The 1969 Glitch in the Crab Pulsar Revisited

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ABSTRACT

Context. Glitches are important to understand the internal structure of neutron stars. They are studied using timing observations. The best studied neutron star in this respect is the Crab Pulsar. The first glitch recorded in this pulsar occurred in 1969 Sep, at an epoch when timing observations (and their analysis) were still in their infancy, the regularity of the observations was relatively poor, and errors on the observations were relatively high in the initial stages of the observations. Lyne et al. (1993) analyzed most of the available data using modern techniques, and showed that this was a typical glitch of the Crab pulsar, with typical glitch parameters.

Aims. This work analyses all available data, and shows that the 1969 event in the Crab pulsar is amenable to radically different interpretations.

Methods. The Crab pulsar was timed by five different groups during this epoch, one at radio and the rest at optical frequencies. These data are available in the public domain, and have been analyzed using the TEMPO2 software.

Results. The 1969 event in the Crab pulsar can be better modeled as a typical glitch that was interrupted by a (recently proposed) non-glitch speed-up event. This work also confirms the existence of a quasi-sinusoidal oscillation in the timing noise of the Crab pulsar, that was reported by Richards et al. (1970), but with a smaller period, and with its amplitude and period decreasing with time, like a chirp signal. Such a coherent oscillation has not been noticed so far in either the Crab or any other pulsar.

Conclusions. This work provides an explanation for the post-glitch behavior of the Crab pulsar glitches of 1969 Sep and 2004 Nov, and similar glitches in other pulsars, in terms of the recently proposed non-glitch speed-up event. If true, then non-glitch speed-up events may not be as rare as believed earlier. This work argues that it is unlikely that the frequency and amplitude modulated sinusoidal variation in the timing noise is due to unmodeled planetary companions.

Key words. (Stars:) pulsars: general – (Stars:) pulsars: individual . .. Crab

1. Introduction

The Crab Pulsar’s long term rotation is well represented by a rotation frequency $\nu$ and its first two time derivatives $\dot{\nu}$ and $\ddot{\nu}$; $\dot{\nu}$ is negative indicating slowdown, and $\ddot{\nu}$ is positive, indicating decreasing slowdown over time. Superimposed over this are two perturbations: (1) abrupt increase in the magnitude of $\nu$ and $\dot{\nu}$ roughly once in a couple of years, known as glitches, and (2) much slower and weaker and random variation in $\nu$ and $\dot{\nu}$ occurring over days, months and years, known as timing noise. Glitches are characterized by a sudden increase in rotation frequency ($\Delta \nu$, positive value) and decrease in its derivative ($\Delta \dot{\nu}$, negative value) at the epoch of the glitch $t_0$. Both parameters are further broken up into a change that is permanent post-glitch ($\Delta \nu_p$ and $\Delta \dot{\nu}_p$), and the remaining that decays exponentially with a typical timescale $\tau$ of $\approx 10$ days. Some glitches in the Crab pulsar have multiple decaying components, with decay time scales ranging from 0.1 to 320 days, which are not relevant here. Further details can be found in Lyne et al. (1993), Espinoza et al. (2011), Lyne et al. (2015) and Vivekanand (2015).

Glitches in the Crab pulsar are studied by first measuring the time of arrival at the observatory, of a fiducial point in its integrated profile, which is usually the first of its two peaks. This is done as frequently as possible, over a duration of several hundreds of days enclosing the glitch. Ideally the cadence of the observations should be once a day, but this is rarely feasible. For example, even if all else was conducive, the optical observations will necessarily have a gap during the months when the Crab pulsar rises above the horizon during daylight. These site arrival times are then converted to barycenter arrival times, using the TEMPO2 software (Hobbs et al. 2006). Next, one obtains the so called pre-glitch reference timing model, which consists of the best fit values of the rotation frequency and its derivatives at the glitch epoch $t_0$, labeled as $\nu_0$, $\dot{\nu}_0$ and $\ddot{\nu}_0$; this is done by a least squares fit to the pre-glitch barycenter arrival times in TEMPO2. Ideally this pre-glitch duration would be sufficiently long. Then the difference between the barycenter arrival times and the pre-glitch reference timing model, known as arrival time residuals $\Delta \phi$ (in seconds of time) are fit to a model of the glitch that has the parameters $\Delta \nu_p$, $\Delta \dot{\nu}_p$, $\tau$, etc. For details see equation 1 of Shemar & Lyne (1996) and equation 1 of Vivekanand (2015).

