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# Glitch-induced pulse profile change of PSR J0742–2822 observed from the IAR

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## ABSTRACT

**Context.** The radio pulsar PSR J0742–2822 is known to exhibit rapid changes between different pulse profile states that correlate with changes in its spin-down rate. However, the connection between these variations and the glitch activity of the pulsar remains unclear. **Aims.** We aim to study the evolution of the pulse profile and spin-down rate of PSR J0742–2822 in the period MJD 58810–60149 (November 2019 to July 2023), which includes the glitch on MJD 59839 (September 2022). In particular, we looked for pulse profile or spin-down changes associated with the 2022 glitch.

**Methods.** We observed PSR J0742–2822 with a high cadence from the Argentine Institute of Radioastronomy (IAR) between November 2019 and July 2023. We used standard timing tools to characterise the times of arrival of the pulses and to study the pulsar rotation and, particularly, the oscillations of  $\dot{\nu}$ . We also studied the evolution of the pulse profile. For both of them, we compared their behaviour before and after the 2022 glitch.

**Results.** With respect to  $\dot{\nu}$ , we find that oscillations diminished in amplitude after the glitch. We find four different components contributing to the pre-glitch  $\dot{\nu}$  oscillations, and only one component after the glitch. With regard to the emission, we find the pulse profile has two main peaks. We detect an increase in the  $W_{50}$  of the total pulse profile of  $\sim 12\%$  after the glitch and we find the amplitude of the trailing peak increased with respect to the amplitude of the leading one after the glitch.

**Conclusions.** We find significant changes in the pulse profile and the spin-down rate of PSR J0742–2822 after its 2022 glitch. These results suggest that there is a strong coupling between the internal superfluid of the neutron star and its magnetosphere, and that pulse profile changes may be led by this coupling instead of being led purely by magnetospheric effects.

**Key words.** methods: observational – pulsars: general – radio continuum: general

## 1. Introduction

Pulsars are neutron stars that present pulsed emission mainly in radio frequencies. The very high moment of inertia of pulsars provides them with a highly stable rotation (Hobbs et al. 2012). However, particularly in young pulsars, their stable rotation can be perturbed by timing noise and glitches. On the one hand, timing noise appears as a continuous and erratic pattern around the simple rotational evolution of the pulsar, and it is unclear whether it originates in the interior of the neutron star or due to alterations in the magnetosphere (Melatos & Warszawski 2009; Lyne et al. 2010; Gügercinoğlu & Alpar 2017; Parthasarathy et al. 2019). On the other hand, glitches are sudden changes in the rotation frequency of pulsars, generally accompanied by a change in the frequency

derivative, which often returns to its pre-glitch value exponentially over different timescales, from one minute to several hundred days (Zhou et al. 2022). Glitches are considered to be provoked by the decoupling of the superfluid interior of the star from the solid crust (Baym et al. 1969; Haskell & Melatos 2015; Gügercinoğlu et al. 2022). Although this process is related to the dynamics inside the neutron star, glitches can also affect pulsar emission (Keith et al. 2013; Antonopoulou et al. 2022).

Investigating the impact of glitches on the spin evolution and the emission of the pulsar can reveal valuable information about the radiation processes occurring near the pulsar's surface and improve our understanding of its internal dynamics. Although nowadays at least 200 pulsars are known to present glitches<sup>1</sup> (Espinoza et al. 2011; Fuentes et al. 2017; Manchester

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<sup>1</sup> <http://www.jb.man.ac.uk/pulsar/glitches.html>

2018; Basu et al. 2022), the relation between glitches, the spin-down rate, and emission changes in the radio band is a relatively understudied topic. To date, there have only been a few reported emission changes clearly related to glitch events.

Lyne et al. (2010) showed that, for some pulsars, there was a strong correlation between the spin-down rate and pulse-profile width, although no glitches were included in that study. Weltevrede et al. (2011) found extremely rare alterations in the pulse profile of PSR J1119–6227 preceded by glitches. Kou et al. (2018) show that after a glitch in PSR B2035+36, the emission state transitioned to two different radiation modes, and there was a significant decrease in the pulse-profile width. Shang et al. (2020) show that the separation between the peaks of the Crab pulsar’s pulse profile displays an increasing trend with time. Yan et al. (2020) report that PSR J1048–5832 switches between a strong mode and a weak mode periodically. Another case is the one of PSR B1822–09, where two glitches are reported by Liu et al. (2022), both associated with pulse profile changes. Zhou et al. (2023) also report a change in the emission profile of PSR J0738–4042 after a small glitch, which is also reported for PSR J1048–5832 by Liu et al. (2024).

In particular, PSR J0742–2822 is known to switch between two magnetospheric states identified by different pulse profiles (Lyne et al. 2010), which correlates with changes in the spin-down rate, suggesting that timing noise can be driven by magnetospheric effects. However, Keith et al. (2013) found that the correlation between the spin-down rate and the pulse width increased strongly after a glitch, indicating that variations in the emission state might be linked to interactions between the neutron star interior and its magnetosphere. Finally, Dang et al. (2021) and Shaw et al. (2022b) show that there are different states of the pulsar characterised by the strength of the correlation between the pulse shape and spin-down rate and that not all the state changes in the spin-down rate are associated with glitches.

