Phase Evolution of the Crab Pulsar between Radio and X-Ray

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Abstract

We study the X-ray phases of the Crab pulsar utilizing the 11-year observations from the Rossi X-ray Timing Explorer, 6-year radio observations from Nanshan Telescope, and the ephemeris from Jodrell Bank Observatory. It is found that the X-ray phases in different energy bands and the radio phases from the Nanshan Telescope show similar behaviors, including long-time evolution and short-time variations. Such strong correlations between the X-ray and radio phases imply that the radio and X-ray timing noises are both generated from the pulsar spin that cannot be well described by the the monthly ephemeris from the Jodrell Bank Observatory. When using the Nanshan phases as references to study the X-ray timing noise, it has a significantly smaller variation amplitude and shows no long-time evolution, with a change rate of $(-1.1 \pm 1.1) \times 10^{-7}$ periods per day. These results show that the distance of the X-ray and radio emission regions on the Crab pulsar has no detectable secular change, and it is unlikely that the timing noises resulted from any unique physical processes in the radio or X-ray emitting regions. The similar behaviors of the X-ray and radio timing noises also imply that the variation of the interstellar medium is not the origin of the Crab pulsar’s timing noises, which is consistent with the results obtained from the multi-frequency radio observations of PSR B1540–06.

Key words: stars: neutron – pulsars: individual (PSR B0531+21) – X-rays: stars

1. Introduction

Pulsars are famous for their rotation stability and highly repeatable pulse shapes. However, when examining pulsar’s periodicity with high precision, there appear to be two main types of irregularities, namely glitch and timing noise. The origin of timing noise remains controversial in spite of years of studies. Models proposed to explain the timing noises of pulsars include the random process (Cordes & Helfand 1980), unmodeled planetary companions (Cordes 1993), the free precession (Stairs et al. 2000), and the interstellar medium (ISM; e.g., You et al. 2007). Hobbs et al. (2010) analyzed the timing properties of 366 pulsars in detail. Their study shows that timing noise is widespread in pulsars and cannot be explained using a simple random walk in the observed rotational parameters. The timing residuals of PSR B1540–06 are consistent at different radio frequencies, which implies that its timing noise is not caused by ISM (Hobbs et al. 2010). The underlying physical processes that cause timing noise are still unclear.

Among all the pulsars, the Crab pulsar is probably the most suitable source to study the origin of timing noise for its frequent spin irregularities and abundant observational data. This pulsar has been comprehensively studied in almost all wavelength bands from radio to very high energy $\gamma$-rays. Its pulse profile shows a double-peak structure in all of these wavebands. Generally, the two dominant pulses in the radio band are denoted as main pulse (MP) and interpulse (IP; Lyne et al. 2013), and the two X-ray peaks are denoted as P1 and P2 (Kuiper et al. 2001). Detailed studies show that the exact pulse morphology varies as a function of photon energy (Abdo et al. 2010; Ge et al. 2012) and the positions of the main peak in different energy bands are not exactly aligned, i.e., the optical, X-ray and $\gamma$-ray pulses lead to the radio pulses (Kuiper et al. 2003; Rots et al. 2004; Oosterbroek et al. 2008; Abdo et al. 2010; Molkov et al. 2010). Recently, secular changes of both the radio and the X-ray profiles were found, though their change rates are different from each other (Lyne et al. 2013; Ge et al. 2016). These changes were attributed to a progressive change in the magnetic inclination (Lyne et al. 2013; Ge et al. 2016), and such magnetic field variations are also confirmed by another study on red timing noise (Yi & Zhang 2015). With seven years of observations, it was found that the X-ray pulse in 2–16 keV leads the radio one by $0.0102 \pm 0.0012$ period and increases with a rate of $(3.3 \pm 2.0) \times 10^{-7}$ period per day (Rots et al. 2004), which could also be explained as systematic errors. Given the secular changes of the radio and X-ray profiles, to study the phase lags between different energy bands and their variations is important to uncover the origin of timing noise and the properties of magnetosphere structure.

