DID THE CRAB PULSAR UNDERGO A SMALL GLITCH IN 2006 LATE MARCH/EARLY APRIL?

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ABSTRACT
On 2006 August 23 the Crab Pulsar underwent a glitch, which was reported by the Jodrell Bank and the Xinjiang radio observatories. Neither data are available to the public. However, the Jodrell group provides monthly arrival times of the Crab Pulsar pulse (their actual observations are done daily), and using these, it is shown that about 5 months earlier the Crab Pulsar probably underwent a small glitch, which has not been reported before. Neither observatory discusses the detailed analysis of data from 2006 March to August; either they may not have detected this small glitch, or they may have attributed it to timing noise in the Crab Pulsar. The above result is verified using X-ray data from RXTE. If this is indeed true, this is probably the smallest glitch observed in the Crab Pulsar so far, whose implications are discussed. This work addresses the confusion possible between small-magnitude glitches and timing noise in pulsars.

Key words: pulsars: individual (Crab Pulsar) – X-rays: stars

1. INTRODUCTION

Glitches in pulsars are probably the only method of studying the internal structure of neutron stars (Baym et al. 1969; Ruderman et al. 1998); see Shemar & Lyne (1996) and Lyne et al. (2000) for an observational perspective, and Haskell & Melatos (2015) for a theoretical discussion of pulsar glitches. Among pulsars that have been observed for their glitch behavior, the Crab Pulsar (PSR B0531+21 or J0534+2200) has been the most closely studied (Lyne et al. 2015). Glitches in this pulsar occur, on average, once every 1.5 yr. Its several glitches have been analyzed and results for them published by Lyne et al. (1988, 1993, 2000), Wong et al. (2001), Espinoza et al. (2011), and Wang et al. (2012), the most recent study being that of Lyne et al. (2015). This work focuses on the glitch that occurred in the Crab Pulsar on 2006 August 23 (henceforth CPG2006), more precisely, on the 5-month duration before CPG2006. Two radio observatories observed it in sufficient detail to derive the relevant glitch parameters—the Jodrell Bank Observatory (Espinoza et al. 2011; henceforth JBO) and the Xinjiang Astronomical Observatory (Wang et al. 2012; henceforth XAO).

The critical pre-glitch reference timing model is obtained by both groups by fitting a simple rotation model to the timing data for a given duration before the glitch (the pre-glitch duration [PGD]); the model typically consists of the pulsar rotation frequency \( \nu \) and its first two derivatives \( \dot{\nu} \) and \( \ddot{\nu} \), at the epoch of the glitch, which is MJD \( \approx 53,970 \) for both observatories. The PGD for the JBO group is about 43 days starting from MJD 53,926 (C. Espinoza 2016, private communication), while that of the XAO group is 280 days, from MJD 53,685 to MJD 53,965. The timing residuals for CPG2006 relative to the pre-glitch reference timing model are analyzed by both groups, obtaining consistent results.

This work shows that a different choice of the PGD for CPG2006 reveals what appears to be a small glitch about 5 months before the main glitch. The monthly radio timing data of the Crab Pulsar from JBO are used to derive the result, and X-ray data from RXTE are used to verify it. In the last section it is argued that this is more likely to be a glitch than timing noise, although the data available strictly do not allow us to discriminate between the two possibilities.

