Abstract: We report on the timing properties of the ‘Crab twin’ pulsar PSR B0540−69 measured with X-ray data taken with the Swift telescope over a period of 1100 days. The braking index of the pulsar was estimated to be $n = 0.03 \pm 0.013$ in a previous study performed in 2015 with 500-day Swift data. This small value of $n$ is unusual for pulsars, and a comparison with an old estimate of $n = 2.1$ for the same target determined ~10 years ago suggests a dramatic change in the braking index. To confirm the small value and therefore the large change of $n$, we used 1100-day Swift observations including the data used in the earlier determination of $n = 0.03$. In this study we find that the braking index of PSR B0540−69 is $n = 0.163 \pm 0.001$, somewhat larger than 0.03. Since the measured value of $n$ is still much smaller than 2.1, we can confirm the dramatic change in the braking index for this pulsar.

Key words: pulsars: general – pulsars: individual (PSR B0540−69)

1. INTRODUCTION

Neutron stars are the left-over cores of massive stars after a supernova explosion. They are composed of extremely dense matter and have very strong magnetic fields ($\sim 10^{12}$ G). They are usually detected as pulsating (rotating) sources in the radio to gamma-ray band (Ostriker & Gunn 1969). Their spin frequency slowly decreases and timing properties in this spinning down process can be characterized by measuring the spin frequency $\nu$ and its time derivatives $\dot{\nu}$ and $\ddot{\nu}$ which are combined to derive the braking index $n = \frac{\ddot{\nu}}{\nu^2}$ (Manchester et al. 1983).

Measuring the braking index for pulsars is difficult because the measurement requires an estimation of the second derivative which is in general very small. In addition, the rotation of neutron stars is known to be irregular due to ‘glitches’, sudden changes in the spin-down rate and to ‘timing noise’, long-term non-period modulations. Thus pulsars’ timing properties can be characterized only by observing the pulsars for a long time. Up to now braking indices have been measured for only about 10 of the 2600 detected pulsars (Table 1) and are typically less than 3 (Lyne et al. 2013).

The braking index of a pulsar can be used to understand the energy-loss mechanisms of the pulsar. For ideal magnetic dipole radiation, the braking index is expected to be around 3 (Lyne et al. 2013), but it can differ due to other energy loss mechanisms (e.g., wind and gravitational wave) or to changes in the mechanical properties. $n$ can be ~1 if energy loss of a pulsar is dominated by the wind or 5 if gravitational-wave radiation is dominant (Kou & Tong 2013; Klein Aranjo et al. 2016). Effects due to changes in the mechanical properties on $n$ are very complex. Several of these effects may operate at the same time, and by measuring $n$, one can infer which effect is dominant. The evolution of a pulsar can be studied because the changes on $n$ can imply any effect of the aforementioned mechanisms.

Until now, a wide range of values for $n$ has been measured. Although the measured braking indices for various pulsars can be between ~1.2 (PSR J0537−6910, perhaps contaminated by frequent glitches; Antonopoulou et al. 2013) or 0.9 (PSR J1734−3333; Espinoza et al. 2011) and 3.15 (PSR J1640−4631; Archibald et al. 2016), most cases are only within 2 $\leq n \leq 3$ (Lyne et al. 2013). Furthermore, $n$ has been observed to change in some pulsars: the braking index of PSR J1119−6127 changed from 2.91 to 2.684 when a glitch occurred (Antonopoulou et al. 2013) and that of PSR J1846−0528 changed from 2.65 to 2.19 after an outburst (Archibald et al. 2013). While it is not yet clearly understood how various pulsars have such values of $n$ and how they change, some theories have been developed: accretion from a hypothetical fall-back disk (Menou et al. 2001), super-fluid decoupling (Antonopoulou et al. 2018), and magnetic-field evolution (Gourgouliatos & Cumming 2013; Blandford & Romani 1988), and an effective change in the moment of inertia (Sedrakian & Cordes 1998). Because there are not many pulsars with a measured braking index, understanding the value and its change on a firm theoretical ground is still lacking. So it is crucial to measure $n$ and its changes for more sources to find extremes to constrain the models.