So far, nine glitches have been reported for PSR J0742–2822 (Basu et al. 2022). The 2022 glitch (glitch #9, Shaw et al. 2022a; Zubieta et al. 2022; Grover et al. 2024) is a unique opportunity to study this pulsar, given that the relative frequency jump was three orders of magnitude higher than for seven of the previous glitches (glitches #1, #2, #3, #4, #5, #6, and #8) and 50 times greater than glitch #7. In this work, we investigate the evolution of the pulse profile of PSR J0742–2822 and spin-down rate along our data span between 2019 and 2023 – including the 2022 glitch – obtained from the Argentine Institute of Radioastronomy (IAR).

This paper is organised as following. In Sect. 2 we describe the pulsar monitoring campaign at IAR and the timing observations used for this work. In Sect. 3 we explain the methods used to track the pulsar rotation, characterise the spin-down rate behaviour, and study the pulse profile evolution. In Sect. 4 we present the changes in the spin-down rate and the radio emission of the pulsar due to the glitch event, and finally in Sect. 5 we discuss the implications of our results, with some concluding remarks in Sect. 6.

## 2. Observations

The IAR observatory is located near the city of La Plata in Argentina. It has two 30-m single-dish antennas 120 m apart. The antennas ‘Carlos M. Varsavsky’ and ‘Esteban Bajaja’ are referred to as A1 and A2, respectively. Observations with A1 have a bandwidth of 112 MHz in one circular polarisation at a central bandwidth of 1400 MHz, while observations with

A2 have a bandwidth of 56 MHz in two circular polarisations at a central frequency of 1428 MHz (Gancio et al. 2020). Since 2019, with the antennas of the IAR, our Pulsar Monitoring in Argentina<sup>2</sup> (PuMA) collaboration has observed a set of bright pulsars in the southern hemisphere with a high cadence (Gancio et al. 2020; Lousto et al. 2024).

Among the monitored targets, there are a number of pulsars that have previously shown glitch activity, including PSR J0742–2822. Here, we analyse 408 observations of PSR J0742–2822 obtained with A2 between MJD 58810 (November 23, 2019) and MJD 60149 (July 24, 2023). The observations have a sample time of 146  $\mu$ s and a typical duration of 30 min, yielding a total of 204 h of observing time. We note that our observations are not flux-calibrated. This prevents us from studying the pulsar flux evolution.

## 3. Methods

### 3.1. Pulsar timing

We processed all the observations with PRESTO (Ransom et al. 2003; Ransom 2011). First, we eliminated radio-frequency interferences (RFIs) with the task RFIFIND and folded the observations with the task PREPFOLD. Then, we used the task PAT in PSRCHIVE (Hotan et al. 2004) to cross-correlate each profile with a template in order to calculate the times of arrival (TOAs). The template was obtained using the tool PSRSMOOTH in PSRCHIVE on a pulse profile with a high signal-to-noise ratio (S/N).

We used TEMPO2 (Hobbs et al. 2006) to characterise the rotation of the pulsar by fitting the TOAs to a simple Taylor expansion,

$$\phi(t) = \phi + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3, \quad (1)$$

where  $t_0$  is the reference epoch, and  $\nu$ ,  $\dot{\nu}$ , and  $\ddot{\nu}$  are the rotation frequency and its first and second derivatives.

In the case of a glitch, the rotation rate suddenly increases. This change in the rotational phase provoked by the glitch can be modelled as follows (Yu et al. 2013):

$$\begin{aligned} \phi_g(t) = & \Delta\phi + \Delta\nu_p(t - t_g) + \frac{1}{2}\Delta\dot{\nu}_p(t - t_g)^2 \\ & + \frac{1}{6}\Delta\ddot{\nu}(t - t_g)^3 + \sum_i \left[ 1 - \exp\left(-\frac{t - t_g}{\tau_d^i}\right) \right] \Delta\nu_d^i \tau_d^i. \end{aligned} \quad (2)$$

Here,  $\Delta\phi$  counteracts the uncertainty on the glitch epoch  $t_g$ , and  $\Delta\nu_p$ ,  $\Delta\dot{\nu}_p$ , and  $\Delta\ddot{\nu}$  are the step changes in  $\nu$ ,  $\dot{\nu}$ , and  $\ddot{\nu}$  at  $t_g$ , respectively. Finally,  $\Delta\nu_d$  represents temporary increases in frequency that recovers in  $\tau_d$  days. From Eq. (2), we can define glitch sizes as