In this paper, by using the 11-year observations from the Rossi X-ray Timing Explorer (RXTE), 6-year radio observations from the Nanshan radio telescope at the Xinjiang Astronomical Observatory (Wang et al. 2001), and the monthly renewed ephemeris from the Jodrell Bank Observatory (Lyne et al. 1993), we investigated in detail the timing behaviors of this pulsar in the X-ray and radio wavebands. First, the phase comparisons between the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE) on board RXTE are used to estimate the instrumental influences on the phase determination. Then, the accuracy of the Jodrell Bank ephemeris is checked by the correlation between the X-ray phases and the radio phases obtained by the Nanshan radio telescope. Furthermore, the X-ray phases are corrected by the new phase indicator from Nanshan radio telescope to study the
relationship between the X-ray and radio timing noises, including the effects of the dispersion measure (DM).

2. Observations and Data Reduction

2.1. Timing Ephemeris from Jodrell Bank

In this study, the time reference for the radio phases from Nanshan and X-ray phases from RXTE of the Crab pulsar is taken as the times-of-arrival (TOAs) from Jodrell Bank radio ephemeris (JBE; Lyne et al. 1993). A 13 m radio telescope at Jodrell Bank monitors the Crab pulsar daily, offering a radio ephemeris\(^5\) that is used for the analyses of RXTE and Nanshan data. The ephemeris we used is in CGRO format, the format required by the RXTE data processing, and it contains the following information: R.A. and decl. in J2000 coordinates, the infinite-frequency geocentric UTC TOA of a pulse, rotation frequency and its first two derivatives, the barycentric (TDB) epoch of the spin parameters, and the root-mean-square radio timing residual. Because of the uncertainties of the radio receiver system and the calibration, we add a systematic error of 40 μs for phases calculated from this ephemeris, as suggested by Rots et al. (2004). All errors of the phases in this paper are 1σ, for both statistical and systematic errors.

2.2. RXTE Observations and Data Reduction

The X-ray observations used in this paper were obtained by both PCA and HEXTE on board the RXTE. The PCA instrument is composed of five Proportional Counter Units with a total photon collection area of 6500 cm\(^2\). Its effective energy range is 2–60 keV, and the time resolution is about 1 μs (in Good Xenon mode; Jahoda et al. 2006). These properties make PCA an ideal instrument to study the detailed temporal properties of pulsars. In this paper, we use the publicly available data in event mode E_250us_128M_0_1s. The time resolution of this mode is about 250 μs. HEXTE consists of two independent detector clusters A and B, and each of them contains four NaI(Tl)/CsI(Tl) scintillation detectors. This instrument is sensitive in 15–250 keV, with a detection area of 1600 cm\(^2\) and a time resolution of 7.6 μs (Rothschild et al. 1998). In its default operation mode, the field of view of HEXTE, each cluster is switched on and off source to provide instantaneous background measurements. The HEXTE data used in this paper are in mode E_8us_256_DX0F.

The PCA and HEXTE data were analyzed by using the FTOOL from the astronomy software HEASOFT (v6.15). The method of data reduction and pulse profile calculation is the same as in Ge et al. (2016), but with the observations selected a little differently. Only 243 observations between MJD 51955 (2001 February 15) and 55927 (2012 January 01) are used in this paper, since from each of these observations high statistical PCA and HEXTE pulse profiles can be obtained simultaneously. The pulse profiles were binned into 1000 phase bins, in energy bands 2–60 keV for PCA and 15–250 keV for HEXTE.