PSR B0540−69 is a young and bright 50-ms pulsar in the Large Magellanic Cloud (Seward et al. 1994). The pulsar is surrounded by a pulsar wind nebula (PWN, $R_{\text{pwn}} \approx 4''$; Kaaret et al. 2001) which has a similar morphology (torus and jet; Campana et al. 2008; Mignani et al. 2012) to that of the Crab nebula.
We used X-ray data of PSR B0540−69 observations with a typical exposure of 2−7 ks were performed with the window timing mode (a time resolution of 1.7 ms) to facilitate measurements of the short 50-ms period of the pulsar. We processed the observational data using the standard Swift pipeline incorporated in HEASOFT 6.20 along with the latest CALDB calibration files. We selected events using a R = 20′′ circular region centered at the source position in the 0.7–7 keV band. The photon arrival times are then corrected to Solar System’s barycenter with the source position α = 05°40′11.202″ and δ = −69°19′54.17″ (Mignani et al. 2010), and the JPL DE200 ephemeris. Because of the short 94-min orbital period of the Swift satellite, long observations suffer from Earth occultation and have observational gaps (occultation). To remove the artifacts of the occultation (e.g., beams), we split an observation into continuous segments when the observation is longer than the Swift orbital period. After pre-calibration and selection, there were 208–1369 photons per segment.

3. Timing Analysis

Young pulsars like PSR B0540−69 tend to be more active (e.g., more glitches and timing noise); therefore, their timing properties seem to be more irregular (e.g., Dib & Kaspi 2014). Indeed, Livingstone et al. (2005) and Ferdman et al. (2015) found some glitches and relatively large timing noise. The latter is a particular concern in the results of Marshall et al. (2016) because they did not find any timing noise. Non-detection of timing noise in their work implies that the pulsar timing noise was significantly smaller in 2015 than in 2010. Indeed, Marshall et al. (2016) noted that there could be small timing noise but it would not change their results significantly. Alternatively, it is also possible that there was significant timing noise in 2015–2016, but the 500-day observations could not distinguish between the real timing behavior (timing solution) and the long-term timing noise because the baseline (∼500 days) was too short.

In this work, we reanalyzed the 500-day Swift data used in Marshall et al. (2016) to confirm their timing solution. We then added recent 600-day Swift observations to extend the baseline and to refine the braking-index measurement. We describe the observations in Section 2 and present the timing analysis and the results in Section 3. We then discuss and conclude in Section 4.

2. Observations and Data Reduction

We used X-ray data of PSR B0540−69 observed by the Swift X-ray telescope (Gehrels et al. 2004) between 2015 Feb. 17 to 2018 Feb. 11. Note that the baseline of the observations we used is about twice that used in Marshall et al. (2016). In this period, 62 Swift observations with a typical exposure of ∼2 ks were performed with the window timing mode (a time resolution of 1.7 ms) to facilitate measurements of the short 50-ms period of the pulsar. We processed the observational data using the standard Swift pipeline incorporated in HEASOFT 6.20 along with the latest CALDB calibration files. We selected events using a R = 20′′ circular region centered at the source position in the 0.7–7 keV band. The photon arrival times are then corrected to Solar System’s barycenter with the source position α = 05°40′11.202″ and δ = −69°19′54.17″ (Mignani et al. 2010), and the JPL DE200 ephemeris. Because of the short 94-min orbital period of the Swift satellite, long observations suffer from Earth occultation and have observational gaps (occultation). To remove the artifacts of the occultation (e.g., beams), we split an observation into continuous segments when the observation is longer than the Swift orbital period. After pre-calibration and selection, there were 208–1369 photons per segment.

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In this case, their timing solution would have been biased due to the noise. The characteristic time scale of the timing noise in PSR B0540−69 was ∼700 days (e.g., Ferdman et al. 2013), and hence, if this trend persisted, timing noise can be characterized only by using data with a > 700-day baseline. Thus, the timing behavior of PSR B0540−69 described by the Swift observations need to be re-investigated carefully.