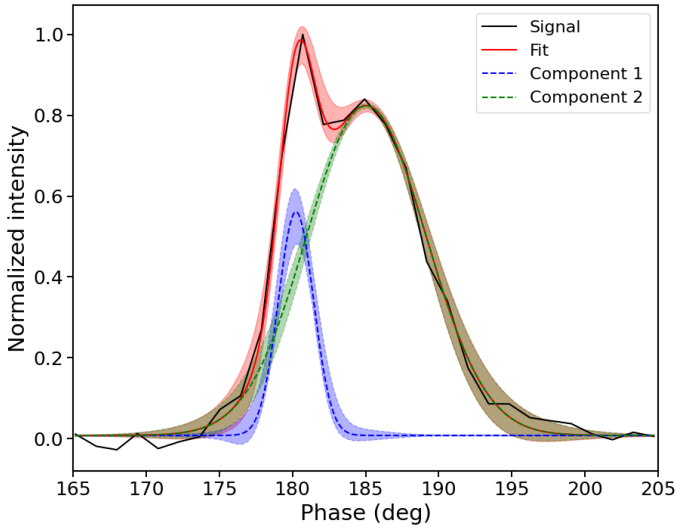
$$\frac{\Delta\nu_g}{\nu} = \frac{\Delta\nu_p + \sum_i \Delta\nu_d^i}{\nu} \quad (3)$$

$$\frac{\Delta\dot{\nu}_g}{\dot{\nu}} = \frac{\Delta\dot{\nu}_p - \sum_i \Delta\nu_d^i / \tau_d^i}{\dot{\nu}}. \quad (4)$$

We can also define the recovery factor for each recovery term as

$$Q_i = \frac{\Delta\nu_d^i}{\Delta\nu_p + \sum_i \Delta\nu_d^i}, \quad (5)$$

<sup>2</sup> <https://puma.iar.unlp.edu.ar>



**Fig. 1.** Example of one of the mean profiles fitted with two Gaussian components with their  $1\sigma$  uncertainties.

and the total recovery factor of the glitch as

$$Q = \frac{\sum_i \Delta v_d^i}{\Delta v_p + \sum_i \Delta v_d^i}. \quad (6)$$

In addition, we characterised the oscillations of  $\dot{\nu}$  with respect to the timing model. We used the Gaussian process regression (GPR) technique to fit the residuals with a square exponential covariance function (Rasmussen & Williams 2006; Shaw et al. 2022b) with the GPTOOLS library (Chilenski et al. 2015). By analysing the second derivative of this fitted function, we derived the evolution of  $\dot{\nu}$  (Keith et al. 2013). We then used the Lomb-Scargle spectral analysis tool (Scargle 1982) to identify possible quasi-periodicities in the evolution of  $\dot{\nu}$  and to evaluate the false alarm probability of the peaks using the FALSE\_ALARM\_PROBABILITY method in the ASTROPY library (Astropy Collaboration 2013).

### 3.2. Pulse profile evolution

We divided our data span into 26 intervals that exclude the glitch, which are at least 15 days long and contain at least 15 TOAs. In each interval, we set  $\ddot{\nu} = 0$  and fitted the values and uncertainties of  $\nu$  and  $\dot{\nu}$ . We used these values to update the file header with the ephemeris of all pulse profiles within the region to align their phases (Liu et al. 2024). Finally, we used the task PSRADD in PSRCHIVE to combine all profiles in the region, resulting in a single high S/N mean profile.

All the mean profiles look like a double-peak signal as shown in Fig. 1. We therefore modelled the profiles as the sum of two Gaussian components as

$$Y = A_1 \exp\left[-\frac{(x - \mu_1)^2}{2\sigma_1^2}\right] + A_2 \exp\left[-\frac{(x - \mu_2)^2}{2\sigma_2^2}\right] + C, \quad (7)$$

where  $A_{1,2}$  are the amplitudes of the leading (left) and trailing (right) components, respectively, and  $\mu_{1,2}$  are the position of their centres. Finally,  $\sigma_{1,2}$  are the widths of each component and  $C$  is the offset of the signal.

To carry out the fit, we applied the MCMC method (Ashton & Talbot 2021) from the BILBY library (Ashton et al.

**Table 1.** Parameters of the timing model for the 2022 glitch in PSR J0742–2822 and their  $1\sigma$  uncertainties, obtained by fitting the data spanning from MJD 59683 to MJD 60149.

Parameter	Value
$t_0$ (MJD)	59000
$\nu$ ( $s^{-1}$ )	5.9960548719(4)
$\dot{\nu}$ ( $s^{-2}$ )	$-6.0348(1) \times 10^{-13}$
$\ddot{\nu}$ ( $s^{-3}$ )	–
DM ( $cm^{-3}pc$ )	73.728(1)
$t_g$ (MJD)	59839.4(5)
$\Delta v_p$ ( $s^{-1}$ )	$2.5619(1) \times 10^{-5}$
$\Delta \dot{v}_p$ ( $s^{-2}$ )	$-4.1(4) \times 10^{-16}$
$\Delta \ddot{v}$ ( $s^{-3}$ )	–
$\Delta v_{d1}$ ( $s^{-1}$ )	$1.23(2) \times 10^{-7}$
$\Delta v_{d2}$ ( $s^{-1}$ )	$8(5) \times 10^{-8}$
$\tau_{d1}$ (days)	48(2)
$\tau_{d2}$ (days)	8(5)
$\Delta\phi$	0.14(2)
$\Delta v_g/\nu$	$4.306(8) \times 10^{-6}$
$\Delta \dot{v}_g/\dot{\nu}$	0.24(16)
$Q_1$ (%)	0.476(7)
$Q_2$	0.3(2)
$Q$	0.8(2)

**Notes.** The DM value was taken from ATNF (<https://www.atnf.csiro.au/research/pulsar/psrcat/>). The glitch epoch and its uncertainty was taken from Shaw et al. (2022a).