2.3. Nanshan Radio Telescope Observations and Data Reduction

The Nanshan 25 m radio telescope, operated by Xinjiang Astronomical Observatory, started to observe the Crab pulsar frequently in 2000 January. As described in Wang et al. (2001), the two hands of circular polarization at 1540 MHz are fed through a 2 × 128 × 2.5 MHz analogue filter bank. The signal is sampled at 1 ms intervals and 1 bit digitized. Time is stamped by a hydrogen maser calibrated with the Global Position system. The integration time of each observation of the Crab pulsar is 16 minutes. After 2010 January, the data were obtained with digital filter bank 3 (DFB3), which was configured to a bandwidth of 0.5 MHz for each sub-channel and 8 bit sampling. The data are folded online with a subintegration time of 1 minute for AFB and 30 s for DFB3, and then written to the disk with 256 bins across the pulse profile for AFB and 512 bins for DFB.

As for the radio observations, the off-line data reduction is performed in the following three steps by using the PSRCHIVE package: (1) the data for the Crab pulsar are de-dispersed using the DM values from the JBE timing results and then summed to produce a total intensity profile; (2) local TOAs were determined by correlating the data with standard pulse profiles of high signal-to-noise ratio, and the pulse TOAs normally correspond to the peak of the main pulse; (3) convert TOAs to the solar system barycenter. The detail data reduction process is the same as in Yuan et al. (2010). Because the data quality is better after 2005 May, we only analyzed those from MJD 53500 (2005 May 10) to 55688 (2011 May 07), and finally got 524 TOAs at 1540 MHz.

3. Phase Calculation and the Linear Fitting Method

3.1. Phase Calculation for RXTE

As described in Ge et al. (2012), the two asymmetrical pulses of the Crab pulsar in the X-ray band could be modeled by the formula (1) proposed by Nelson et al. (1970).

\[
L(\phi - \phi_0) = N + a(\phi - \phi_0) + b(\phi - \phi_0)^2 + c(\phi - \phi_0) + d(\phi - \phi_0)^2 e^{-h(\phi - \phi_0)} + I, \tag{1}
\]

where \(L\) is the intensity at phase \(\phi\), \(I\) is the baseline of the light curve, \(\phi_0\) is the phase shift, \(N\) is the pulse height of the profile, and \(a, b, c, d,\) and \(h\) the shape coefficients. The pulse phase is measured in phase units, of the range (0, 1). We fitted the shape of P1 with a relatively broad phase window (−0.055, 0.0355) centered at phase −0.01.

The calculation procedures of phases of P1 and the estimation of their statistical errors are the same as in Ge et al. (2012). The X-ray phases with high precision are obtained after the fitting procedure, and we denote the phases of the X-ray pulse P1 as \(\Phi_P\) and \(\Phi_H\) for PCA and HEXTE, respectively.

3.2. Phase Calculation for Nanshan

The calculation procedures of the radio phase of MP for Nanshan (\(\Phi_M\)) are as follows. (1) Remove the dispersion effect for TOAs using the DM values from JBE (Lyne et al. 1993). In this step, we need to reckon the DM values in Nanshan

\[\]
observations using linear interpolation. The time delay \( t_{\text{DM}} \) caused by DM is

\[
t_{\text{DM}} = D \times \frac{\text{DM}}{\nu^2},
\]

where \( D \) is the dispersion constant, \( D = 4.1488 \times 10^3 \) MHz\(^2\) pc\(^{-1}\) cm\(^3\) s, and \( \nu \) is the centered frequency, i.e., 1540 MHz (Lyne & Graham-Smith 2012). Because the JBE DM values were not obtained in the same time as the Nanshan observations, the DM at the time of Nanshan observations were obtained with linear interpolation. (2) Convert the TOAs from Jodrell Bank and Nanshan to the TDB time system. (3) Calculate \( \phi_J \) for Jodrell Bank and \( \Phi_N \) relative to \( \phi_J \) with formula (3) and (4), respectively.

