determined the phase of the X-ray main pulse for each observation with a typical error in the individual data points of 50 μs. The total ensemble is consistent with a phase that is constant over the monitoring period, with the X-ray pulse leading the radio pulse by 0.01025$\pm$0.00120 period in phase, or 344$\pm$40 μs in time. The error estimate is dominated by a systematic error of 40 μs, most likely constant, arising from uncertainties in the instrumental calibration of the radio data. The statistical error is 0.00015 period, or 5 μs. The separation of the main pulse and interpulse appears to be unchanging at time scales of a year or less, with an average value of 0.4001±0.0002 period. There is no apparent variation in these values with energy over the 2-30 keV range.

The lag between the radio and X-ray pulses may be constant in phase (i.e., rotational in nature) or constant in time (i.e., due to a pathlength difference). We are not (yet) able to distinguish between these two interpretations.

Subject headings: X-rays: stars, pulsars: individual (Crab pulsar)

1. Introduction

For many years it has been assumed that the main pulse and interpulse of the Crab pulsar (PSR B0531+21) are perfectly lined up in phase over the full range of the electromagnetic spectrum. Even though there have been reports in the past that this alignment may not be as perfect as generally assumed, the absolute calibration of spacecraft clocks was not sufficiently accurate to allow a precise measurement of the phase difference. The most compelling result predating the Rossi X-ray Timing Explorer (RXTE) observations was presented by Masnou et al. (1994), based on Figaro II observations covering 0.15 to 4.0 MeV, that were made in 1986 and 1990. While discounting the 1986 result which has a considerable uncertainty due to potential errors in the dispersion measure, we consider the 1990 result (the γ-ray pulse leading the radio pulse by 375±148 μs) fairly reliable, though the error is probably underestimated.

The precision with which absolute time can be determined with the RXTE clock allows us to time X-ray pulses with an accuracy better than 10 μs, depending on pulse shape, as shown by Rots et al. (1998b). At the same time, the Crab pulsar monitoring program at Jodrell Bank provides timing ephemeris data, reduced to infinite frequency. These (monthly) timing ephemerides represent fits to the daily time-of-arrival measurements with rms residuals of order 20-50 μs. This allows us to measure and monitor the radio to X-ray phase difference of the pulses with an error of about one milli-period. We have reported on these results in the past (Rots et al. (1998a), Rots, Jahoda, & Lyne (1998c), Rots, Jahoda, Lyne, & Manchester (2000a), Rots, Jahoda, & Lyne (2000b)).

At optical wavelengths, Sanwal (1999) has reported a time delay of 140 μs (optical leading the radio), but the details are not easily accessible. Shearer et al. (2003) report that, in the case of giant radio pulses, the optical pulse in the wavelength range 600-750 nm is leading the radio pulse by 100±20 μs. Romani et al. (2001), on the other hand, claim that the optical (355-825 nm) and radio peaks are coincident within 30 μs, based on test observations with a prototype transition-edge sensor detector. However, it is not clear whether the timing calibration of the instrument was complete at the time.

Ulmer et al. (1994) presented results from OSSE observations (50-100 keV), indicating that the hard X-ray to radio lag was $<30\pm30$ μs. It would appear that the estimate of their errors was too optimistic. Nolan et al. (1993) present pulse profiles but no absolute phases. Kuiper et al. (2003) report on INTEGRAL data, covering 6-50 keV, and deriving a time delay (the radio trailing) of 280 ± 40 μs for a single epoch.

The precise timing of the pulses in the different wavelength regimes has important repercussions for the understanding of the nature and spatial origin of the emission processes that give rise to the pulses in different parts of the spectrum. Romani & Yadigaroglu (1995) have suggested that, while the radio precursor comes from the polar cap, the pulse and interpulse originate in the outer gap in the magnetosphere, with the higher energy pulses being generated at significantly greater height. Thus, measuring the pulse shapes and the absolute timing throughout the electromagnetic spectrum places important constraints on the shape of the the outer gap and on the height in the magnetosphere at which the radiation is generated.

