Spin-down and emission variations for PSR J0742–2822

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Abstract PSR J0742–2822 is known for the quasi-periodic changes in the observed pulse profile and spin-down rate. In this paper, we analysed 13 years of timing data obtained with Nanshan 25-m radio telescope and the Parkes 64-m radio telescope. We found that the average values of the spin-down rate ($\dot{\nu}$) of this pulsar changed in four different states. We investigated the correlation between $\dot{\nu}$ and $W_{50}$, and found that the correlation has changed in different $\langle \dot{\nu} \rangle$ states. Moreover, not all the changes of $\langle \dot{\nu} \rangle$ states and correlation can be associated with the glitch activities. We obtained the long term evolution of $\gamma$-ray flux (0.1-300GeV) and the pulse profiles corresponding to the four different states using Fermi-LAT Pass 8 (P8R3) data from 2008 August 5 to 2019 October 1. We did not detected significant change in $\gamma$-ray flux and pulse profile. Our results suggest that the connection between pulsar rotation and emission is more complex than previously reported for this pulsar.

Key words: pulsars: general - stars: pulsar - methods: timing

1 INTRODUCTION

Pulsars are the most stable rotators in the universe. They slow down gradually because the rotational energy convert into highly energetic particles and electromagnetic radiations. However, for many pulsars, their slow down usually disturbed by the timing noise, which exhibit as a continuous irregular fluctuation in the timing residuals. Hobbs et al. (2010) analysed the timing irregularities for 366 pulsars and found that the spin-down rates are correlated with the amplitude of timing noise. They also noted that the glitch
recoveries usually dominated the timing noise in younger pulsars and a quasi-periodic time-correlated structure is seen in the residuals in many older pulsars. Lyne et al. (2010) studied the timing behaviours of 17 pulsars, which have quasi-periodic timing residuals and their spin-down rates switched between two or more states in a time scale from month to year. They displayed that the evolution of spin-down rates for six pulsars are correlated with the evolution of pulse profile. Such correlations indicate that the timing noise might be caused by the magnetospheric state changes.

Although the spin-down rate ($\dot{\nu}$, where $\nu$ is the pulsar spin frequency first time derivative) switched in two or more different states were studied in many pulsars (eg: Lyne et al. 2010; Kerr et al. 2016; Brook et al. 2016), the correlation between the changes of pulsar spin-down and pulse emission were rarely observed. Usually, $\dot{\nu}$ from a low state($|\dot{\nu}|_{\text{low}}$) changed to a high state ($|\dot{\nu}|_{\text{high}}$) can be triggered by the pulsar glitch activities. For example, both the spin-down rate change of PSR J2037+3621 and the first spin-down rate increase of PSR J2021+4026 in 2011 October is occurred after a pulsar glitch (Kou et al. 2018; Allafort et al. 2013). However, some pulsars experienced state changed without a glitch. For example, the spin-down rate of PSR J2043+2740 changed from $|\dot{\nu}|_{\text{low}}$ state to $|\dot{\nu}|_{\text{high}}$ state and remain in $|\dot{\nu}|_{\text{high}}$ state over about 1500 days, after this, its recovered to $|\dot{\nu}|_{\text{low}}$ state (Lyne et al. 2010). The spin-down rate of PSR J1001−5507 changed from $|\dot{\nu}|_{\text{low}}$ state to $|\dot{\nu}|_{\text{high}}$ state over about 800 days and no glitch was detected before this process (Chuwude & Buchner 2012). Similarly, the second spin-down rate increase of PSR J2021+4026 at 2018 February has not to be detected a glitch before that (Takata et al. 2020). Therefore, spin-down change in these pulsars can not be explained by the standard glitch model.

In addition, the spin-down rate variation of these pulsars are related to the variation of pulse emission (Lyne et al. 2010; Chuwude & Buchner 2012; Allafort et al. 2013; Kou et al. 2018).

PSR J0742−2822 (B0740−28) is found by the Bologna 408 MHz Pulsar Search Project (Bonsignori-Facondi et al. 1973). This is a radio loud $\gamma$-ray pulsar with rotation period $P_0 = 0.16676 \, s$, rotation energy loss rate $\dot{E} \sim 1.43 \times 10^{35} \, \text{erg/} s$ and characteristic age, $\tau_c \sim 1.57 \times 10^5 \, \text{yr}$. Eight glitches are detected in this pulsar up to now (see: the Jordell Bank Pulsar Glicht Table1). Lyne et al. (2010) studied PSR J0742−2822 and found that $|\dot{\nu}|$ and pulse profile exhibits rapid oscillation. In addition, the spin-down and pulse shape change has a correlation. The Lomb-Scargel and wavelet spectral analyses show the highly periodic features (broader, less well-defined peaks). Keith et al. (2013) found no correlation between the observed pulse shape and spin-down rate for at least 200-d prior to a glitch at MJD 55020, following which the correlation becomes strong. These observations indicate that emission state changing may be caused by the interaction between the interior of the neutron star and the magnetospheric of the pulsar.