Figure 1 is a plot of $\Delta \phi$ against the epoch of observation for the Crab pulsar glitch of 1969, using exactly the same data, as well as exactly the same pre-glitch reference timing model, as that of Lyne et al. (1993). This is identical to panel 1 of their Figure 9 in minute detail. Figure 1 clearly demonstrates the parabolic variation of post-glitch $\Delta \phi$ for a typical glitch (see Espinoza et al. 2011 for more examples). The glitch parameters derived by Lyne et al. (1993) are given in their Table 4, and also in Table 3 of Wong et al. (2001) in a modified form.

The following sections show that the arrival time residuals $\Delta \phi$ of the Crab pulsar during the 1969 glitch can behave radically differently, depending upon the choice of the pre-glitch reference timing model.
The data cadence is very non-uniform. The Hamburg and Rochester observatories do not contribute at all to the pre-glitch segment; the Arecibo, Princeton and Harvard groups contribute 24, 26 and 19 arrival times, respectively (the last is discussed in greater detail in the Appendix). Lyne et al. (1993) did not explore the first four pre-glitch solutions of Table 2 and section 4.3 discusses their solution in greater detail.

Table 2 gives five pre-glitch reference timing models at the glitch epoch $t_0 = \text{MJD} 40494$, using five different ranges of pre-glitch epochs. The first model uses all pre-glitch data (73 barycenter arrival times), from epoch $\approx t_0 - 210$ to epoch $t_0$ days; the residuals $\Delta \phi$ with respect to this model are shown in Figure 2. The quasi-sinusoidal variation of $\Delta \phi$ in this figure is timing noise.

To test the stability of the results of the following sections, and also to approach progressively the pre-glitch reference timing model used by Lyne et al. (1993), three additional models were obtained, given in rows 2 through 4 of Table 2. Each of them uses approximately half of the data of the previous model, by using a pre-glitch epoch range whose starting point is roughly half of the range of abscissa of the previous model, but whose ending point is $t_0$. The epoch range of model 4 is one month, starting at $t_0 - 30$ days and ending at $t_0$; this is exactly the range used by Lyne et al. (1993). However model 4 has 10 data points, which is three more than that of Lyne et al. (1993), because of the three additional arrival times from the Harvard group. Model 5 is the same as model 4 except that the data is exactly that used by Lyne et al. (1993).
interrupted by a non-glitch speed-up event occurring at about 61 days after the glitch. The pre-glitch reference timing model in the first row of Table 1 has been used. The dashed sinusoid is explained in the text.

4. Post-glitch residuals

Figures 2 and 3 show the post-glitch residuals Δφ obtained by using the pre-glitch reference timing model in the first row of Table 2. The data in both figures is the same. However, it is modeled differently as discussed below.

4.1. A glitch interrupted by a non-glitch speed-up event

The Δφ of Figure 2 can be modeled as a typical glitch that is interrupted by a non-glitch speed-up event occurring at about 61 days after t₀. The post-glitch Δφ from t₀ to t₀ + 61 days in Figure 2 are fit to equation 1 of Vivekanand (2015), which models a typical glitch. The solid line from t₀ to t₀ + 61 days in Figure 2 represents the glitch, whose continuation is the dashed line. The best fit glitch parameters are: Δνₚ = +0.42(1) × 10⁻⁷ Hz, Δνₚ = −3.9(3) × 10⁻¹⁵ s⁻², Δνᵣₚ = 2.92(5) × 10⁻⁷ Hz, and τ = 3.7(2) days. These are very different from the values derived by Lyne et al. (1993) and given in Wong et al. (2001) (their τ = 18.7 ± 1.6 days).

For an uninterrupted glitch one would have expected the subsequent data to continue further along the dashed line in Figure 2. Instead of that, it turns downward in a parabolic manner, which is the hallmark of the recently proposed non-glitch speed-up event (Vivekanand 2017). The data in Figure 2 beyond t₀ + 61 days is fit to a parabolic curve which implies that the Δνₚ has changed from the glitch value of −3.9(3) × 10⁻¹⁵ to 15.74(6) × 10⁻¹⁵ s⁻². Thus the Crab pulsar can be modeled as having undergone, around epoch t₀ + 61 days, a persistent change of 15.74(6) × 10⁻¹⁵ s⁻² in ν, which is of similar magnitude as that reported in Vivekanand (2017).

The above combination of two separate solutions occurs for a range of choice of the point of inflection t₀ + 61 days, from t₀ + 42 to t₀ + 75 days. The point chosen here minimizes the discontinuity between the two solutions, which is 0.17 ms in Figure 2. Clearly this is a radically different interpretation of the 1969 event in comparison to that of Lyne et al. (1993). The next section discusses yet another radically different interpretation.