\[
\phi_J = f_0(T_J - T_0) + \frac{1}{2} f_1(T_J - T_0)^2 + \frac{1}{6} f_2(T_J - T_0)^3,
\]

\[
\Phi_N = \text{mod} \left[ f_0(T_N - T_0) + \frac{1}{2} f_1(T_N - T_0)^2 + \frac{1}{6} f_2(T_N - T_0)^3 - \phi_J, 1 \right],
\]

where \( T_J \) and \( T_N \) are the TOAs in the TDB time system, from Jodrell Bank and Nanshan to the TDB time system. The Pearson's correlation coefficient \( r \) (Lee Rodgers & Nicewander 1988) is a suitable parameter to describe the influence of the timing noise on \( \Phi_P, \Phi_H, \) and \( \Phi_N \) quantitatively. Because the Nanshan and RXTE observations were not done simultaneously, and the time series of \( \Phi_N \) is serially dependent when checking the autocorrelation function, the Nanshan phases at the time of X-ray observations (\( \Phi_N' \)) are computed by linear interpolation between the neighboring \( \Phi_N \) values.

### 3.3. Methods for Phase Analysis

#### 3.3.1. Linear Fitting

In order to study the phase variations versus time and the correlations between phases from different data sets, we fit the data points with a linear function. For the variation of a parameter versus time, if the slope deviates significantly from zero, long-term evolutions should exist. For the correlations between two parameters, the slope can also tell us information about how these two parameters are correlated, as we will discuss in Section 4.

In this paper, the fitting method is the robust linear modeling (RLM) from the R statistical software package (Feigelson & Babu 2012), which has been used to study both the phase variations versus time and the correlations between different phases. The MASS (Modern Applied Statistics with S) library based on R-language has the rlm function for RLM. In this function, the fitting is achieved using an iteratively reweighted least-square algorithm. Similarly, the linear fitting for the phase correlations between different data groups is also achieved by this method, as listed in Tables 1 and 2.

#### 3.3.2. Correlation Analysis

The Pearson’s correlation coefficient \( r \) (Lee Rodgers & Nicewander 1988) is a suitable parameter to describe the

### 4. Results

The X-ray phases \( \Phi_P \) and \( \Phi_H \) are the phases of the X-ray main peaks relative to JBE, from the PCA and HEXTE data respectively. In order to study the relation of the radio and X-ray phases on both long and short timescales, we need to check the accuracy and reliability of these phases first.

#### 4.1. The X-Ray Phases from PCA and HEXTE and Their Correlation

As shown in Figure 1, the X-ray phases \( \Phi_P \) and \( \Phi_H \) exhibit simultaneous variations on all timescales. Previous work showed that the X-ray phases from PCA gradually increase with a change rate of \((3.3 \pm 2.0) \times 10^{-7}\) period per day (MJD 50129–52941; Rots et al. 2004) or \((6.6 \pm 1.3) \times 10^{-7}\) period per day (MJD 51955–55142; Ge et al. 2012). Here we analyze more observations, in a longer time range MJD 51955–55927, and both PCA and HEXTE showed the same trend with the change rates of \((5.0 \pm 0.9) \times 10^{-7}\) and \((4.5 \pm 0.9) \times 10^{-7}\) period per day, respectively. Besides the increasing trends, \( \Phi_P \) and \( \Phi_H \) have two kinds of variations on short timescales, which are the slow variations (e.g., in MJD 52600–53000 and

### Table 1

| Instrument | MJD          | Energy Band | Change Rate \((10^{-7} \text{ period/day})\) | Intercept \((10^{-3} \text{ period})\) |
|------------|--------------|-------------|---------------------------------------------|---------------------------------------|
| PCA        | 51955–55927  | 2–60 keV    | 5.0 ± 0.9                                   | −8.8 ± 0.1                            |
| HEXT E     | 51955–55927  | 15–250 keV  | 4.5 ± 0.9                                   | −8.7 ± 0.1                            |
| PCA        | 53500–55693  | 2–60 keV    | 4.8 ± 2.1                                   | −9.0 ± 0.2                            |
| Nanshan    | 53500–55688  | 1540 MHz    | 6.3 ± 1.0                                   | −1.6 ± 1.0                            |
| PCA\textsuperscript{a} | 53500–55693 | …           | −1.1 ± 1.1                                  | −7.4 ± 0.1                            |
| HEXT E\textsuperscript{b} | 51955–55927 | …           | −0.2 ± 0.3                                  | 0.2 ± 0.04                            |
| PCA\textsuperscript{c} | 50129–52941 | 2–16 keV    | 3.3 ± 2.0                                   | …                                     |
| PCA\textsuperscript{d} | 51955–55142 | 2–60 keV    | 6.6 ± 1.3                                   | …                                     |