In this paper, combined with the data of Nanshan and Parkes radio telescope, we obtained the long-term variation of the spin-down rate and the pulse profile of PSR J0742−2822 over 13 years of data span, and investigated the correlation between them. In addition, we also analysed the variation of the $\gamma$-ray flux and pulse profile of this pulsar with the Fermi-LAT data.

2 OBSERVATIONS AND ANALYSIS

2.1 Radio data

Timing data of PSR J0742−2822 from the Nanshan 25-m radio telescope was collected between 2006 October and 2020 January by a cryogenic receiver, which has a center frequency of 1540 MHz and a bandwidth of 320 MHz. Before 2010, the data was recorded by an analogue filter bank (AFB), which with $2 \times 128 \times 2.5 \, \text{MHz}$ channels (see: Wang et al. 2001). Since January 2010, a digital filter bank (DFB) was used to recorded timing data. The DFB has 8-bit sampling and 1024×0.5 channels (for the details see Dang et al. (2020)). The sub-integration times of the AFB and DFB are 1 minutes and 30 seconds, respectively. The observing cadence of this pulsar is about three times per month and the integration time is 4 minutes for each observation.

Timing data from the Parkes 64-m radio telescope were carried out between July 2007 and April 2018 with a central observing frequency 1369 MHz. The raw data are recorded by a series of digital

1 http://www.jb.man.ac.uk/pulsar/glitches/gTable.html
Spin-down and emission variations for PSR J0742−2822

After obtaining the data, we employed the PSRCHEL software (Hotan et al. 2004) to excise radio-frequency interference, and to incoherently de-disperse, and to scrunch data in time, frequency, and polarization to form mean pulse profiles. All available data were summed for each system to form a standard profile as a template. And then, the mean pulse profile of each observation was cross-correlated with the template to generate the times of arrival (ToAs) of topocentric pulse. For the sake of eliminating the effects of Earth's motion, these ToAs were transformed to that at the solar-system barycentre (SSB). Here, we used the solar system ephemeris DE421 (Folkner et al. 2009) and the Barycentre Coordinate time (TCB). The offsets between the Nanshan and Parkes ToAs were included in the timing model. To correct the measured uncertainties, we employ the EFAC/EQUAD plugin determined the “EFAC” and “EQUAD” for the original uncertainties and the extra noise in quadrature, respectively.

2.2 Fermi LAT data

To investigate the high energy emission of PSR J0742−2822, we selected the Fermi-LAT Pass 8 (P8R3) data in a radius region of interest (ROI) centered at the 4FGL J0742.8−2822 position and the energy range is 0.1-300 GeV. The data span a total of 11 yr from 2008 August 5 to 2019 October 1. The long-term light curve for the full data span and in a radius region of interest (ROI) centered at the 4FGL J0742.8−2822 position using the binned likelihood analysis in the Fermi science tools. All the events were converted in the front and the back sections of the tracker (i.e.evtype = 3), and the point source analyses (i.e. evtclass = 128) was adopted as the event class. We only collected the data within the time intervals determined as high quality (i.e. DATA QUAL > 0). Besides, to reduce the pollution of γ-ray caused by Earth’s albedo, we filter the photons with zenith angles < 90°. In order to explain the contribution from the spectral, we constructed a background emission model. This model contains all the catalogue sources of 4FGL within 10° of the ROI centre, the diffuse emission of the galactic (gll_iem_v07) and the isotropic diffuse emission (iso_P8R3_SOURCE_V2_V1) circulated by the Fermi Science Support Center. Use the âAJgtlikeâ tool of the Fermi science tools, we excised the insignificant sources and obtained the best-fit spectra of all background sources. Subsequently, we divide the whole time of data span into 40 days time bins and fixed the contribution of spectral using the background emission model. Using the binned likelihood analysis, we refit the flux (> 100MeV) of PSR J0742−2822. Furthermore, we extract the source events within 1° radius center at the target and use the âAJgtbaryâ tool of the science tools convert the time of arrival of all photons to the solar-system barycentre (SSB). Then we obtained the pulse profile using the FERMI plugin of the TEMPO2.