There are several ways to determine a pulsar’s timing solution. Here we used two methods: direct period measurements for the individual time series

Table 1

| Pulsar     | ν (Hz) | ν′ (10⁻¹² s⁻²) | Characteristic Age (kyr) | n | Ref.       |
|------------|--------|----------------|--------------------------|---|------------|
| J0534+2200 | 29.946923 | −3.77535      | 1.26                     | 2.342(1) | Lyne et al. (2015) |
| J0537−6910 | 62     | −1.992        | 4.93                     | −1.22(4) | Antonopoulou et al. (2018) |
| J0835−4510 | 11.200 | −0.15375      | 11.3                     | 1.7(2)   | Espinoza et al. (2017) |
| J1119−6127 | 2.4512027814 | −0.2415507 | 1.6                      | 2.91(5)−2.684(2) | Antonopoulou et al. (2015) |
| J1328−6238 | 2.20698010518 | −0.16842733 | 2.67                     | 2.598(1) | Clark et al. (2016) |
| J1513−5908 | 6.615115248350 | −0.6694371307 | 1.56                     | 2.83(3)  | Livingstone et al. (2011) |
| J1640−4631 | 4.843410287 | −0.2280830   | 3.4                      | 3.15(3)  | Archibald et al. (2016) |
| J1734−3333 | 0.855182765 | −0.01666702  | 8.13                     | 0.9(2)   | Espinoza et al. (2011) |
| J1833−1034 | 16.15935711336 | −0.52751130 | 4.85                     | 1.857(1) | Roy et al. (2012) |
| J1846−0258 | 3.0621185502 | −0.6664350   | 0.73                     | 2.65(1)−2.16(1) | Archibald et al. (2015) |

Mori et al. 2004, Madsen et al. 2013). The rotation properties are well measured to the second derivative with a characteristic age τc = ν/2π of ∼1700 years and a braking index of n ≈ 2.1 (e.g., Livingstone et al. 2005). The most interesting property of this pulsar is a large change in the braking index which was measured to be n = 2.123 ± 0.012 between 1999 and 2011 with RXTE in 2−60 keV band (Ferdman et al. 2013), but a recent study reported n = 0.03 ± 0.013 using the 500-day Swift observations taken between 2015 and 2016 (Marshall et al. 2016). Such a large change and a small value of n have not been seen in any other pulsars. The braking index of n ≈ 2.1 before 2010 seems to be reliable because several works have obtained similar values (n ≈ 2.1) by independently analyzing the long (>10 years) RXTE and/or BeppoSAX (2−30 keV) observations (Cusumano et al. 2003, Livingstone et al. 2005, Ferdman et al. 2013, Zhang et al. 2001). However, n = 0.03 derived from 500-day Swift data in Marshall et al. (2016) has not been carefully examined. Thus, a careful reinvestigation is needed.

In this work, we reanalyzed the 500-day Swift data used in Marshall et al. (2016) to confirm their timing solution. We then added recent 600-day Swift observations to extend the baseline and to refine the braking-index measurement. We describe the observations in Section 2 and present the timing analysis and the results in Section 3. We then discuss and conclude in Section 4.

1 Usually “timing solution” means the real timing behavior and the long-term noise together. Here, however, we separate them for clarity.
and phase connection. The former uses the $Z_{1}^{2}$-test (de Jager et al. 1989) to measure the periodicity in individual observations. This is a robust method for a period detection to avoid any minor irregularity but is not sensitive to describe the timing properties. The latter, the phase connection, is more sensitive to timing noise because it uses both the periodicity and the pulse shape, but requires that the observations should be inspected with specific time intervals. The observation data that we use satisfied the time-interval requirement for the phase connection method; therefore, we used the more sensitive technique which enabled us to measure $\nu$ and the timing noise. Aforementioned two methods may result in different solutions when the baseline is long and the pulsar exhibits a timing anomaly during the observations (e.g., [An et al. 2013].