\textsuperscript{a} These parameters correspond to the values at MJD 54000.

\textsuperscript{b} The parameters for X-ray phases from PCA corrected by data of the Nanshan Telescope.

\textsuperscript{c} The parameters for the phase lags between HEXTE and PCA.

\textsuperscript{d} The result from Rots et al. (2004).

\textsuperscript{e} The result from Ge et al. (2012).
and phase jumps (three points around MJD 53350, corresponding to the JBE in one month).

Correlation coefficient is calculated to estimate the degree of correlation between $\Phi_P$ and $\Phi_H$. As shown in Figure 2 and listed in Table 2, $\Phi_H$ is almost proportional to $\Phi_P$, with a slope of $0.98 \pm 0.02$ and the Pearson’s coefficient $r = 0.96$, which means that they vary synchronously with the same amplitude.

The synchronous variations between $\Phi_P$ and $\Phi_H$ imply that they have the same origin.

4.2. The Correlation between X-Ray and Nanshan Phases

The Nanshan radio phases $\Phi_N$ are also obtained by using the same JBE, and they show variations in different timescales too,
as illustrated in Figure 1(e) and Figure 3(a). Compared with \( \Phi_P \) in the same time range, \( \Phi_N \) shows similar fluctuations, especially in MJD 55000–55200 as in the zoomed in Figure 3(b). For the secular change, \( \Phi_N \) increases linearly with a change rate of \( (6.3 \pm 1.0) \times 10^{-7} \) period per day in MJD 53500–55688, which is consistent with the change rate \( \Phi_P \), \( (4.8 \pm 2.1) \times 10^{-7} \) period per day in the same time range. These two change rates that were obtained in a relatively short period are also consistent with the results obtained from the whole time range for \( \Phi_P \) and \( \Phi_H \). As shown by the cross marks in Figure 2, \( \Phi_N' \) and \( \Phi_P \) exhibit a strong linear correlation, with the Pearson’s coefficient \( r = 0.78 \) (Table 2) and a slope of \( 0.72 \pm 0.04 \). The strong correlation between \( \Phi_N' \) and \( \Phi_P \) means that \( \Phi_N \) and \( \Phi_P \) also have a strong correlation.

The fitted slope between \( \Phi_N' \) and \( \Phi_P \) \( (0.72 \pm 0.04) \) is different from 1, the expected values of \( \Phi_N \) and \( \Phi_P \) have the same variation amplitude and an exactly linear correlation. One may think that there is some physics behind this. Nonetheless, we realized that this result probably originated from the data handling process. Since the X-ray and Nanshan radio observations are carried out in different times, we obtained the Nanshan phases at the time of X-ray observations with linear interpolation \( (\Phi_N' \Delta t) \), so as to study their correlation. This linear interpolation will reduce the amplitudes of the radio timing noises, and the larger the amplitude is, the bigger the fraction of the variation that will be reduced. As a result of this linear interpolation process, the slope can be smaller than 1.

If the JBE can describe the spin of the Crab pulsar accurately, \( \Phi_N \) should be constant over time, because \( \Phi_N \) is also inferred from the radio data. However, as given above, \( \Phi_N \) has a secular change with a significance of nearly \( 6.3 \sigma \), and both its long-time and short-time variations are similar to the X-ray ones that are also derived from the JBE. It is very likely that the temporal behaviors of the Crab pulsar cannot be accurately described by those spin parameters in the JBE, which also causes the apparent variation of the X-ray to radio phase lags.