In this paper we will present the results of the RXTE monitoring campaign of the Crab Pulsar from the start of that mission. We have adopted the radio nomenclature for the features in the pulse profile (main pulse, bridge, and interpulse).

2. Observations

The observations presented here were made as part of an on-going monitoring campaign of the Rossi X-ray Timing Explorer's (RXTE). Observations of about 1000 s in duration were initially made at weekly, later bi-weekly, intervals, with the exception of a period from mid-May until mid-July when the Crab pulsar is too close to the sun.

In this paper we shall use the events in the 2-16 keV range, collected with the RXTE's Proportional Counter Array (PCA) in 177 observations between MJD 50129 and 52941. For the first four and a half years the observations were made in pulsar fold mode, with approximately 80 bins per period. Halfway through the fifth year this was changed to an event mode with 250 μs time resolution.

The accuracy of the RXTE clock in absolute time is about 8 μs for data taken before 29 April 1997 (MJD 50567); see Rots et al. (1998b). After that date, the error decreased to 2 μs (Markwardt 2003). This accuracy can be achieved by applying the fine clock corrections supplied by the RXTE GOF. In addition to the clock correction, there is an instrumental delay correction for the PCA of 16-20 μs. Without the fine clock correction the uncertainty in absolute time is 100 μs.

The radio timing ephemeris is derived from Jodrell Bank observations, daily at 610 MHz and weekly at 1420 MHz. See, e.g., Lyne, Pritchard, & Graham-Smith (1993). Reduced to "infinite frequency", the ephemeris provides the dispersion-corrected time of arrival of the center of the main pulse and is published on the world-wide web[1]. The ephemeris records contain: range of validity (MJD, UTC); phase-zero in MJD (UTC; geocenter); RA, Dec (J2000, FK5); ν and its first two derivatives; rms of the solution's fit. The timing ephemeris records, each of which covers one month, are created by the Tempo package, on the basis of the JPL solar system ephemeris DE200. In the period prior to MJD 50870 the Crab pulsar suffered a substantial amount of variable multipath scattering within the nebula; see also Wong, Backer, & Lyne (2001). While the Jodrell Bank staff endeavored to remove the effects of this from the data, there was uncertainty in doing so, and this is reflected in the quoted errors and in the increased scatter. The errors quoted in the ephemeris also contain a contribution arising from unknown systematic effects in the system, such as unmodeled delays in filterbanks and imperfect polarization calibration. This amounts to about 40 μs and should not be treated as a statistical error which reduces upon averaging. Most likely, there will have been little change in its actual value over time.

3. Analysis

The observations were analyzed using the program *faseBin* which applies the barycenter correction, ties the arrival times to the radio timing ephemeris, and bins the events in absolute phase. *faseBin* is the core of the *Ftool* (Blackburn 1995) *fasebin*. The unpulsed component is then subtracted and the data are integrated over the energy range 2-16 keV. A typical 2-16 keV pulse profile is shown in Fig. 1.

At this point we needed to decide how to define the phase of the main X-ray pulse. The problem is that, while the radio pulse is very symmetric, the X-ray pulse is clearly asymmetric. In order to avoid any assumptions concerning the modeling of the pulse shape to enter into our analysis, we decided to use the peak of the pulse as representative of the X-ray phase. To this end we used three different peak finding algorithms, each designed to be free of model assumptions to the extent possible: a parabolic fit to the highest bin in the profile and its two neighbors, using 200 phase bins; fitting a Lorentzian function to the phase range 0.98 to 1.00, using 400 phase bins; and calculating the first moment over

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[1]http://www.jb.man.ac.uk/~pulsar/crab.html

that part of the pulse where the bins exceed 80% of the highest bin, using 800 phase bins. This procedure allows us to determine the pulse phase in an individual observation with an accuracy of 1 milliperiod. We did investigate whether the time resolution of the observations gives rise to an additional systematic error and found this not to be the case: Lorentzian fits to two back-to-back observations made in the fall of 2003 with resolutions of 250 μs and 16 μs, respectively, differed by less than 0.1 milliperiod.