2. OBSERVATIONS

The Crab Pulsar was monitored daily by JBO since 1984, mainly at 610 MHz frequency (Lyne et al. 2015). Occasionally it was also observed in the 1400–1700 MHz band. The XAO has been monitoring the Crab Pulsar once a week at 1540 MHz since 2000 January (Wang et al. 2012). Both groups estimate the arrival time of the integrated pulse profile (IP) of the Crab Pulsar and use these data to study the several glitches in this pulsar by means of standard techniques. Neither of the above two data are available in the public domain. However, JBO also publishes monthly arrival times of the Crab pulsar IP, referred to the solar system barycenter, and scaled to infinite frequency, in the so-called Jodrell Bank Crab Pulsar Monthly Ephemeris (Lyne et al. 1993; henceforth JBCPME). Data from this ephemeris spanning the epoch 2005 November 15 to 2007 May 15 (MJD 53,689 to MJD 54,235), yielding 19 timing residuals, have been used for this work. In practice, one requires daily timing residuals to properly analyze the glitches in the Crab Pulsar. However, JBCPME also contains very accurate \( \nu \) and \( \dot{\nu} \) at each monthly epoch, which help in converging to a sufficiently accurate pre-glitch reference timing model. Thus, the monthly radio data used in this work are suitable to demonstrate the existence of the smaller glitch, which is the main goal of this work; derivation of statistically rigorous glitch parameters requires the original daily observed data. Although this work uses only the Crab Pulsar’s timing residuals, the main result is also evident in the \( \nu \) and \( \dot{\nu} \) listed by JBCPME, as discussed in the last section.

The X-ray data used in this work were obtained from the Proportional Counter Array (PCA; Jahoda et al. 1996) and the High Energy X-ray Timing Experiment (HEXTE; Rothschild et al. 1998) aboard RXTE observatory. The PCA consists of five proportional counter units (PCUs) operating in the 2–60 keV range, having a field of view of 1° in the sky and a time resolution of 1 \( \mu \)sec (see “The ABC of XTE” guide on the RXTE website\(^\text{1}\)). The HEXTE instrument consists of two independent clusters of detectors. Each cluster contains four NaI(Tl)/CsI(Na) phoswich scintillation photon counters and

\(^{1}\) http://www.jb.man.ac.uk/pulsar/crab.html

\(^{2}\) heasarc.gsfc.nasa.gov/docs/xte/data_analysis.html
has a field of view of 1° in the sky. Effectively this instrument is sensitive to photons in the 15–240 keV range, and each photon’s arrival time accuracy is ≈7.6 μs (see “The ABC of XTE” guide). The first RXTE observation used in this work was obtained on 2005 November 18 (MJD 53,692), and the last on 2007 April 23 (MJD 54,213); the corresponding observation identification numbers (ObsIDs) are 91802-02-10-00 and 92802-01-21-00, respectively. This yielded 34 PCA timing residuals, but only 32 HEXTE residuals, since there were insufficient X-ray photons in the HEXTE data of ObsIDs 91802-02-12-00 and 92802-01-04-00. The PCA data were obtained in the event mode with identifier $E_{250\mu s\_128M\_0\_1s}$, after being integrated into time intervals of 244.14 μs, and binned in energy into 128 channels having nonuniform energy widths. In 20 ObsIDs useful data were available when all five PCUs were switched on; in nine of them, when only four PCUs were switched on; and so on. Even when only one PCU was switched on (ObsIDs 92802-02-06-00 and 92802-03-05-00) the data had a sufficient number of photons to yield a statistically significant pulse profile.

3. ANALYSIS OF RADIO DATA

The top panel of Figure 1 shows the radio timing residuals of the Crab Pulsar, relative to the pre-glitch reference timing model given in Table 1, during the epoch under consideration. The pre-glitch reference timing model was obtained using the first five data in the top panel of Figure 1, in the range MJD 53,673.5 to MJD ≈ 53,812.0, translating to day −296.69 to ≈ −158.19 in abscissa. This duration will henceforth be referred to as the PGD. The TEMPO2 (Hobbs et al. 2006) best-fit parameters of these data are shown in Table 1. The standard deviation of the five data, from the model derived by TEMPO2, is $TRES = 38.6 \mu s$. However, TEMPO2 estimates $TRES$ using 5 degrees of freedom, whereas the number to use is 2, since three parameters have been fit for. The appropriate value of standard deviation is $\sqrt{38.6^2 \times 5/2} = 61 \mu s$. 