3 RESULTS

We use both Nanshan and Parkes data to investigate the long term variation of and the full widths of the pulse profile at 50% of the peak pulse amplitude (W50) (see: Figure 1 (a) and (b)). The correlation between W50 and is shown in Figure 1 (c). Use the Fermi-LAT data, we also investigated the variation of the γ-ray flux and pulse profile of this pulsar (Figure 1 (d)). The detail of the results are as follows.

3.1 Changes of the spin-down rate

The panel (a) of Figure 1 is the variation of , which show a quasi-periodic structure. Using the autocorrelation function (eg: Perera et al. 2015), we obtained the time-scale of the quasi-periodic of is about 170-d. The values of and of PSR J0742−2822 were obtained by fitting the timing solutions for subsequent partially overlapping sections of data. For each data sections, we contain 150-d and overlapping 130-d. We also can see that the average values of the frequency first derivatives (⟨⟩) has a seemingly permanent change and changes among four different states. The time range, the correspond ⟨⟩ and increment relative to the previous average value, Δ⟨⟩, are given in Table 1, respectively. From

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Footnote: 2 https://data.csiro.au/dap/
MJD 54000 to 55225, $\dot{\nu}$ have an average value, $\langle \dot{\nu} \rangle \sim -6.0436(6) \times 10^{-13}\,s^{-2}$ (state I). After MJD 55225, $\langle \dot{\nu} \rangle$ reduced by about $\Delta \langle \dot{\nu} \rangle \sim -0.73(9) \times 10^{-15}\,s^{-2}$ and changed to a new state (state II). This state continues with $\langle \dot{\nu} \rangle \sim -6.0509(9) \times 10^{-13}\,s^{-2}$ until to MJD 56380. Since then, $\langle \dot{\nu} \rangle$ increased to another state, the corresponding $\langle \dot{\nu} \rangle$ and $\Delta \langle \dot{\nu} \rangle \sim -6.0343(9) \times 10^{-13}\,s^{-2}$ and $1.7(1) \times 10^{-15}\,s^{-2}$ (state III), respectively. After MJD 57730, $\langle \dot{\nu} \rangle$ decreased gradually to $-6.0448(8) \times 10^{-13}\,s^{-2}$, the corresponding increment $\Delta \langle \dot{\nu} \rangle \sim -1.1(1) \times 10^{-15}\,s^{-2}$ (state IV), which consistent with the initial level ($\sim$ MJD 54000-55225) within the uncertainty. Two glitches were reported in the literature, which correspond to our data span at MJD 55020 and MJD 56727, respectively. We found that the $\langle \dot{\nu} \rangle$ changed from state I to II may be caused by the glitch at MJD 55020. No glitch was detected before $\langle \dot{\nu} \rangle$ change from state III to IV. Furthermore, we did not detected the permanent-like change in $\dot{\nu}$ after the MJD 56727 glitch.

Table 1: The average value of the frequency first derivatives ($\langle \dot{\nu} \rangle$) and its increment ($\Delta \langle \dot{\nu} \rangle$) in four states. Uncertainties in parentheses are in the last quoted digit and are 1 $\sigma$, which obtained from the standard uncertainty propagation.

<table>
<thead>
<tr>
<th>State number</th>
<th>Range (MJD)</th>
<th>$\langle \dot{\nu} \rangle$ (10^{-13},s^{-2})</th>
<th>$\Delta \langle \dot{\nu} \rangle$ (10^{-15},s^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>54000-55225</td>
<td>-6.0436(6)</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>55225-56380</td>
<td>-6.0509(9)</td>
<td>-0.73(9)</td>
</tr>
<tr>
<td>III</td>
<td>56380-57730</td>
<td>-6.0343(9)</td>
<td>1.7(1)</td>
</tr>
<tr>
<td>IV</td>
<td>57730-58700</td>
<td>-6.0448(8)</td>
<td>-1.1(1)</td>
</tr>
</tbody>
</table>