The absolute phase of the peak of the X-ray main pulse (with respect to the peak of the radio main pulse, using the Lorentzian fits), as a function of time (in Modified Julian Days) is shown in Fig. 2; the errors are a combination of the 1 milliperiod error mentioned above and the rms deviations in the fits of the radio timing ephemerides and typically amount to 40 μs. Independently from these statistical errors there is the systematic error of up to 40 μs introduced by the radio receiver system and calibration, as mentioned in the previous section.

4. Results and Discussion

Fig. 2 shows the history of the main X-ray pulse phase, with the occurrences of glitches marked. Glitches 7 through 12 are taken from Wong, Backer, & Lyne (2001), while the glitch numbered 8 corresponds to Note 12 on the Jodrell Bank web page and adding one to glitch numbers 12 through 18 yields the corresponding Note numbers (13 through 19) on that page. We have monitored the X-ray emission more closely following two glitches, but found no unusual behavior.

The data points in this figure can be divided into four quality categories. First, the data points that are based on timing ephemerides prior to MJD 50870 obviously display larger deviations than the later ones; we attribute this to the poorer quality of those radio ephemeris records. Second, there are a number of points with high error estimates (>5 milliperiods), associated with glitches; the monthly timing ephemeris records are not sufficiently fine-grained to handle glitches properly. Third, there are seven outlyers (below phase 0.9860) that are clearly well below the remaining data points. In all cases these represent either all observations covered by a single ephemeris record or observations at the edge of such a record; hence, we attribute these to inaccuracies in the timing ephemerides. Fourth, the remaining 111 data points form a normal distribution with the expected rms scatter of 1 milliperiod. This indicates that the data are consistent with a constant value. The data points from the first three categories are represented by open circles in Fig. 2; the high-quality data points (category 4) are shown as filled circles.

In order to determine the phase of the X-ray main pulse we have excluded all data points that were deemed flawed (i.e., in the first three categories above). Least-squares fits (weighted averages) to the results from the three different peak-finding algorithms that we used lead us to conclude that the X-ray main pulse leads the radio main pulse (as defined by the radio timing ephemerides) by 10.25±0.15 milliperiod, or 344±5 μs, with a reduced χ^2 of 1.3. The quoted errors represent the differences between the results from the three methods. The statistical errors in the three individual fits are smaller. In addition, of course, there is still the uncertainty of the 40 μs systematic error in the radio ephemerides. We emphasize that, although we believe these error estimates to be realistic, a different definition of the pulse phase may lead to larger discrepancies. Ideally, one should analyze the data that are available in the different spectral bands with a uniform pulse definition.

The result obtained by Kuiper et al. (2003) of 280±40 μs for a single INTEGRAL observation is probably to be considered consistent with our findings, especially since it used a timing ephemeris record at MJD 52685 that gives rise to slightly elevated phase values in our data. However, the phases that they quote for the main pulse on MJD 52683 and MJD 52697, derived from the same RXTE observations that we have used, differ from our values by +1.7 and +1.1 milliperiods, respectively. We believe that this difference is due to the definition of the phase that is used by these authors. Kuiper et al. (2003) define the phase of the main peak as the position of an asymmetric Lorentzian fit to the phase range 0.95 to 1.05. This definition, in our opinion, is not as free of model-dependent assumptions as our analysis methodology; it appears that there is a systematic offset of about 40-50 μs. Note that, since these authors used the same Jodrell Bank timing ephemeris records, the radio systematic error does not play a role here.