4.2. An interesting alternate analysis

This section describes an interesting analysis of the data in Figure 3 which mimics some behavior of an anti-glitch (Archibald et al. 2013). This section is meant to show the variety in the interpretation of the data in Figure 3 and does not imply that an anti-glitch has occurred.

All post-glitch Δφ are fit to equation 1 of Vivekanand (2015), which models a typical glitch. The values of the glitch parameters in Figure 3 are: Δνₚ = −0.87(2) × 10⁻⁷ Hz, Δνₚ = +7.49(2) × 10⁻¹⁵ s⁻², Δνᵣₚ = +1.81(5) × 10⁻⁷ Hz, and τ = 31(1) days, where Δνᵣₚ is the exponentially decaying component. These are very different from the values derived by Lyne et al. (1993) and given in Wong et al. (2001), where Δνₚ = +0.51(1) × 10⁻⁷ Hz and Δνᵣₚ = −1.4(4) × 10⁻¹⁵ s⁻². Numerically their values are much smaller, but more importantly their signs are inverted. Thus, whereas for a typical glitch in the Crab pulsar Δνₚ increases and Δνᵣₚ decreases at the glitch epoch, in Figure 3 it is the exact opposite, which is one possible property of an anti-glitch. This is why Δφ in Figure 3 curves in the opposite sense to that in Figure 2 beyond epoch ≈ t₀ + 30 days. Their Δνᵣₚ = +0.7(1) × 10⁻⁷ Hz, which is smaller than the value derived here, but of the same sign, which is why Δφ in Figure 3 curves downwards at the glitch epoch, as in a typical glitch. Thus this is a complex behavior.

For a wide range of initial values of the parameters, the fit converges to the kind of curve shown in Figure 4 although the final parameter values differ. It is reiterated once again that the Δφ in Figure 3 is fit to a curve that is expected from a typical glitch. The resulting glitch parameters, however, are quite dif-
The practice of deriving only $v_0$ and $v_0$, and using a $v_0$ that is consistent with the Crab pulsar’s braking index, merits scrutiny. Braking index defines the secular (long term) rotation history of any pulsar. The above practice is justified if the pre-glitch reference timing model is obtained over several hundreds of days, or equivalently several cycles of timing noise (as has been done for the best three Crab glitches in [Lyne et al. (2015)]). By obtaining $v_0$ and $v_0$ over a month of data span, one is fitting into the local timing noise curve, whose variations (which are quite severe in the Crab pulsar) can lead to even negative values of $v_0$. This is evident in the several negative $v_0$ values listed in the Jodrell Bank Crab Pulsar Monthly Ephemerides (CGRO format) [Lyne et al. (1993)].

In summary, the pre-glitch reference timing model in the last row of Table 2 shows that same post-glitch behavior as in Figure 1, while the corresponding solution of [Lyne et al. (1993)] shows the behavior in Figure 1; these are dramatically different behavior at epochs beyond $\approx 50$ days after the glitch. Numerically the two solutions are statistically different, although they are both supposed to be derived from exactly the same data.

### 5. Periodic variation of timing noise

In Figure 2, the $\Delta \phi$ variation is known as timing noise. It has been known that the timing noise of the Crab pulsar has quasi-periodic variation of periods ranging from 200 to 800 days ([Lyne et al. 1993], [Richards et al. 1970]) have reported a quasi-periodic variation of a much smaller period, of 77 ± 7 days, between May 10 and Sep 16 of 1969. The variation seen from epoch $t_0$ = 150 to $t_0$ days (almost the same range as that of [Richards et al. 1970]) looks like a frequency modulated sine wave, with a slightly smaller period. It can be modeled as a sinusoid whose period and amplitude are decreasing with time. The dashed curve in Figure 2 represents the best fit sinusoid having the formula

$$\Delta \phi(t) = a + (b + qt) \sin \left( \frac{2 \pi t}{c + pt} + d \right)$$

where $r$ is the epoch in days (with respect to $t_0$ in Figure 2). At epoch $r = 0$, the period of the sinusoid is $c = 55.7 \pm 2.1$ days, and its amplitude is $b = 0.21 \pm 0.02$ ms. The period decreases at the rate $p = -0.15 \pm 0.01$ per day per epoch, while the amplitude decreases by $a = -0.002 \pm 0.0002$ ms per day. This is reminiscent of a non-linear chirp signal of a radar. To the best of our knowledge such a signal has so far not been reported in the timing noise of the Crab or any other pulsar. The $\Delta \phi$ variation before epoch $t_0 = 150$ may lead one to speculate whether this is merely the tail end of a much larger chirp signal; however this data does not fit the later data as a coherent oscillation.