3.2 Correlation between the spin-down rate and radio emission

It is known that the profile parameters of PSR J0742-2822 oscillate between two different modes (Lyne et al. 2010; Keith et al. 2013). In this paper, we use $W_{50}$ as the pulse profile parameters of this pulsar. The panel (b) in Figure 1 is the variations of $W_{50}$ of both Parkes and Nanshan data with time. The gap between MJD 56670 and 57450 of Nanshan data resulted from the instrument upgrade. It is obvious that $W_{50}$ changed rapidly between narrow and wide mode, the change time-scale is about 200-d. Although the value of $W_{50}$ of Parkes and Nanshan data is different caused by the different center frequency and different back-end, the trend is well consistent. We have investigated the long-term variation of the cross-correlations coefficients ($\rho$) between $W_{50}$ and $\dot{\nu}$ during about 13 years data span. Here, we only use $W_{50}$ from the Nanshan data, because it has longer data span than Parkes data. In order to obtain $\rho$, we use the interpolation to keep match the time solutions of $W_{50}$ and $\dot{\nu}$. The panel (c) in Figure 1 shows the variation of $\rho$ between $W_{50}$ and $\dot{\nu}$ for 300-d windows and overlapping 150-d. The gray region in panel (c) is $-0.4 < \rho < 0.4$, which stands for no correlation between $W_{50}$ and $\dot{\nu}$. As we seen, no correlation was detected before 1000-d before MJD 55020 glitch. After this glitch, $\rho$ increased and remained in a hight state over about 1360-d (from MJD 55020 - MJD 56380). We can not obtain the values of $\rho$ in the data gap due to lack of data. With $\langle \dot{\nu} \rangle$ changes to state IV, the correlation gradually becomes strong first (where $\rho$ is close to −1) and then becomes weaken again after about 600 days. According to the trend of the $\rho$ values, we predict that $\rho$ values might remain in a weak state in the data gap.

3.3 Long-term variation of the $\gamma$-ray flux and profile

We investigated the long-term evolution of $\gamma$-ray flux (0.1-300 GeV) for PSR J0742-2822 in Figure 1 (d). Each bin is 40 day and the total data span from 2008 August 1 to 2019 October 1. The horizontal red dash lines and red dotted lines in panel (d) represent for the average values of $\gamma$-ray flux and its 3 $\sigma$ uncertainties, which from the standard uncertainty propagation, respectively. Table 2 gives the average value of the 0.1-300 GeV flux ($F_{\text{Flux}}$) and its increment ($\Delta F_{\text{Flux}}$) and the fractional change ($\frac{\Delta F_{\text{Flux}}}{F_{\text{Flux}}}$)
in four states. It is obviously that the uncertainties of flux increments are large than its value. Therefore, we believe that the γ-ray flux of this pulsar does not change significantly when ⟨\dot{\nu}⟩ changes.

We have obtained the γ-ray pulse profile for the whole data span and each ⟨\dot{\nu}⟩ states (see: Figure 2 and 3). The photons were selected within a 1° radius of the pulsar and the photon energy range was from 0.1-300 GeV. The phase of each photon were assigned by the radio timing solution. In order to compare the differences of the profile in each ⟨\dot{\nu}⟩ states with the profile of whole data span, we normalized all pulse profiles. The panels (a)-(d′) of Figure 3 show the residuals of the total integral profile subtracted the profile in each ⟨\dot{\nu}⟩ states. Although the γ-ray pulse profile appears to be different in different states, we cannot confirm this changes because of the small number of photons.

4 DISCUSSION

In this paper, we found that the spin-down rate of PSR J0742−2822 oscillate around an average value (|⟨\dot{\nu}⟩| ∼ 6.0436(6) × 10^{−13}s^{-2}) over about three years, after MJD 55225, a permanent-like
Fig. 2: Normalized pulse profile of PSR J0742−2822 generated with photon energy from 0.1-300 GeV in all the data span.

Fig. 3: Normalized pulse profile of PSR J0742−2822 generated with photon energy from 0.1-300 GeV in each \( \langle \dot{\nu} \rangle \) state. Panel (a)-(d) are the pulse profile for the state I, II, III and VI, respectively. The panel (a)-(d') is the residual after the total integral profile in Figure 2 subtracted the profile in each panel.