As to the question whether the lag between the X-ray and radio pulses is constant in phase (i.e., the lag is rotational in nature) or in time (i.e., the lag represents a pathlength difference), the data are not conclusive. The former would require the phase offset in Fig. 2 to be constant with time, while the latter would require the phase to increase linearly with a slope of $+1.0 \times 10^{-8}$ period/day. A linear fit to the good data in Fig. 2 yields a slope of $(+3.3 \pm 2.0) \times 10^{-7}$. This result is probably affected by Malmquist bias and possibly other sources of systematic errors. Unless our measurement accuracy can be dramatically improved, it will require at least another seven years of monitoring before we can answer this question definitively in this manner. If indeed we are dealing with a time offset, this would correspond to a pathlength difference of about 100 km.

Additional analysis of the RXTE data reveals that the PCA and HEXTE pulses are perfectly aligned to within 1 milliperiod (i.e., no phase change over the 2 to 30 keV energy range), while pulse phase determinations over a 12-hour Crab observation show less than

1 milliperiod variation in the phase of the main pulse. This is all within the measurement errors.

We have measured the phase difference between the X-ray main pulse and interpulse, a quantity that is independent of any uncertainties in the radio timing ephemeris records. The average value over the 7.6 year period is 0.4001±0.0002 period. There do not appear to be any variations on time scales of the order of a year or less, but we cannot entirely exclude systematic variations or systematic errors of the order of 1 milliperiod on time scales of several years.

5. Conclusion and Summary

The X-ray main pulse leads its radio counterpart by about 344±40 μs (systematic error); the statistical error is 5 μs. This is more than twice the time difference of 140 μs that Sanwal (1999) determined for the optical B band and three times the 100 μs measured by Shearer et al. (2003) in red light. The time or phase difference appears to have been constant over the past eight years, but the data are not accurate enough to distinguish between the two. The errors in individual measurements range up to 50 μs. We should caution the reader when making comparisons with results in other wave bands. First, various authors have used different definitions of the pulse phase. In our estimation, our own definition agrees with that used in the radio band, as does the definition of Shearer et al. (2003), but that is probably not true for most other reports. Second, the scatter in values for individual observations is fairly large (a milliperiod) and may be intrinsic. Greater accuracy can only be achieved with a statistically significant set of observations.

As we have mentioned, there is a systematic error of up to 40 μs in the offset due to uncertainties in the instrumental lags and calibration of the radio equipment. Such an error would most likely remain constant in time and it does not affect the comparison with results from other wavebands since all use the same Jodrell Bank timing ephemeris records.

The phase difference between the two X-ray pulses is constant at 0.400 period, within the measurement errors. It is also equal to the phase difference between the radio main pulse and interpulse, within the measurement error. It may be of interest to note that in the X-ray pulse profile the trailing edges of the pulse as well as the interpulse are distinctly steeper than their leading edges. This does not appear to be the case for the optical interpulse.

If the X-ray to radio lag were a true phase lag, attributable to the (radial) energy distribution across a cone, with the pulses occurring near the cone edges, one would expect the placement to be symmetrical, i.e., one X-ray pulse to be leading, the other trailing. As it stands, both X-ray pulses are leading by the same amount. The simplest explanation for this phenomenon is that we are dealing with a time delay reflecting a pathlength difference: the radio pulses originate approximately 100 km closer to the surface of the neutron star, as already suggested by Masnou et al. (1994).