2019) to fit Eq. (7) to all the mean profiles. We obtained three million samples from 10 000 steps performed with 300 walkers for each fit, with a burn-in of 3333 iterations. An example fit is shown in Fig. 1. Subsequently, we used 10 000 posterior samples to obtain the best-fitting parameters of interest with their  $1-\sigma$  uncertainties.

On the one hand, regarding the pulse profile, we studied the evolution of the pulse width at half maximum  $W_{50}$ , and the shape parameter  $S$  (as defined by Keith et al. 2013), which is the ratio between the normalised intensities of the leading peak and the trailing peak. On the other hand, we studied the evolution of the Gaussian components by characterising the evolution of the distance between their centres,  $\Delta = \mu_2 - \mu_1$ , the ratio between their amplitudes,  $r_A = A_2/A_1$ , and between their widths,  $r_W = \sigma_2/\sigma_1$ .

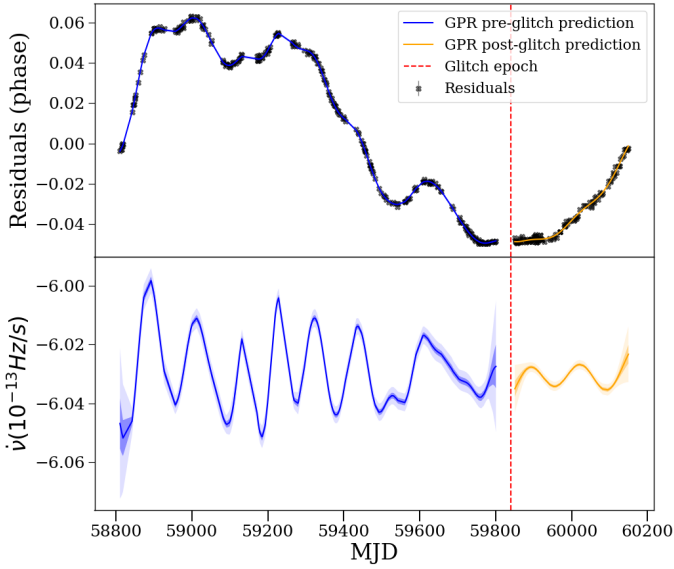
## 4. Results

### 4.1. Timing solution and glitch characterisation

We assumed the glitch epoch reported by Shaw et al. (2022a) and used a code based on nested sampling<sup>3</sup> (Skilling 2004) to determine the best timing solution for the glitch parameters. The code employs PINT software (Luo et al. 2021), with a short data span of  $\sim 100$  d around the glitch in order to not be affected by red noise. In addition to the recovery term reported in Zubieta et al. (2024), we find a second and shorter recovery term with a marginal logarithmic Bayes factor of 1.3. We do not find evidence of a change in  $\ddot{\nu}$ . In Table 1 we present the updated parameters for the timing solution including the glitch event.

We used the GPR technique to calculate the oscillation of  $\dot{\nu}$  around the rotational model shown in Table 1, following the same procedure as Shaw et al. (2022b) and Keith et al. (2013)

<sup>3</sup> <https://github.com/kbarbary/nestle>



**Fig. 2.** Rotational analysis of PSR J0742–2822. Top panel: Residuals after fitting the glitch (black dots) and the GPR prediction (solid curves). Bottom panel: Evolution of  $\dot{\nu}$  obtained from the GPR prediction after the glitch was removed from the residuals; the shaded regions correspond to the  $1\text{-}\sigma$  confidence intervals.

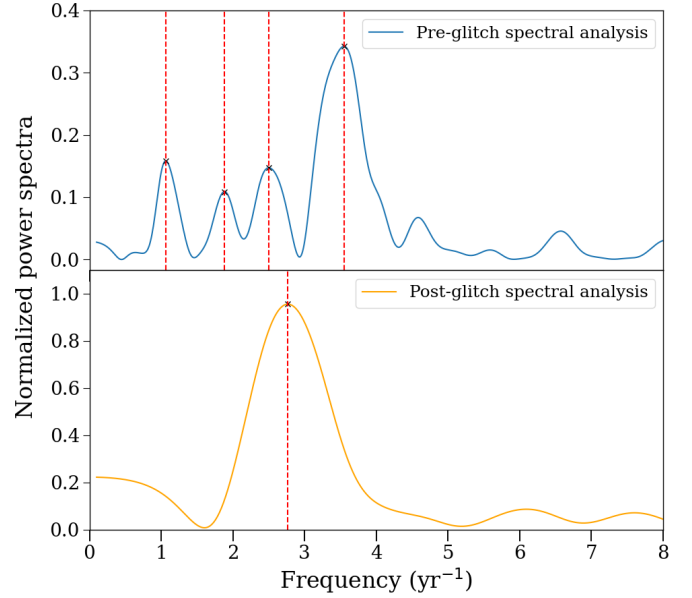
to obtain an unbiased solution for the oscillations of  $\dot{\nu}$  in the presence of red noise. We performed independent GPR predictions for the pre-glitch and the post-glitch residuals. In Fig. 2 we show the post-fit timing residuals with the GPR prediction, and the second derivative of the GPR prediction, which is  $\dot{\nu}$ . Fig. 2 shows that the standard deviation of  $\dot{\nu}$  is much smaller after the glitch ( $\sigma_{\dot{\nu}}/\dot{\nu} \sim 0.17\%$ ) than before the glitch ( $\sigma_{\dot{\nu}}/\dot{\nu} \sim 0.82\%$ ).