### 6. Discussion

This work demonstrates that the 1969 event in the Crab pulsar can be better understood as a typical glitch that was interrupted by a non-glitch speed-up event (Vivekanand 2015). This is based on the variation of post-glitch $\Delta \phi$ as a function of epoch shown in Figure 2. These results hold even after ignoring the nine radio data that have flag “A” and one data that has flag “C”, which have higher error bars.

Although this is the first time that such behavior has been explicitly highlighted in any pulsar, it appears that this has been seen before but not recognized as such. The Crab pulsar glitch of

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1. [http://www.jb.man.ac.uk/pulsar/crab.html](http://www.jb.man.ac.uk/pulsar/crab.html)
to the Crab pulsar is unknown. The decreasing period and amplitude of the sinusoid with time are consistent with a planetary companion falling into the Crab pulsar, due to orbital decay.

The first problem with this scenario is how did the planetary companion appear suddenly orbiting the Crab pulsar. The rapidly decreasing $\Delta$ before $t_0=150$ in Figure 2 can probably be used to argue that it represents the capture of this planetary companion by the Crab pulsar.

Next, one would have to assume that this planetary companion is made up of neutral material, so as not to encounter intense electrical and magnetic resistance within the magnetosphere of the Crab pulsar. However, it is not clear whether material that was neutral to start with will continue to remain neutral within the magnetosphere of the Crab pulsar, which is expected to be the site of intense radiation, even in the closed field lines of the Crab pulsar. Further, the planetary companion probably cannot avoid being vaporized by the Crab pulsar’s radiation in the magnetosphere (see Cordes and Shannon (2008)). Therefore it is not clear that such a planetary companion can survive the Crab pulsar’s environment and remain stable for $\approx 150$ days.

Finally, the sinusoidal variation of timing noise appears to have been terminated abruptly just before the 1969 glitch. In principle the planetary companion could free fall into the Crab pulsar instantaneously, but one needs a physical mechanism for the planetary companion to suddenly lose its entire angular momentum and free fall into the Crab pulsar. This would be as dramatic as its sudden appearance $\approx 150$ days earlier. If such a scenario is credible, then it is difficult not to associate the Crab pulsar glitch of 1969 with the impact of this planetary companion upon the surface of the neutron star. However, the Crab pulsar has undergone several glitches where such planetary companions have not been invoked.

Brook et al. (2014) report the possible impact of an asteroid, much smaller than Earth, on PSR J0738–4042. This caused non-periodic torque variations, and also caused changes in the integrated profile of the pulsar. Profile changes are expected since the planetary companion is expected to be vaporized and ionized by the pulsar radiation, which would cause additional electric current on the magnetic field lines. However the original observers (see Table 1) have not reported any profile variations in the Crab pulsar around the epoch of the sinusoidal variation in Figure 2. This further argues against the possibility of an in falling planetary companion.

In summary, while it is in principle possible to explain the periodicity observed in Figure 2 as being due to an orbiting Earth sized planetary companion, whose orbit is decaying with time, currently such a scenario does not appear to be credible, unless more detailed theory is invoked.

Starovoit & Rodin (2017) have recently shown that an Earth sized planetary companion may be orbiting PSR B0329+54, but the orbital period is much longer, $\approx 28$ years, in comparison to the $\approx$ weeks that are involved here.

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Appendix A: Details of the Observations

This work uses only a small fraction of the data that is available in the references in Table 1. The number of arrival times in each of the references are 615, 348, 600, 32 and 239, respectively, totaling 1834, tabulated as Julian days up to the eleventh decimal
place, along with a timing accuracy in micro seconds (µs). In addition, the dispersion constant has been tabulated for the radio data (six digit number in units of sec.MHz²), while the Gregorian dates of the arrival times (year, month, day, hours, minutes and seconds, the last up to the sixth decimal place) have been tabulated for the Princeton, Hamburg and Harvard data. Thus, there are about eleven thousand numbers to be read out from five pdf files, about 40% of them having a large number of digits. The numbers could be copied and pasted from only the Princeton reference, and that too in a very limited manner. The rest of the references are about eleven thousand numbers to be read out from five pdf files.