Figure 1. Timing residuals of the Crab Pulsar relative to the pre-glitch reference timing model given in Table 1. Residual 0 in each panel refers to the mean value of the residuals belonging to the pre-glitch duration of that panel. The dotted vertical lines are epochs after which a phase cycle of +1 had to be inserted into the timing data (using command PHASE +1 in TEMPO2). Data only up to MJD 54,146 (day 175.81) have been shown to highlight the small depression extending from MJD ≈ 53,812.0 (day ≈ −158.19) to MJD 53,970.19 (day 0.0); this has been marked as SGD in the figure. Top panel: radio timing residuals from JBCPME. Middle panel: X-ray timing residuals from the RXTE/PCA data. Bottom panel: X-ray timing residuals from the RXTE/HEXTE data.

Table 1

| Parameter | Value |
|-----------|-------|
| Epoch (MJD) | 53,750.0000002354282 |
| $\nu$ (Hz) | 29.774922671(1) |
| $\nu$ (s$^{-2}$) | $-372853.5(4) \times 10^{-15}$ |
| $\nu$ (s$^{-3}$) | $1.2(1) \times 10^{-20}$ |

Note. The errors in the last digit of each number are shown in parentheses.
By including the next five timing residuals in the top panel of Figure 1, from MJD $\approx 53,812.0$ to MJD 53,970.19, or day $\approx -158.19$ to 0.0 in abscissa, the TEMPO2 best-fit parameters are $\nu = 29.7749226293(8)$ Hz, $\dot{\nu} = -372852.4(4) \times 10^{-15}$ s$^{-2}$, and $\ddot{\nu} = 1.14(1) \times 10^{-20}$ s$^{-3}$. The TRES of these 10 data is 223.3 $\mu$s, but the appropriate value of standard deviation is $\sqrt{223.3^2 + 10/7} = 267 \mu$s. The two variances differ by 267$^2 - 61^2 = 67568$, while the standard error on this difference is $\sqrt{2 \times (267^4/7 + 61^4/2)} = 38287$. The two variances differ by 67568/38287 = 1.76 standard errors, i.e., the latter variance is significantly larger than the former at the 92% confidence level. Attempts made to obtain statistical fits with standard deviation less than 267 $\mu$s failed (for example, by choosing a different reference epoch, by altering initial values of the parameters by hand, etc.). Therefore, using radio data right up to MJD 53,970.19, to derive the pre-glitch reference timing model, is not justified. The reason is the small depression extending from MJD $\approx 53,812.0$ to MJD 53,970.19 (day $\approx -158.19$ to day 0.0) in the top panel of Figure 1, which will henceforth be referred to as the small glitch duration (SGD). The main glitch that follows is clearly evident in the top panel of Figure 1. It starts at MJD 53,970.19 and extends up to MJD 54,250.5, or day 0.0 to 280.31 (henceforth referred to as the main glitch duration [MGD]), although data only up to MJD 54,146 (day 175.81) have been shown in Figure 1 to highlight the depression.

Figure 2 shows a closer view of the top panel of Figure 1; earlier what looked like a depression now looks more like a glitch. Data points 3–7 in Figure 2 (five radio data points belonging to SGD) have been fit to the function $f(t)$ in Equation (1), the fit taking into account their errors,

$$f(t) = a_1(t - t_1) + \frac{b_1}{2}(t - t_1)^2 + c_1\left(1 - \exp\left(-\frac{(t - t_1)}{\tau_1}\right)\right) + c_2\left(1 - \exp\left(-\frac{(t - t_2)}{\tau_2}\right)\right),$$

where the parameters $t_{1,2}$ (epoch of the glitch), $a_{1,2}$ (related to the permanent change in rotation frequency at the epoch of the glitch $\Delta \nu_p$), $b_{1,2}$ (related to the permanent change in rotation frequency derivative $\Delta \dot{\nu}_p$), $c_{1,2}$ (related to the exponential change in rotation frequency $\Delta \nu_o$), and $\tau_{1,2}$ (decay timescale of the glitch) are all allowed to vary during the nonlinear fit (see Shemar & Lyne 1996; Vivekanand 2015, for further details on Equation (1)). Several equivalent fits are obtained by choosing the initial value of $t_1$ between day $-160$ and day $-131$, which...
is the range of epoch between the last data point of PGD and the first data point of SGD; the corresponding \( \tau_1 \) obtained are 5.7 and 3.0 days, respectively; larger values of \( t_1 \) yield smaller values of \( \tau_1 \), as is expected. An illustrative fit, obtained using the initial value of \( t_1 = -146 \) (midway between the above two numbers), is shown in the second row of Table 2. The corresponding \( f(t) \) is plotted as the dashed line in Figure 2. While the nonlinear fit converges to the solution given with a standard deviation of 62 \( \mu s \), fitting five data points to a function with five parameters leaves no degrees of freedom to estimate the errors on the parameters.