In addition, oscillations seem to have higher-frequency components before the glitch than after the glitch. In order to quantify it, we performed a Lomb-Scargle analysis for the pre-glitch oscillations and the post-glitch oscillations independently. The results are shown in Fig. 3. We find four frequency components for the pre-glitch  $\dot{\nu}$  oscillations, while we detect only one for the post-glitch  $\dot{\nu}$  oscillations. The peaks detected in the Lomb-Scargle analysis are enumerated in Table 2, ordered by their relative intensities in the Lomb-Scargle analysis.

#### 4.2. Pulse profile evolution

We analysed 26 mean profiles. Eighteen of them are pre-glitch observations between MJD 58810 and MJD 59800, and eight are post-glitch observations between MJD 59851 and MJD 60149. From the post-glitch profiles, one of them corresponds to a date when the glitch had not finished its recovery phase, while the rest correspond to the post-glitch recovery data span. We show all mean profiles normalised by the amplitude of the leading peak in Fig. 4.

The pulses shown in Fig. 4 reveal that for all pre-glitch pulses, the leading peak is greater in amplitude than the trailing peak. However, for some of the post-glitch pulses, the trailing peak is greater than the leading one. Furthermore, for some of the post-glitch pulses, the trailing peak is further away in phase from the leading peak than for the pre-glitch pulses. Fig. 4 also shows the average normalised pulse profile before the glitch and after the glitch recovery (solid blue and yellow lines), clearly exposing the changes in the amplitude of the trailing peak and the distance from the leading peak. In addition, we marked the



**Fig. 3.** Top panel: Lomb-Scargle analysis of the pre-glitch GPR prediction for  $\dot{\nu}$ . Bottom panel: Lomb-Scargle analysis of the post-glitch GPR prediction for  $\dot{\nu}$ . We consider the peaks that have a false alarm probability lower than 1%.

**Table 2.** Frequencies of the oscillations of  $\dot{\nu}$  detected with the Lomb-Scargle analysis.

Peak	Pre-glitch frequency ( $\text{yr}^{-1}$ )	Post-glitch frequency ( $\text{yr}^{-1}$ )
Primary	3.5(7)	2.7(12)
Secondary	1.1(3)	–
Third	2.5(5)	–
Fourth	1.9(3)	–

**Notes.** We took the FWHM for the uncertainty of the peaks and only considered peaks with a false alarm probability lower than 1%.

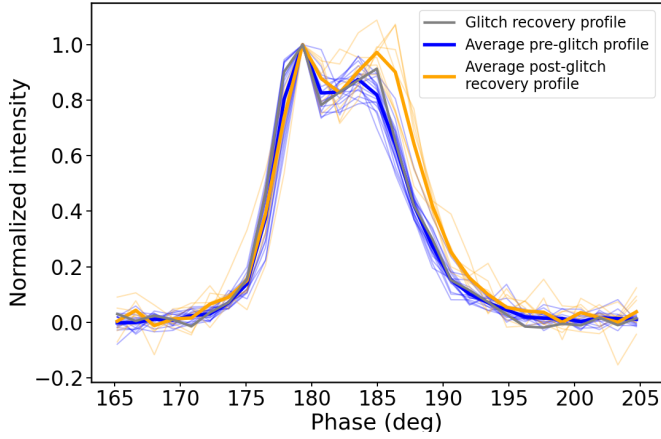
only profile that is within the post-glitch recovery data span. This profile looks like a transition between the pre-glitch profile and post-glitch recovery profile.

We then fitted all the pulses with a two-component Gaussian model, as explained in Sect. 3.2. From the posteriors, we studied the behaviours of  $W_{50}$ ,  $\Delta$ ,  $S$ ,  $r_A$ , and  $r_W$ .