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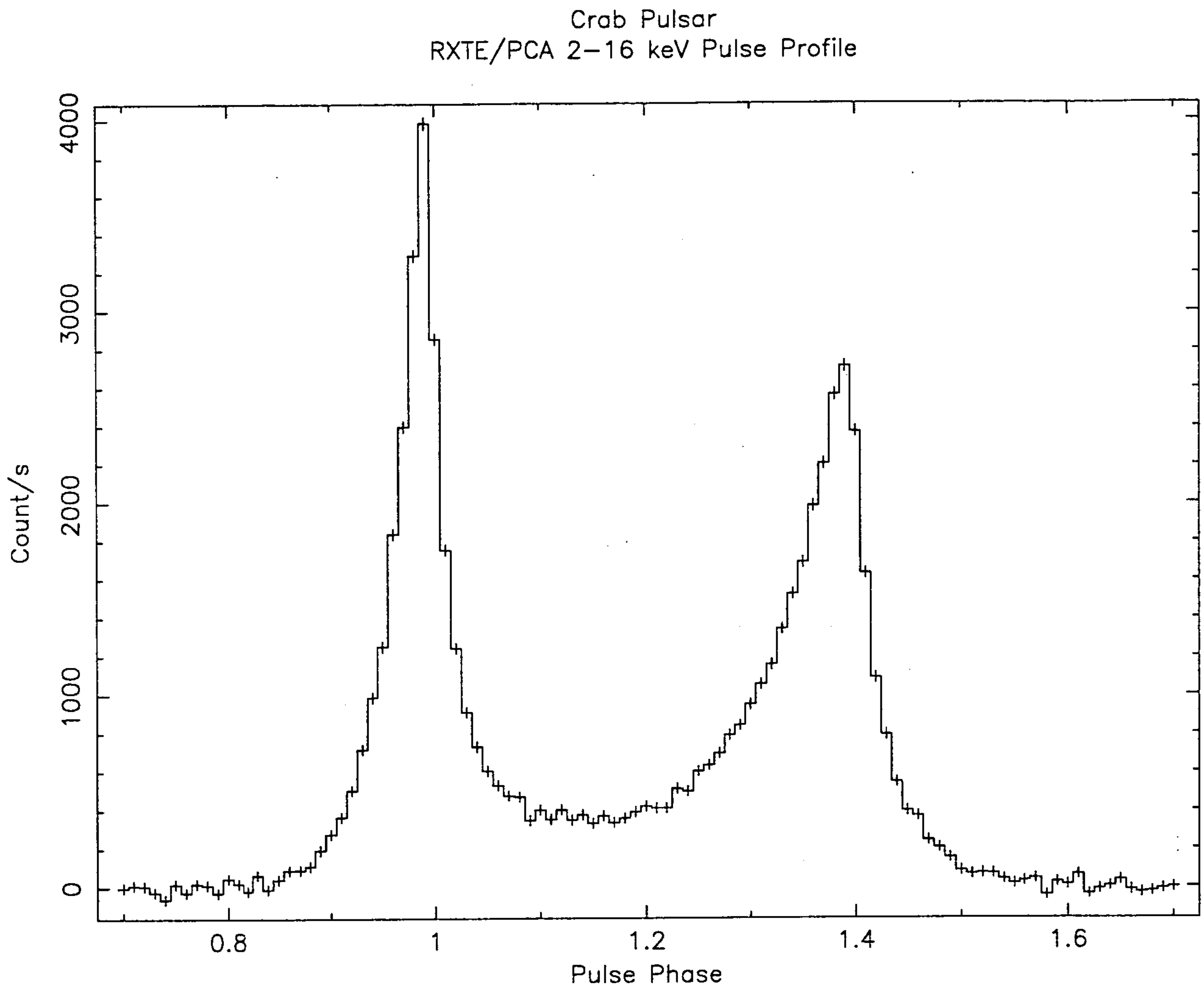

Fig. 1.— Typical RXTE pulse profile for the Crab pulsar. The events are binned in 100 bins per period; errors are indicated by vertical bars.