Attempts to fit the data to a modified \( f(t) \), which does not contain the last \( (c_1 \) and \( \tau_1 \) term, converge to values of \( t_1 \) lower than the epoch of the last data point of PGD. These are unrealistic solutions, since the first residual after a glitch must have a more negative value than that of the pre-glitch reference timing model. This shows that inclusion of the decay time is critical in the fit, further supporting the assertion that what looks like a small depression is probably a small glitch, although timing noise cannot be ruled out. However, one must keep in mind that the function \( f(t) \) has five parameters, and only five data are used in the fit in this section. While it is true that a set of five data points cannot be fit to an arbitrary function of five parameters, partially if the function is a mixture of polynomials and exponential, one must be open to the possibility that the data of SGD may also be due to timing noise.

Next, the radio data belonging to MGD are fit to the function \( g(t) \) of Equation (1). Ideally this should be done after subtracting \( f(t) \) from the timing residuals of MGD. Here it is assumed that \( f(t) \) is much smaller than \( g(t) \) for the MGD epochs; hence, \( g(t) \) is fit to the residuals without subtracting \( f(t) \), since the derived glitch parameters are not expected to be statistically rigorous anymore. It has been verified that results of both approaches are statistically consistent. A fit varying all parameters converges to the unrealistic situation of \( \tau_2 \) being less than the epoch of the last data of SGD. By fixing \( t_2 \) at various epochs between that of the last data point of SGD and that of the first data point of MGD (noninclusive), various solutions can be obtained in which \( \tau_2 \) varies consistently. Solutions closer to the former data point appear to have lower standard deviation. The solution shown in the second row of Table 3 is an illustrative one, where \( t_2 \) has been fixed to a value midway between the above two points, while the rest of the four parameters have been varied. The corresponding curve is the dot-dashed curve in Figure 2. Although the parameters in the second row of Table 3 are consistent with the results derived by both JBO and XAO for CPG2006, the radio data used in this work are not suitable to derive rigorous glitch parameters. It is therefore concluded that the CPG2006 event was preceded by a small glitch. However, it should be kept in mind that this result depends critically on the pre-glitch reference timing model derived above, for which unfortunately only five radio timing residuals were available. Therefore, the results of this section do not rule out timing noise altogether.

### Table 2

Results for the Smaller Glitch, Derived from the Best-fit Parameters, That Are Obtained by Fitting \( f(t) \) to the Data of the Smaller Glitch (SGD) in Figures 2 and 3 (Data Imply Timing Residuals in SGD, Relative to the Model of Table 1)

| Data    | \( t_1 \) (MJD) | \( \Delta \nu_p \) (10^{-6} Hz) | \( \nu_p \) (10^{-13} s^{-2}) | \( \Delta \nu_r \) (10^{-6} Hz) | \( \tau_d \) (days) |
|---------|----------------|--------------------------------|--------------------------------|--------------------------------|-------------------|
| JBCPME  | 53,824.2       | 0.005                          | -0.018                         | 0.066                          | 5.2               |
| PCA     | 53,811.9       | 0.008 ± 0.003                  | -0.019 ± 0.004                 | 0.03 ± 0.03                    | 8.3 ± 6.7         |
| HEXTE   | 53,811.9       | 0.005 ± 0.006                  | -0.015 ± 0.006                 | 0.03 ± 0.04                    | 15.7 ± 12.4       |

Note. In all three cases, the epoch of the glitch \( t_1 \) is chosen or fixed as explained in the text. No error bars are shown for the radio case since no degrees of freedom are left after the fit.