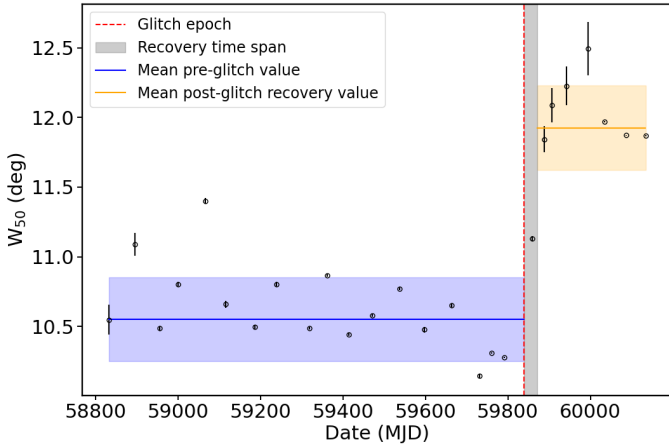
In Figs. 5 and 6, we show the evolution of  $W_{50}$  and  $\Delta$ , respectively. These parameters behave similarly between each other as expected. Figure 5 shows that before the glitch,  $W_{50}$  is generally below  $11^\circ$ , while after the glitch, except for the glitch recovery pulse profile, it is above  $11.5^\circ$ . The glitch recovery value of  $W_{50}$  may indicate a transition between its pre-glitch and post-glitch value.

Something similar happens with  $\Delta$ . Fig. 6 shows that  $\Delta$  lies below  $5.6^\circ$  in most of the pre-glitch pulse profiles, and above  $5.75^\circ$  for the majority of the post-glitch cases. It also shows an intermediate value of  $\Delta$  for the glitch recovery pulse profile. This behaviour describes the increasing distance of the trailing peak with respect to the leading peak after the glitch as shown in Fig. 4, indicating the Gaussian components are more separated after the glitch.

Regarding the shape parameter,  $S$ , Fig. 7 shows that for all the pulse profiles before the glitch,  $S > 1$ , which means that the



**Fig. 4.** All the normalised mean pulse profiles studied in this work with the pre-glitch and post-glitch recovery mean pulse (solid blue and yellow lines, respectively). The profile of the glitch recovery data span is marked with a solid grey line.

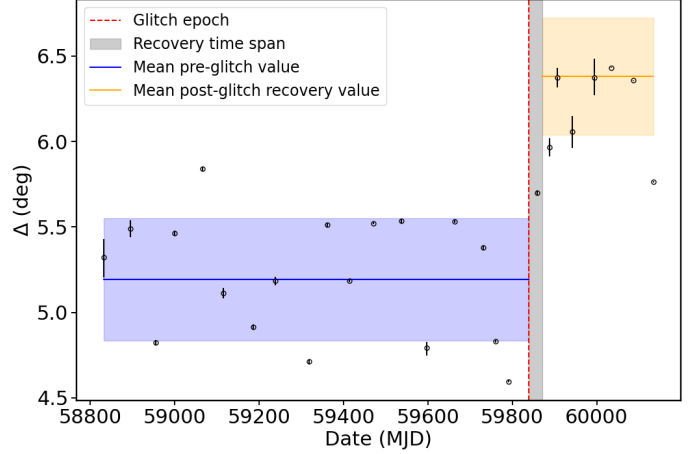


**Fig. 5.** Evolution of  $W_{50}$ . The horizontal bands correspond to the  $1\sigma$  mean values in the pre-glitch (blue) and post-glitch recovery (orange). The vertical grey band marks the glitch recovery timespan.

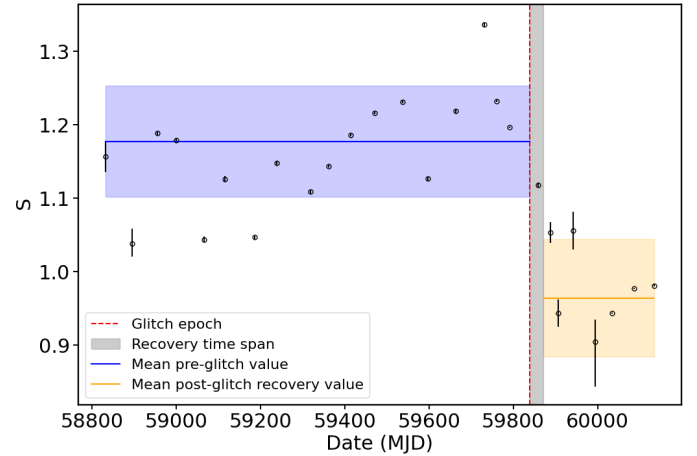
leading peak is always greater than the trailing one. However, for the post-glitch recovery profiles, only two cases correspond to  $S > 1$ , while the rest of them clearly have  $S < 1$ . Therefore, the trailing peak surpassed the leading peak in amplitude after the glitch. Again, the glitch recovery value of  $S$  is intermediate between the pre-glitch mean value of  $S$  and its post-glitch recovery mean value.

We also studied the evolution of the Gaussian components by comparing their parameters through  $r_A$  and  $r_W$ . Fig. 8 shows the evolution of the ratio between the amplitudes of the components,  $r_A$ . Although there is no significant change in the value of  $r_A$ , the dispersion of the values after the glitch is much smaller than before the glitch, which might be an indicator of the stability of the magnetosphere. With respect to  $r_W$ , as seen in Fig. 8, the width of the trailing component increases significantly with respect to the leading one, and it also presents an intermediate value for the glitch recovery profile.