The pdf file of each observatory was input to two independent Optical Character Recognition (OCR) software after it was broken up into much smaller pieces, whose size depended upon the quality of the print in that pdf file. The poor print quality of the Hamburg pdf file proved to be particularly challenging. The text output of each OCR software was visually compared with the corresponding pdf file, number by number, and corrections made if required. Then the text outputs of the two OCR software were compared with each other using the diff utility of the Linux operating system, and corrections made if required. This was done sufficiently slowly to account for human fatigue. After about a month, the final text outputs were once again visually compared, number by number, with the corresponding pdf files.

Barycenter arrival times are tabulated only by the Princeton, Hamburg and Harvard groups. These can not be combined together because each group has used a different method of barycentric correction. These three groups tabulate site arrival times in both the Gregorian and Julian dates. However, The Hamburg Julian dates have been derived from the corresponding Gregorian dates using a different formula (this is explained in their reference). Therefore their barycenter arrival times can not be used, even just by themselves, in a modern software such as TEMPO2. This occurred because of the need to reconcile the discontinuous time scale in which site arrival times are measured (Coordinated Universal Time or UTC) with the continuous Terrestrial Time scale (TT) in which barycenter arrival times are computed; this process was still evolving in those days, as also was the method of barycentric correction.

In this work, the Gregorian site arrival times of these three groups have been processed by the software routine iaucal2jd, available in the IAU Standards of Fundamental Astronomy (SOFA) software library, to obtain the corresponding Julian site arrival times. Next, the Julian site arrival times of all groups were processed using the TEMPO2 software to obtain the barycenter arrival times, using the ephemeris in Table A.1.

Table A.1. Crab Pulsar’s ephemeris used for barycentric correction, obtained from the ATNF pulsar catalog (Manchester et al. 2005).

| PARAMETER     | VALUE       |
|---------------|-------------|
| RAJ (h:m:s)   | +05:34:31.973 |
| DEC (d:m:s)   | +22:00:52.06  |
| PMRA (mas/yr) | -14.7       |
| PMDEC (mas/yr)| +2.0        |
| POSPEOC (MJD) | 40706       |

 TEMPO2 already has the geocentric coordinates of the Arecibo and Princeton observatories; for the rest of the observatories they are given in Table A.2. They are obtained by first getting the geodetic coordinates from the observatory web sites, and also from general sites. They have also been verified using Google maps. The Rochester geodetic coordinates are given in their reference. Then the geodetic coordinates are converted to geocentric coordinates using the software routine iauGd2gc of SOFA.

Table A.2. Geocentric coordinates of three observatories in meters. Their accuracy is expected to be ≈ 100 meters, which is sufficient to time the Crab pulsar.

| TELESCOPE    | X     | Y     | Z     |
|--------------|-------|-------|-------|
| Hamburg      | 3743367 | 676245 | 5102506 |
| Harvard      | 1489772 | -4466751 | 4287249 |
| Rochester    | 1023510 | -4582206 | 4303547 |

Consistency checks were done on the data extracted from each observatory file. For the Arecibo group, the first three fits in their Table 2 were verified. The derived values of ν₀ and ν₀ were consistent with their values within errors. However the derived ν₀ differed by about 0.001 to 0.01 micro Hertz (µHz), which is probably on account of a residual phase gradient due to differences in barycentric correction. Figure 3 in the reference of the Princeton group has been verified using the values of ν₀, ν₀ and ν₀ in their Table 3, although the curvatures are slightly different probably due to the same reasons. Similarly some figures in the reference of the Hamburg group have been reproduced with minor differences.

Alignment of data from different observatories is achieved by using known site arrival time offsets, that are listed in Table A.3. It was found that these offsets indeed aligned the data. The offsets proposed by Horowitz et al. (1971) for the Harvard and Rochester data were found to be unnecessary.

Table A.3. Site arrival time offsets with respect to the Princeton observatory data. The Hamburg observatory data has two offsets, the first during 1969/1970, and the second during 1970/1971 (Lohsen, 1983). The Arecibo offset is obtained from Slowikowska et al. (2009), and is very close to the value used by Groth (1975).

| TELESCOPE     | OFFSET  |
|---------------|---------|
| Arecibo       | -235 (µS) |
| Hamburg1      | -2430 (µS) |
| Hamburg2      | +116 (µS)  |

Although the Rochester group tabulate 239 arrival times, they have ≈ 10 observations per day; so they have essentially observed for only 29 independent days.

In this work the solar system ephemeris DE200 of JPL has been used, and TEMPO2 has been used in the TEMPO1 compatibility mode; this results in the barycentric correction being done in the TDB units. The results have been verified using the more modern DE421 ephemeris, and working in the TCB units.

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