### 4.3. The X-Ray Phases Using the Nanshan Radio Ephemeris

The simultaneous secular changes and fluctuations of the X-ray and Nanshan radio phases imply that they may be caused by the timing noise of the Crab pulsar or the inaccuracies in the JBE. In order to further check the relations between the X-ray and radio phases, here we use the Nanshan phases \( \Phi_N \) as the phase references, and obtain the corrected X-ray phases \( \Phi_{\text{PC}} \) from PCA data, which has a lower variation amplitude (i.e., standard deviation) 0.0013 compared to 0.0020 of \( \Phi_P \) as shown in Figure 3(c). Moreover, \( \Phi_{\text{PC}} \) keeps almost constant over the time range MJD 53500–55693 with a change rate of \( (-1.1 \pm 1.1) \times 10^{-7} \) period per day. The disappeared secular change of the new X-ray phases suggests that the JBE is inaccurate.

### 5. Origin of the Phase Variation and Timing Noise

There are several factors that can result in the variabilities of the observed X-ray phases: the instability of the time system, the change of the instrument response, the timing noise of the pulsar, the inaccuracies of the ephemeris, and the intrinsic variation of the X-ray emitting region relative to the radio ones. The effects of these factors are discussed in the following.

#### 5.1. Time System and Instrument Response

The Mission Operations Center of RXTE performs clock calibrations several times a day, using the User Spacecraft Clock Calibration System method, and the timing accuracy was improved from 4.4 to 2.5 \( \mu \text{s} \) on 1997 April 29 (Jahoda et al. 2006). Besides, the instrumental delay correction for the PCA is 16–20 \( \mu \text{s} \) and for the HEXTE it is 0–1 \( \mu \text{s} \). The barycenter corrections by FTOOL has an accuracy of better than 1 \( \mu \text{s} \) and
has also subtracted 16 \( \mu s \) to account for the instrumental delay in the PCA.\(^7\) Therefore, the maximum timing uncertainties is \( \sqrt{2.5^2 + 1^2} + 4 = 6.7 \mu s \), which has a much smaller impact on the timing measurement for X-ray photons than the 40 \( \mu s \) systematic error from JBE (Rots et al. 2004).

If the time systems of RXTE and the Nanshan telescope were inaccurate, wrong timing recorders would be assigned and thus would cause the abnormal phases. For PCA and HEXTE, the consistent variations might have been caused by the irregularity of the time system because they use the same time information from the satellite.\(^8\) However, considering that \( \Phi_P \) and \( \Phi_N \) have very similar variations and they are based on two independent time systems, the inaccuracy of the time systems cannot account for the observed phase fluctuations.

The aging of detectors would also have impacts on the timing recorders. As the X-ray phase lag of the Crab pulsar evolves with energy (Molkov et al. 2010; Ge et al. 2012), the phase lag will change if the detection efficiency curve varies due to the instrument aging or other factors (Garcia et al. 2014). However, the change of the response functions of the X-ray instruments cannot explain the correlation between \( \Phi_P \) and \( \Phi_N \), because the detectors are totally different.

5.2. Inaccuracies in JBE

The inaccuracy in the ephemeris have direct impacts on the phase calculations for the X-ray and Nanshan phases. The effect of ISM, pulsar proper motion, glitches, as well as timing noises could all generate inaccurate parameters.

5.2.1. Effect of the ISM

Because of the existence of ISM, the arrival time of radio pulses is dependent on frequency. Both the mismeasurement of DM and the scattering of ISM have an impact on radio observations and phase results.