To quantify the change in the profile after the glitch, in Table 3 we used the  $1\sigma$  value of all the parameters studied above. We also included the standard deviation of  $\dot{\nu}$  before and after the glitch. We did not study separated oscillations for the glitch recovery data span given that it is too short to perform adequate



**Fig. 6.** Evolution of the distance between the centres of the Gaussian components. The horizontal bands correspond to the  $1\sigma$  mean pre-glitch value and the  $1\sigma$  mean post-glitch recovery value, respectively. The vertical grey band marks the 33-day glitch recovery epoch.

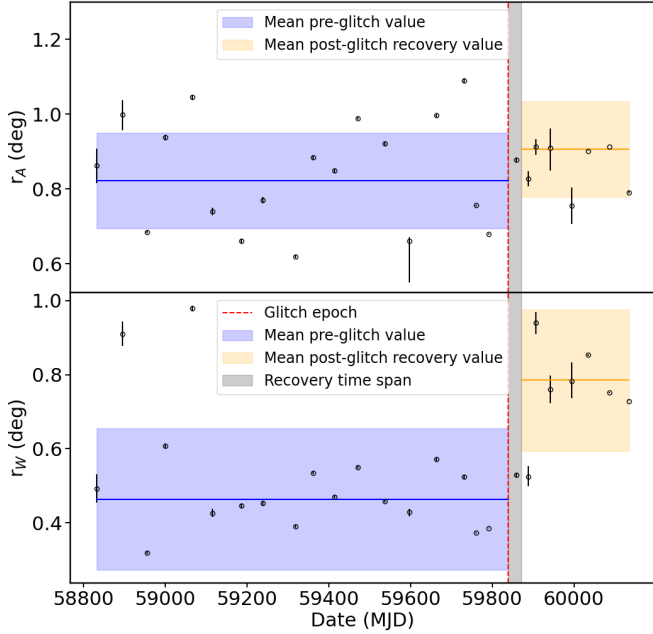


**Fig. 7.** Evolution of the shape parameter  $S$ . The horizontal bands correspond to the  $1\sigma$  mean pre-glitch value and the  $1\sigma$  mean post-glitch recovery value, respectively. The vertical grey band marks the glitch recovery data span.

GPR predictions. From Table 3 we conclude that  $W_{50}$ ,  $\Delta$ , and  $r_W$  indicate that the pulse profile is wider after the glitch due to the widening of the trailing Gaussian component. Also,  $S$  shows that the peak of the trailing component was amplified after the glitch with respect to the leading component. This may indicate that only the trailing component became brighter after the glitch, which also resulted in a widening of that component. Regarding  $r_A$ , the mean value did not change significantly after the glitch, but the dispersion is 2.5 times smaller after the glitch than before it. For all the parameters studied here, the values that correspond to the glitch recovery profile lie between their pre-glitch and post-glitch recovery values. We also note that, together with the change in the profile, the oscillations of  $\dot{\nu}$  also changed, decreasing significantly after the glitch.

## 5. Discussion

Generally, glitches are thought to be driven by the superfluid interior of the neutron star, while pulse profile evolution and spin-down oscillating behaviours are considered to be driven



**Fig. 8.** Evolution of the ratio between the amplitudes and the widths of the Gaussian components. The horizontal bands correspond to the  $1\sigma$  mean pre-glitch value and the  $1\sigma$  mean post-glitch recovery value, respectively. The vertical grey band marks the glitch recovery data span.

**Table 3.** Comparison of parameters of interest before the glitch, during the glitch recovery, and afterwards. We note that  $\sigma_{\dot{\nu}}/\dot{\nu}(\%)$  refers to the relative standard deviation of  $\dot{\nu}$ .

Parameter	Pre-glitch	Recovery phase	Post-recovery
$W_{50}$ (deg)	10.6(3)	11.13(4)	11.9(3)
$\Delta$ (deg)	5.2(3)	5.70(3)	6.4(3)
S	1.18(7)	1.118(7)	0.96(8)
$r_A$	0.82(15)	0.88(1)	0.90(15)
$r_W$	0.46(17)	0.53(11)	0.79(1889)
$\sigma_{\dot{\nu}}/\dot{\nu}(\%)$	0.82	–	0.17

**Notes.** The best-fitting values and  $1\text{-}\sigma$  errors shown here were obtained from the posterior distributions from the MCMC chains.

by magnetospheric changes (Baym et al. 1969; Antonelli et al. 2022). However, in some pulsars, there have been detections of changes in the spin-down behaviour or pulsar emission after a glitch. In the case of PSR J0742–2822, Keith et al. (2013) detected a change in the correlation between the spin-down frequency derivative and the pulse profile shape after its 2009 glitch. Dang et al. (2021) and Shaw et al. (2022b) show that there are different states for the correlation between the spin-down rate, but that not all the changes in the spin-down rate are associated with glitches.

The glitch observed in 2022 in PSR J0742–2822 was significantly larger than any previously reported events for this pulsar, with a fractional frequency jump almost 50 times greater than the largest glitch recorded prior to 2022 (Basu et al. 2022). This event resulted in a fractional frequency increase of  $\frac{\Delta\nu}{\nu} \sim 4300 \times 10^{-9}$  (Shaw et al. 2022a; Zubieta et al. 2023), while previous glitches typically exhibited relative increases of  $\frac{\Delta\nu}{\nu} \leq 92 \times 10^{-9}$ .