change detected in \( |\langle \dot{\nu} \rangle| \), which changed to a high state (\( \sim 6.0509(9) \times 10^{-13} \text{s}^{-2} \)), the corresponding increment, \( \Delta \langle \dot{\nu} \rangle / \langle \dot{\nu} \rangle \sim 0.12\% \). Although the time interval between glitch at MJD 55020 and \( |\langle \dot{\nu} \rangle| \) change at MJD 55225 is about 205 days, which has exceeded the general glitch recovery time scale, we still can not rule out the possibility that the glitch active at MJD 55020 lead to the increase of spin-down
The glitch event affects the spin-down rate. Keith et al. (2013) found that the correlation between the pulse profile parameters and $\dot{\nu}$ was detected in PSR J0742–2822 after a glitch at MJD 55200, no correlation for about 200 days before that and they believe that this was triggered by the glitch at MJD 55200. We have also detected the change of correlation between $\dot{\nu}$ and $W_{50}$ during Keith et al. (2013)’s data span. We found that the correlation disappeared after 1400 d, which coincides with the decrease of spin-down rate. This event did not involve glitch, as a small glitch occurred 350 d later. During MJD 57730-58700, the $\langle |\dot{\nu}| \rangle$ change to a high state($\langle |\dot{\nu}| \rangle \sim 6.0448(8) \times 10^{-13} \text{ s}^{-2}$) and the inverse correlation between $\dot{\nu}$ and $W_{50}$ gradually becomes strong first and then decay, which is independent of glitch, as no abrupt jump was detected in spin frequency. Therefore, changes of the $\langle |\dot{\nu}| \rangle$ and the correlation could not be only attribute to the glitch events. Generally, glitches are believed to originate from the interior of the neutron star, but emissions are believed to originate from the magnetosphere. The detected glitch-triggered variation of emission provide us opportunity to study the interaction of rotation and emission, but for PSR J0742-2822 the connection between pulsar rotation and emission is more complex.

The change of $\dot{\nu}$ reflects the change of external braking torque of pulsar. The permanent-like relative change of $\langle |\dot{\nu}| \rangle$ can be caused by changes in the inclination angle (Link et al. 1992; Link & Epstein 1997). According to the MHD simulation of Spitkovsky (2006), the relationship between the relative change of spin-down rate ($\Delta \langle |\dot{\nu}| \rangle/\langle |\dot{\nu}| \rangle$) and the magnetic angle ($\alpha$) can be expressed as follow:

$$\frac{\Delta \langle |\dot{\nu}| \rangle}{\langle |\dot{\nu}| \rangle} = \frac{\sin 2\alpha \Delta \alpha}{(1 + \sin^2 \alpha)}$$

(1)

The average increase of $\langle |\dot{\nu}| \rangle$ is 0.12% and 0.18% for the state change at MJD 55225 and 57730, respectively. Therefore, for the relative increase of $\langle |\dot{\nu}| \rangle$ at MJD 55225 and 57730, the corresponding increase in the inclination angle is 0.09° and 0.15° respectively (Here, we take $\alpha = 37^\circ$ Yadigaroglu & Romani 1995)). The out flowing particle wind and precession is a possibility caused the permanent-like relative change of $\langle |\dot{\nu}| \rangle$ (e.g. Kou & Tong 2015; Kou et al. 2018; Takata et al. 2020).

Generally, the particles acceleration of pulsar is thought to be occurred in the open zone, on the magnetic field line above each pole passing through the light cylinder. The $\gamma$-ray emission of pulsar is produced in an acceleration region near the light cylinder (Abdo et al. 2009). The glitch event affect the structure of the magnetospheric around the light cylinder, which may lead to changes in $\gamma$-ray emission. The changes in $\alpha$ results in the change of duration of the line of sightâ¯ÅZs pass through the pulse emission cone, and hence lead to measurable changes of the pulse profile. According to the Link & Epstein (1997), the corresponding increment of the total pulse flux is $\sim |\Delta \alpha|/W_{\text{half}}$, where $W_{\text{half}}$ is the half of the width of the emission cone. We use the value of $W_{\text{half}} = 5^\circ$ obtained by Yadigaroglu & Romani (1995), the corresponding changes in the flux $\sim 2\%$ and 3% for the $\langle |\dot{\nu}| \rangle$ state change at MJD 55225 and 57730 respectively. We do not detected significant change of $\gamma$-ray flux and the $\gamma$-ray pulse profile of PSR J0742–2822, which may due to its $\gamma$-ray flux is relatively weak ($\sim 3.2 \pm 0.6 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$).
5 SUMMARY

In this paper, we have

1. Found that $\langle \dot{\nu} \rangle$ of PSR J0742–2822 changes in four different states.
2. Investigated the correlation between $\dot{\nu}$ and $W_{50}$ and found that the correlation changed with time. Besides, not all the changes of $\langle \dot{\nu} \rangle$ states and correlations can be associated with the glitch activities.
3. Obtained long term evolution of $\gamma$-ray flux (0.1-300GeV) of this pulsar using about 11-years of Fermi-LAT Pass 8 (P8R3) data and did not detected significant change in $\gamma$-ray flux.

We expect the long-term regular radio observation of this pulsar in the future, as well as more sensitive $\gamma$-ray telescope to monitor it, to help us better understand the relationship between spin-down and radiation.

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