During MJD 55050–55350, the variation amplitudes of DM are larger than in the other time periods, which is apparently consistent with the questionable points in this time range. The phase change caused by DM could be obtained using \( \Phi_{N0} - \Phi_N \), and its impact on the Nanshan phase could be evaluated by comparing it with \( \Phi_N \). However, as shown in Figure 4, the phase change caused by DM is smaller than the phase fluctuation in both X-ray and Nanshan phases in MJD 55050–55350, as the DM effect has been removed in the JBE (Lyne et al. 1993). So, the large fluctuation in the X-ray and Nanshan phases in MJD 55050–55350 could not be explained by the DM effects.

As for the scattering of ISM, its influence on TOA could be evaluated by the following formula (Lyne & Graham-Smith 2012).

\[
 t_{\text{scatt}} = \left( \frac{\text{DM}}{1000 \text{ pc cm}^{-3}} \right)^{3.5} \left( \frac{400 \text{ MHz}}{\nu_{\text{MHz}}} \right)^{4.5}.
\]

For the Crab pulsar, \( \text{DM} = 56.78 \text{ pc cm}^{-3} \), and when \( \nu_{\text{MHz}} = 1540 \text{ MHz (Nanshan radio band)} \), \( t_{\text{scatt}} \approx 0.2 \mu s \). In the X-ray band \( t_{\text{scatt}} \) would be much smaller. It is thus clear that the influence of ISM scatting on the Nanshan and X-ray phases could be disregarded.

5.2.2. Effect of the Proper Motion

With accurate measurement by the Hubble Space Telescope, the proper motion of the Crab pulsar has been obtained as \( \mu_\alpha = -11.8 \text{ mas yr}^{-1} \) for R.A. and \( \mu_\delta = 4.4 \text{ mas yr}^{-1} \) for decl. (Kaplan et al. 2008). However, the JBE uses a constant position for the Crab pulsar, and the influence of proper motion on the relative phases should be considered. If the pulsar position is changing, the time residuals should show oscillations with gradually increasing amplitude (Helfand et al. 1977), which could be roughly described by \( \Delta \Phi_{\text{pm}} = h \cdot \sin \alpha \cdot \Delta \theta / c_0 \cdot f \), where \( h \) is the distance between the Earth and the Sun, \( c_0 \) is the speed of light, and \( \alpha \) is the decl. of the Crab pulsar. Taking into account the proper motion, the maximum value of the amplitude is 0.0035 periods for 10 years. However, the impact of proper motion is counteracted when the time is longer than one month, because the X-ray and Nanshan phases are the relative phases to JBE that were updated monthly. We check the power spectrum of these relative phases to see whether variation power exists on the timescale of about a month, which could be the impact of pulsar proper motion on the relative phases, and eventually no significant signals in the power spectrum of \( \Phi_P \) and \( \Phi_H \) have been found. Thus, the proper

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\(^7\) http://heasarc.gsfc.nasa.gov/docs/xte/abc/time.html
\(^8\) http://heasarc.nasa.gov/docs/xte/time_news.html
motion is not the main reason for the long-term variation of the X-ray and Nanshan phases. Similarly, the inaccuracy of solar system ephemeris could not account for the long-term variation of the X-ray phases.

5.2.3. Check of the Spin Parameters

Inaccurate spin parameters could lead to phase deviation. There are some outliers in X-ray and Nanshan phases, especially the X-ray phases around MJD 53350, which are obtained by using one ephemeris. These results remind us to check the reliability of the JBE parameters, from the aspects of glitches, rotation frequencies, and radio reference TOAs.

Because the parameters of glitches have not been included in the JBE directly (Lyne et al. 1993), we need to check whether the significant residuals are caused by the glitches. However, we find that the obviously abnormal phases are not coincident with the glitch epochs. The effects of glitches after their occurrence month are greatly reduced. In MJD 53341–53372 there is no glitch, so the outliers in this period did not result from glitches.