3.1. Detailed frequency measurements

We first used the more robust but less sensitive method, the $Z_{1}^{2}$-test (Buccheri et al. 1983) for a sanity check, which basically computes the $Z_{1}^{2}$ statistic value in the folded light curve at assumed periods. The $Z_{1}^{2}$ value will be large if there is periodicity at some frequency, so one can find the best $\nu$ that maximizes the $Z_{1}^{2}$ value by scanning $\nu$ near the known value ($\nu \approx 19.696$ Hz for PSR B0540–69). Uncertainties for $\nu$ measurements were obtained by running simulations. We did this for each data segment and show the best frequencies that we determined in Figure 2. It is clear from the figure that the frequency changes with time; hence, we measured the first derivative ($\dot{\nu}$) by fitting the frequency trend with a linear function. The fit was acceptable with $\chi^2_{\text{min}}/\text{dof} = 46.3/71$, and the best-fit frequency and the derivative are $\nu = 19.69633(1)\text{Hz}$ and $\dot{\nu} = -2.533(3) \times 10^{-10} \text{s}^{-2}$ at the epoch of MJD 57281.24147641701, respectively. $1-\sigma$ uncertainties are estimated by scanning $\nu$ and $\dot{\nu}$ to find a range for the parameters in which $\chi^2$ is less than $\chi^2_{\text{min}} + 2.3$. We also fitted the trend with a quadratic function to measure the second derivative ($\ddot{\nu}$) but the uncertainty for the quadratic term is large, so we only derived a 90% upper limit of $\ddot{\nu} < \ddot{\nu}_{\text{test}} + 1.28 \Delta \nu = 2.9 \times 10^{-20} \text{s}^{-3}$, assuming a normal distribution. Because we cannot measure $\ddot{\nu}$ with this method, we tried a more sensitive method described below.

3.2. Phase semi-coherent method

We applied the phase-connection method (so-called phase semi-coherent analysis) to measure the period second derivative. The Phase semi-coherent method (e.g., see Livingstone et al. 2005) starts from an existing timing solution for the first data set (a part of the whole data) to be analyzed and gradually improves the solution by adding more data. With the first data set and the timing solution for the data, a rotation phase for each detected photon is computed using $\phi(t) = \phi_{0} + \nu t + \frac{\dot{\nu}}{2} t^2 + \frac{\ddot{\nu}}{6} t^3$, where $\phi(t)$ is the rotation phase of the photon detected at time $t$; $\phi_{0}$ is the reference phase, and $\nu$ and its derivatives are the timing solution. An initial pulse profile is generated by constructing the phase histogram (pulse profile, see Fig. 2 bottom). Using the initial timing solution, we construct the pulse profile for the next observation and compare with data. Although the two pulse profiles can be compared directly, it is better to use a continuous function to represent the pulse profiles to reduce the effects of statistical fluctuations. Thus, we model the profiles with a sine function (Fig. 2) and check to see if the profiles align (no relative shift, i.e., phase-connect). If the phase shift of the new profile with respect to the previous one is less than 1 cycle ($\Delta \phi < 1$), we keep including the next data. Note that we were not seriously concerned for the fit between the profile and the sinusoidal function because we compare the relative shift only. As we keep doing this, the phase shift with respect to the initial profile may get larger (slow drift with time) and eventually become greater than 1 and thus, we are not able to phase-connect the new profile to the initial one if the initial timing solution is not perfect. If this occurs, we update the timing solution by varying $\nu$, $\dot{\nu}$, and $\ddot{\nu}$ to phase-connect all the data up to the point just before the disconnection. We repeat this procedure until the last observation. In these process, it may not be possible to phase-connect all the data perfectly (i.e., no relative shift) with only three timing parameters $\nu$, $\dot{\nu}$, and $\ddot{\nu}$, and there may be small ($< 1$) relative phase shifts between observations which cannot be modeled with the polynomial with degree 3. These residual phase shifts are usually attributed to timing noise.