### Table 3

Results for the Larger Glitch, Derived from the Best-fit Parameters, Obtained by Fitting \( g(t) \) to the Data of the Main Glitch (MGD) in Figures 2 and 3 (Data Imply Timing Residuals in MGD, Relative to the Model of Table 1)

| Data    | \( t_1 \) (MJD) | \( \Delta \nu_p \) (10^{-6} Hz) | \( \nu_p \) (10^{-13} s^{-2}) | \( \Delta \nu_r \) (10^{-6} Hz) | \( \tau_d \) (days) |
|---------|----------------|--------------------------------|--------------------------------|--------------------------------|-------------------|
| JBCPME  | 53,977.5       | 0.083 ± 0.007                  | -0.223 ± 0.004                 | 0.5 ± 0.2                      | 8.9 ± 2.7         |
| PCA     | 53,969.5       | 0.110 ± 0.004                  | -0.233 ± 0.005                 | 0.4 ± 0.1                      | 7.8 ± 2.1         |
| HEXTE   | 53,969.5       | 0.108 ± 0.004                  | -0.232 ± 0.005                 | 0.3 ± 0.1                      | 8.9 ± 2.4         |

Note. In all three cases, the epoch of the glitch \( t_2 \) has been fixed midway between the last data point of SGD and the first data point MGD.

### 4. ANALYSIS OF X-RAY DATA

The results derived using radio data are now verified using X-ray data from RXTE. Vivekanand (2015, 2016) discuss in detail the analysis of Crab Pulsar data from the HEXTE and PCA instruments, respectively. In this work one has to additionally filter the PCA data for time markers, using the tool fselect along with a bitfile containing the script “Event == b1xxxxxxxxxxxxxxx” (see “The ABC of XTE” guide), because of the data mode of PCA. The same must be done when using the tool seeext to obtain the light curve.

TEPMG2 fits to the eight PCA residuals and the seven HEXTE residuals in the PGD (see the middle and bottom panels of Figure 1) resulted in pre-glitch reference timing models that had standard deviation of data TRES of 111 and 114 \( \mu s \), respectively. After taking into account the true degrees of freedom, the above two standard deviations become 140 and 151 \( \mu s \), respectively. By including the SGD data also, the TEMPO2 fits yield pre-glitch reference timing models with corrected standard deviations of 231 and 268 \( \mu s \), respectively. By the argument of the previous section, both sets of variances (231, 140 and 268, 151) differ at the 82% confidence level. Therefore, both the PCA and the HEXTE data confirm the result of the previous section, that one is not justified in
including the SGD data to obtain the pre-glitch reference timing model for CPG2006.

Although the glitch behavior in the X-ray data of SGD is evident when these timing models are used, they are clearly worse than the pre-glitch reference timing model obtained from the radio data. Therefore, the latter has been used to analyze the X-ray data.

The top panel of Figure 3 shows a closer view of the middle panel of Figure 1. Fitting the function \( f(t) \) to the seven PCA data in the SGD does not converge to a solution if all five parameters are varied, for several initial values of \( t_1 \) and \( \gamma_1 \). Therefore, for illustrative purposes \( t_1 \) was fixed midway between the last PCA data point of PGD and the first PCA data point of SGD. The corresponding \( f(t) \) is plotted as the dashed line in the top panel of Figure 3, while the corresponding parameters, or the results derived from them, are listed in the third row of Table 2; the standard deviation of the data from this solution is 76 μs. Attempts to fit the function \( g(t) \) to the 19 PCA data of MGD by varying all five parameters resulted in unrealistic solutions of \( t_1 \). Therefore, for illustrative purposes \( t_1 \) was fixed midway between the last HEXT data point of SGD and the first HEXT data point of MGD. The corresponding \( g(t) \) is plotted as the dot-dashed line in the bottom panel of Figure 3, while the corresponding parameters, or the results derived from them, are listed in the last row of Table 3.