Furthermore, we check the parameters of JBE in MJD 53341–53372 in case the JBE parameters are inaccurate. First, we compare the rotation frequencies inferred from JBE and those we searched from the three RXTE observations in this period. The maximal difference between them is $(0.3 \pm 1.2) \times 10^{-5}$ Hz for PCA and $(2.0 \pm 5.8) \times 10^{-5}$ Hz for HEXT, where the uncertainties are only from our frequency searching process, which show that the frequencies we calculated from these three observations are consistent with the JBE predictions. Second, we calculate the TOAs of these three X-ray observations using the frequencies we obtained above and the software TEMPO2 (Edwards et al. 2006; Hobbs et al. 2006), and then compare them with the TOAs inferred from the JBE time solution and the FTOOL command FASEBIN. As shown in Figure 1, TOAs obtained with the above two methods are consistent. Therefore, both the JBE frequencies and the TOA calculation process are reliable, and the remaining possibility is that the reference TOA of JBE in MJD 53341–53372 is inaccurate, which causes the abnormal lags between the X-ray and radio phases. We note that the inaccuracy of JBE TOAs has also been found by the Jodrell Bank Observatory, as on the web page of JBE it is pointed out, “DO NOT trust the geocentric pulse arrival times yet!”

5.3. Is There a Significant Intrinsic Variation of the X-Ray Emitting Region Relative to the Radio Ones?

It is important for pulsar physics to find out whether the fluctuations and long-term evolutions of the X-ray phases are intrinsic, i.e., due to the relative geometric variations between the X-ray and radio emitting regions. We find that there are two observational facts contradicting this hypothesis. As shown in Figure 2, the Nanshan radio phases are highly correlated with the X-ray phases derived from the PCA observations, which means that the two phases wander simultaneously. Furthermore, by using the Nanshan phases as a reference, the X-ray phases have a smaller fluctuation amplitude and the long-term evolution disappears (Figure 3(c)), which also implies that the X-ray and radio emitting regions do not have significant relative changes. Thus, the X-ray and radio phase fluctuations are both dominated by the pulsar spin.

5.4. Constraints on Timing Noises

The almost constant phase-lag between the X-ray and radio bands also supplies information about the origins of timing noises. Variations of the DM and thus the variations of ISM between the earth and pulsars have been detected, which can lead to the radio timing noises of those pulsars (You et al. 2007, and references there in). However, because the ISM has no effect on the X-ray TOAs, the constant value of the X-ray phase $\Phi_r$ means that most of the timing noises are not from the ISM, which is consistent with the results of PSR B1540–06 obtained from the multi-frequency radio observations (Hobbs et al. 2010). Thus ISM variation cannot account for all the timing noises of the Crab pulsar.

6. Summary

Utilizing the 11-year X-ray observations from the RXTE, 6-year radio observations from Nanshan Telescope, and the ephemeris from the Jodrell Bank Observatory, we study the evolution of the X-ray and radio phases of the Crab Pulsar. The X-ray phases from PCA and HEXTE exhibit synchronous variations on all timescales, and X-ray and Nanshan phases also have a strong correlation with a Pearson’s coefficient $r = 0.78$. We find that the simultaneous secular changes and fluctuations of the X-ray phases $\Phi_r$, $\Phi_H$ and the Nanshan phases $\Phi_N$ are quite possibly caused by the unreliable reference TOAs in the JBE parameters. Using the Nanshan phases as a timing reference, the corrected X-ray phases $\Phi_r$ show lower variation amplitude and remain almost constant over time with a change rate of $(-1.1 \pm 1.1) \times 10^{-7}$ period per day.

Based on the results above, we conclude that the distance of the X-ray and radio emission regions on the Crab pulsar does not show detectable secular changes, and the timing noises are not the result of any unique physical processes in the radio or X-ray radiation regions. In addition, the variation of the ISM is not the origin of Crab pulsar’s timing noises, which is consistent with the results obtained from the multi-frequency radio observations of PSR B1540–06 (Hobbs et al. 2010).

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