Before proceeding to analyze the 1100-day data, we confirmed the previous results (see Table. 2) by actually fitting the 500-days data with the same data used to infer $n = 0.03$ (25 Swift observations made between MJDs 57070 and 57546; Marshall et al. 2016). We find $\nu = 19.696323386(2) \text{s}^{-1}$, $\dot{\nu} = 2.528649(1) \times 10^{-10} \text{s}^{-2}$, and $\ddot{\nu} = 0.16(3) \times 10^{-21} \text{s}^{-3}$, yielding $n = 0.05(1)$. These are consistent with the previous solution within statistical uncertainties. We found no clear timing noise.
Figure 2. 0.5–7-keV pulse profiles of PSR B0540−69. *Top:* the pulse profiles in the first ∼500-day data produced with the known timing solution of Marshall et al. (2016). *Bottom:* The pulse profile made with the 1100-day data and the refined solution. Blue and black points are pulse profiles of the source before and after background subtraction, respectively. Best-fit sine functions are also shown in lines, and the background profile is shown in red. We used 128 bins for the profiles and showed two cycles for clarity. The profiles for 500-day and 1100-day data look similar, having pulsed fraction of 0.295(6) and 0.280(4).

Figure 3. Timing residuals after fitting out the cubic trend (timing solution) from the phase-shift measurements of the 1100-day data.

We note that the timing noise pattern in Figure 3 is similar to that measured by Livingstone et al. (2005) and Ferdman et al. (2015) using >10 y data. Additionally, notice that even in the first ∼500 days, there is a residual long-term trend (timing noise) which was not seen when using the previous timing solution.

3.3. Timing noise

Physical origin and evolution of timing noise is not yet well understood and is therefore unpredictable. Only by using a long baseline can timing noise (high-order polynomials) be distinguished from the timing solution (low-order polynomials). However, the concern is that there can be some mixing between the solution and the noise. Thus, the timing solution may change a little if we model the timing noise with high-order polynomials or sine functions and fit the data (e.g., Fig. 3) to include the noise model. A standard way to model and fit the timing noise is to use the power spectrum of the timing residual (whitening). This method can be applied to the residuals (Fig. 3) with the TEMPO2 package (Hobbs et al. 2006). We performed ‘whitening’ using TEMPO2, and the whitened residuals are shown in Figure 4. The changes in the timing solution due to the whitening are small (insignificant). As a crosscheck, we fitted the phase residual data with a timing noise model, polynomials or sinusoidal functions and find that $n$ changes from 0.163 (before whitening) to 0.164 (after whitening). These two are statistically consistent. We found that the change in the timing solution is very small in this case as well (see Table 2).

4. DISCUSSION

We measured the timing properties of PSR B0540−69 using the *Swift* data covering 1100 days. The timing solution obtained with the more robust $Z^2_1$ test is consistent with that measured with the phase-coherent
method. The measured $\nu$, $\dot{\nu}$, and $\ddot{\nu}$ with the phase-coherent method imply a braking index of $n = 0.163 \pm 0.001$. We further attempted to model or whiten the timing noise and found that the timing solution is not sensitive to the timing noise models.

The solution we obtained for PSR B0540–69 is different from the previous ones (see Table. 2 in Livingstone et al. (2003), Ferdman et al. (2015), and Marshall et al. (2016). The discrepancy with those in Livingstone et al. (2003) or Ferdman et al. (2015) can be easily understood because our measurements were done far later in time from theirs; PSR B0540–69 is a young and active pulsar, and thus, the timing properties might have changed due to glitches or a spin-state transition (significant change in the rotational properties). Indeed Marshall et al. (2013) suggested a spin-state transition in MJD 55900 after two glitches in MJD 51348 and MJD 52925; hence, solutions measured before (e.g., Livingstone et al. 2003; Ferdman et al. 2015) and after (this work and Marshall et al. 2016) can differ. The discrepancy with that of Marshall et al. (2016) is small but still statistically significant. We attribute the discrepancy to the timing noise. Perhaps, their results may be biased by undetermined timing noise. By properly isolating and accounting for the timing noise, we were able to determine the timing solution more accurately.