The bottom panel of Figure 3 shows a closer view of the bottom panel of Figure 1. Fitting the function \( f(t) \) to the six HEXT data in the SGD by varying all parameters led to results similar to those in the PCA case. Therefore, for illustrative purposes \( t_1 \) was fixed midway between the last HEXT data point of PGD and the first HEXT data point of SGD. The corresponding \( f(t) \) is plotted as the dashed line in the bottom panel of Figure 3, while the corresponding parameters, or the results derived from them, are listed in the last row of Table 2; the standard deviation of the data from this solution is 57 μs. Attempts to fit the function \( g(t) \) to the 19 HEXT data of MGD by varying all five parameters resulted in unrealistic solutions of \( t_1 \). Therefore, for illustrative purposes \( t_1 \) was fixed midway between the last HEXT data point of SGD and the first HEXT data point of MGD. The corresponding \( g(t) \) is plotted as the dot-dashed line in the bottom panel of Figure 3, while the corresponding parameters, or the results derived from them, are listed in the last row of Table 3.

The behavior of the fits to X-ray data in Figure 3 is very similar to that in Figure 2. It is therefore concluded that the X-ray data confirm the results obtained from radio data.

5. DISCUSSION

It is clear from the analysis of the monthly radio data (Figure 2, Table 2, and the analysis of Section 3) that the Crab Pulsar probably suffered a small glitch before CPG2006.
This is verified by the X-ray data (Figure 3, Table 2, and the analysis of Section 4).

As already mentioned, the data available for this work are quite sufficient to demonstrate the existence of something that looks like a small glitch, but not to derive rigorous glitch parameters. So the parameters used to plot the functions \( f(t) \) and \( g(t) \) in Figures 2 and 3 (listed in Tables 2 and 3) should be taken as illustrative. Even then, the values of \( \tau_2 \) in Table 3 are consistent with the value of 7.3 ± 0.3 days derived by Wang et al. (2012). The value of \( \Delta \nu_p + \Delta \nu_n \) in the second row of Table 3 is 0.58 ± 0.20 \( \mu \)Hz, which is consistent with the value of 0.41 ± 0.09 derived by Wang et al. (2012). The ratio of change in rotation frequency derivative \( (\Delta \nu_p + \Delta \nu_n)/\nu \times 10^9 \) from the second row of Table 3 is 19 ± 7, which is consistent with the value of 21.8 ± 0.2 derived by Espinoza et al. (2011). The ratio of change in rotation frequency derivative \( (\Delta \nu_p + \Delta \nu_n)/\nu \times 10^9 \) from the second column of Table 3 is 1.8 ± 0.7, which is roughly consistent with the value of 3.1 ± 0.1 derived by Espinoza et al. (2011) and the value of 1.3 estimated by Wang et al. (2012). Thus, the illustrative radio solution in the second row of Table 3 is consistent with earlier estimates; it is expected since the small glitch perturbs only weakly the pre-glitch reference timing model for the main glitch. The X-ray solutions in the last two rows of Table 3 are consistent with this radio solution. This can also be taken as indirect validation of the illustrative radio solution for the small glitch in Table 2, since this is used to derive the solution for the main glitch. The X-ray solutions in the last two rows of Table 2 are consistent with the radio solution for the small glitch (second row of Table 2), as expected.

The small glitch is also evident in the \( \nu \) and \( \bar{\nu} \) data of JBCPME. By fitting a straight line to the five \( \bar{\nu} \) data of the PGD, it is seen that the next five \( \bar{\nu} \) (belonging to the SGD) lie systematically lower (larger in magnitude) than the line, by at least \(-18(\pm7) \times 10^{-15} \) s\(^{-2}\), which is the typical signature of a very small glitch in the Crab Pulsar. By doing the same with the \( \nu \) data, it is seen that \( \nu \) increases systematically in the SGD. Although one expects such an increase to be sudden just after a glitch, this result also indicates that the \( \nu \) and \( \bar{\nu} \) of the Crab Pulsar had probably behaved similar to those during a glitch in the boundary region between PGD and SGD.