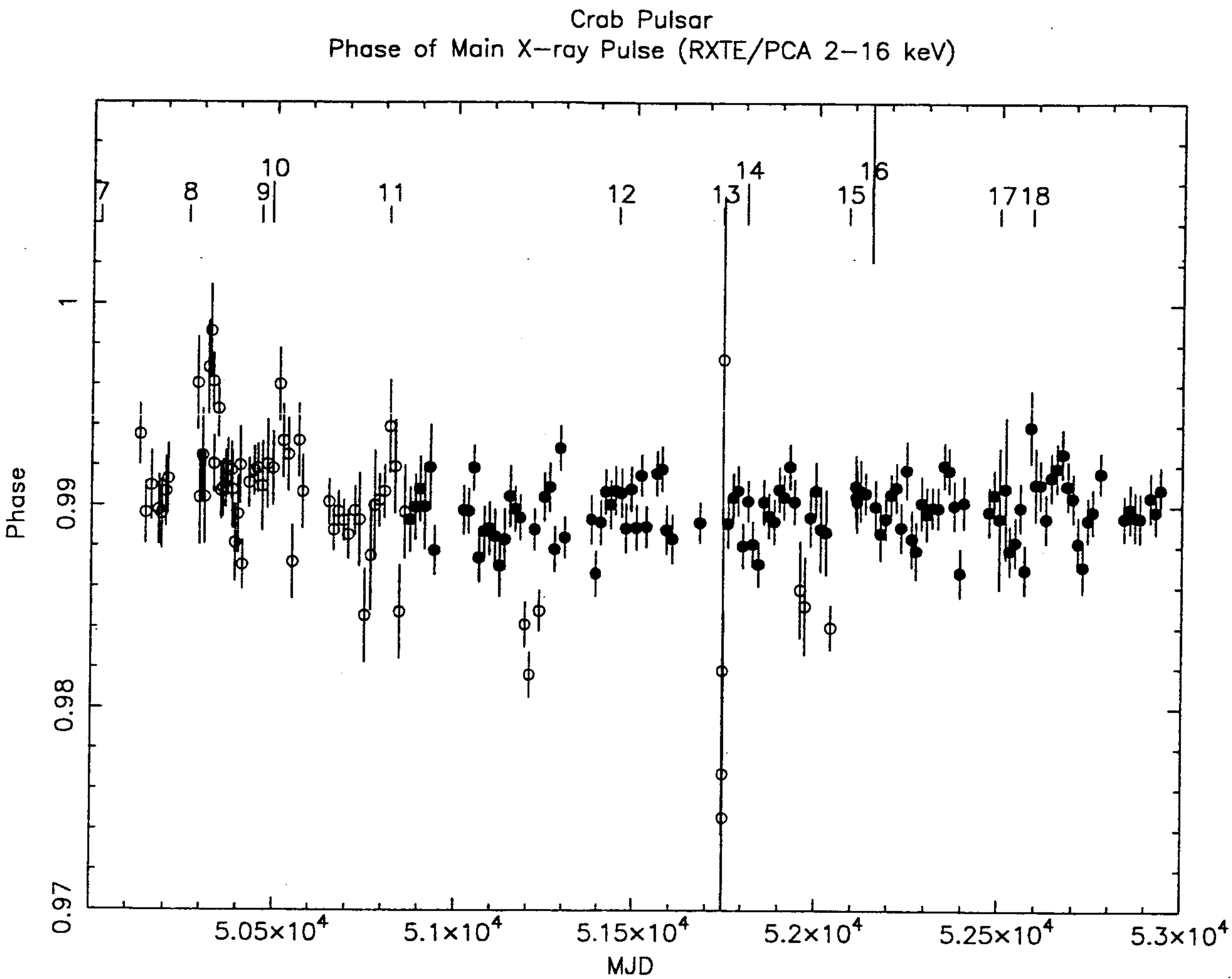

Fig. 2.— Phase of the X-ray main pulse relative to the Jodrell Bank radio timing ephemerides for 177 RXTE observations as a function of time. The phase is calculated by fitting a Lorentzian function to the phase range 0.98 to 1.00 with 0.0025 bin size (see text). The error bars represent statistical errors only. Filled circles represent high-quality data points, open circles data points of questionable quality. Numbered tick marks indicate the times of glitches (see text).