Based on our new solution, we can estimate the bias in the previous result due to the timing noise. As shown in Figure 4, the timing noise in the first $\sim$500 days seems to follow a cubic trend with an amplitude of $\sim 10$ ms ($\phi_{\text{max}} \approx 0.2$). We therefore modeled the residuals with a cubic function: $\phi(t) = at^3 + bt^2 + ct + d$, where we reset the zero of $t$ to be at MJD 57546.08, the last data point in the 500-days time span. We find $a = -3.82 \times 10^{-22} \text{ s}^{-3}$, $b = 1.73 \times 10^{-15} \text{ s}^{-2}$, and $c = 2.22 \times 10^{-8} \text{ s}^{-1}$ in the fit. These values can be compared with $\phi(t)$ in section 3.2, resulting in $\nu_{\text{bias}} = 6a = -2.3 \times 10^{-21} \text{ s}^{-3}$, $\dot{\nu}_{\text{bias}} = 2b = 3.5 \times 10^{-15} \text{ s}^{-2}$, and $\ddot{\nu}_{\text{bias}} = c = 2.22 \times 10^{-8} \text{ s}^{-1}$, which are sufficient for explaining the discrepancy. Hence, we argue that indeed the previous solution is biased due to the timing noise. This concern, however, was already noted in Marshall et al. (2016); the authors argued that the effects of the timing noise would not be large. Our quantitative analysis suggests that the impact of the timing noise on the solution and $n$ is statistically significant but is not very large in absolute values as they argued.

As noted above, the most intriguing features of PSR B0540–69 are the extremely small value and the large change of $n$ as suggested previously. We arrive at the same conclusion with our study performed with a more accurate timing solution; we confirmed the the main conclusion of Marshall et al. (2016). Although such a small value of $n$ and large change (likely accompanied with the state change; Marshall et al. 2015) are not yet well understood, it is suggested that evolution of magnetic field in the neutron star (Gourgouliatos & Cumming 2013, changes of mechanical properties of the pulsar (Sedrakian & Cordes 1998), and/or a putative accretion disk (e.g., accretion rate; Menou et al. 2001) may result in a small value of $n$ and the change. We found that $n = 0.163$ was larger than the previous one ($n = 0.031$). While this difference could be due to timing noise, it may also imply some changes in the pulsar or in the putative disk.

Timing changes often occur contemporaneously with a radiative change but in PSR B0540–69 no significant evidence for a radiative change was found (Marshall et al. 2015). However, PSR B0540–69 is in a crowded region of the sky and is surrounded by a PWN (Kaaret et al. 2001). The 16″ angular resolution of Swift is not enough to resolve the pulsar from the 4″ nebula or the nearby sources. Furthermore, the Swift observations are all in the timing mode without any 2D images. Thus, unchanging (constant in time) contamination from the nearby sources and the PWN may dominate the flux, making accurate measurements of small changes in the pulsar flux hard. Future Chandra observations (0.5″ angular resolution) for spatially resolved spectroscopy (e.g., An et al. 2014) may be useful to measure a change in the flux of the pulsar and/or the nebula.

We finally note that a further timing analysis with longer (>500 days) Swift data has been performed by Marshall et al. (2018). In this AAS abstract, they reported that the braking index $n$ of PSR B0540–69 is still near 0, but details on the timing solution are not available. It would be interesting to check if they detected the timing noise and if their timing solution agrees with ours. This can be done in the near future.

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### Table 2

Several timing solutions for PSR B0540−69 obtained in previous works as well as this work

| Observation date (MJD) | Epoch (MJD) | Marshall | This Work (AW) | This Work (BW) |
|-----------------------|-------------|----------|----------------|----------------|
| 57070−57546           | 57281.24    | 57070−58068 | 57281.24 |
| ν (Hz)                | 19.696323901(22) | 19.696323365(1) | 19.696323365(2) |
| ν (10⁻¹⁰ s⁻²)         | −2.5286507(15)   | −2.528664(1)   | −2.528664(2)   |
| ν̇ (10⁻¹³ s⁻³)        | 0.104(41)      | 0.531(4)      | 0.531(8)      |
| Braking index (n)     | 0.031(13)     | 0.163(1)     | 0.164(1)     |

1 AW means After whitening, BW means before whitening

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