The PGD in the radio data apparently cannot be extended to lower epochs; the residuals for the epochs MJD 53,658 and MJD 53,628 lie systematically above those of the five PGD residuals. This is also apparent in the \( \bar{\nu} \) data of JBCPME, which are more positive before the PGD.

Did the glitch detector of Espinoza et al. (2014) detect this small glitch? It probably did, and probably classified it as one of their 381 Glitch Candidates (GCs). Espinoza et al. (2014) allow for the possibility that some of the GCs might be real glitches, but believe that most of them are due to timing noise. Therefore, it is likely that Espinoza et al. (2014) believe that this event is not a glitch but is on account of timing noise. The fact that the \( c_1 \) and \( \tau_1 \) terms in \( f(t) \) (in Equation (1)) are required to give a sensible fit to the SGD data gives some support for the belief that one is dealing with a glitch and not timing noise. On the other hand, Espinoza et al. (2014) may have missed this glitch, due to their methodology. They use 20 times of arrival (TOAs) to obtain the pre-glitch reference timing model and fit a quadratic function to the next 10 TOAs. It is possible that these numbers are inadequate for sensing the small glitch of this work. Furthermore, they were looking for a sudden rise in rotation frequency \( \nu \), whereas, as indicated by the \( \nu \) data of JBCPME, this may be a slower glitch. In this context, this work focuses attention on the problem of distinguishing between a small glitch and timing noise in pulsars.

It appears unlikely that the small glitch and CPG2006 are causally connected, since they are separated by about \( \approx \)150 days. There are glitches in the Crab Pulsar separated by much smaller time—the glitches of MJD 50,459 and MJD 50,489 are separated by a mere 30 days, although there is doubt whether the latter is a glitch at all (Wong et al. 2001).

As Espinoza et al. (2014) point out, although the exact mechanism for glitches is not fully understood, the glitch magnitude distribution in general, and the magnitude of the smallest glitch in particular, in the Crab Pulsar is important information. The magnitude of a glitch is related to the number of superfluid vortices that unpin during the event (see Alpar et al. 1996; Ruderman et al. 1998). Clearly the smallest glitch in a pulsar will set constraints on the minimum size of the region in the inner crust that is involved in the glitch process. The numbers derived in the second row of Table 2 are not reliable enough to estimate rigorously the magnitude of the small glitch. This is best done using the daily sampled data of the JBO. The higher the dynamic range of glitch magnitudes (the ratio of the maximum to the minimum observed glitch magnitude) in the Crab Pulsar, the better one can derive the distribution of glitch magnitudes; some theoretical models predict a power-law distribution (Warszawski & Melatos 2008).

The size of a glitch depends on the number of unpinned vortices, the details of pinning and repinning of these vortices, and the location of unpinning (Warszawski & Melatos 2011). In particular, the size of a glitch depends on the pinning strength, stronger pinning causing larger glitches, although Warszawski & Melatos (2011) point out that this belief is not very obvious—contrary behavior is also possible. Therefore, the smallest possible glitch in a pulsar may set constraints on the distribution of pinning strengths in the crust, at the lower end of the distribution. The smallest possible glitch in a pulsar may also suggest that the crust is lighter rather than heavier (Warszawski & Melatos 2011), which may have implications for the equation of state of a neutron star.

In summary, this work demonstrates a peculiar behavior of the timing residuals of the Crab Pulsar that started around 2006 late March/early April and continued up to the epoch of the main glitch. This work has shown that this behavior is consistent with that of a small glitch. If this is true, then this is probably the smallest glitch detected so far in the Crab Pulsar, whose implications have been discussed above. On the other hand, this work does not rule out timing noise. Therefore, future pulsar timing programs will need not only better sensitivity but also fast cadences in order to be able to study the small glitches regime. If it turns out that this is indeed timing noise, then there are far-reaching implications for the definition of timing noise. The current consensus is that timing noise is supposed to be that which is left over in timing residuals after the effects of secular variations and glitches have been removed (Lyne et al. 1993). Clearly the understanding of the term “timing noise” needs to be revised if it starts behaving like a small glitch.

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