For this work we studied the spin-down rate evolution and the pulse profile behaviour across the 2022 giant glitch and we detected a clear change in both of them induced by the glitch.

This glitch-induced variation in the pulsar emission thrusts the study of the complex relation between the pulsar rotation and the pulse-profile emission. For example, studying radiative changes during glitches detected ‘in live’ could be key to understanding the magnetospheric structure of neutron stars (Palfreyman et al. 2018).

Shaw et al. (2022b) show that the standard deviation of  $\dot{\nu}$  around the timing model varying with time is not stable, and Dang et al. (2021) find that, in some cases, the average value of  $\dot{\nu}$  changes after the pulsar has gone through a glitch. In Table 3, we report the change in  $\dot{\nu}$  due to the glitch. Also, we show that the standard deviation around  $\dot{\nu}$  is  $\sigma_{\dot{\nu}}/\dot{\nu} \sim 0.82\%$  for most of the 1000 days in our pre-glitch data span, while for the 300 days of observations after the glitch, the standard deviation decreases significantly down to  $\sigma_{\dot{\nu}}/\dot{\nu} \sim 0.17\%$  (bottom panel of Fig. 2). Considering the scenario where the glitch is triggered when the critical lag between the superfluid interior of the star and the rigid crust is reached (Antonopoulou et al. 2022; Haskell 2016), the post-glitch decrease in the standard deviation of  $\dot{\nu}$  may indicate that the system rapidly reestablishes equilibrium as the superfluid and crust regain rotational synchronisation.

We also find a significant change in the periodicity spectra of the spin-down rate evolution (Fig. 3). In Shaw et al. (2022b), they find that the periodicity of the  $\dot{\nu}$  evolution had a peak in  $2.8(1)\text{ yr}^{-1}$ , although the spectrum is highly noisy and have many peaks. Here, although with a much smaller data span, we find clearer spectrum with four peaks before the glitch, and only one peak after the glitch. Both of these results are consistent with our result in Zubieta et al. (2024), where we conclude that red noise had diminished after the glitch. Considering that we detect four frequencies contributing to red noise before the glitch, and only one after the glitch, such red-noise components may correspond to different regions inside the neutron star responsible for the pulsar braking torque. Assuming that the oscillations are driven by the coupling between different regions of the superfluid interior and the solid crust (Gügercinoğlu et al. 2023; Gügercinoğlu & Alpar 2017), these regions might decouple from the braking torque of the star during the glitch and then re-couple again on different timescales. In addition, if oscillations of the frequency derivative were driven by oscillations in the magnetic field (Zhang & Xie 2012), this result might point to a reconfiguration of the magnetosphere during the glitch. The idea of a reconfiguration or a stabilisation of the magnetosphere after the glitch is also supported by the fact that the dispersion of  $r_A$  is much smaller after the glitch than before it, together with the more stable behaviour of  $\dot{\nu}$ . Therefore, the evidence gathered here shows that the pulsar magnetosphere was likely affected by the decoupling between the superfluid interior and the crust of the neutron star during the glitch (Palfreyman et al. 2018), or by the mechanism that triggered the glitch (Gügercinoğlu & Alpar 2020).

In addition, Zhou et al. (2024) also detect that the typical periodicity and amplitude of the  $\dot{\nu}$  oscillation in PSR J1522–5735 changed after each glitch, which is a similar behaviour that we detect for PSR J0742–2822. This was interpreted in terms of the vortex creep model. During external driven events such as glitches, the vortices that are pinned to the neutron star’s crust are unpinned and then repinned in new positions. This rearrangement alters the vortices’ oscillations around their equilibrium configuration. As a result, the frequency and amplitude of these oscillations change. These vortex oscillations generate variable torques on the crust, leading to fluctuations in the pulsar’s spin-down rate ( $\dot{\nu}$ ) after each glitch (Gügercinoğlu et al. 2023).

We also detect that the transition between the pre-glitch and post-glitch magnetospheric states is not discrete. We find evidence for an intermediate magnetospheric state probably related to the glitch recovery epoch. This novel detection opens the door to further study the correlation between the superfluid interior of the neutron star and the different magnetospheric states, suggesting that the latter may be driven by the dynamics of the superfluid or vice versa, as well as a strong coupling between the magnetosphere and the superfluid dynamics. It is intriguing whether the recovery timescales of the superfluid may also affect the pulsar emission. This could be possible if the magnetosphere is also coupled to the different regions of the superfluid interior with their respective recovery timescales (Gügercinoğlu et al. 2023).

The change in  $r_w$  after the glitch indicates that the widening of the pulse profile is mainly caused by the widening of one of its components, in particular, the trailing peak. Consequently, it may be that the different components of the pulse profile have different coupling strengths to the different magnetic field lines in the magnetosphere and in turn to the superfluid interior of the neutron star, and therefore they are differently affected by the glitch. For example, if the glitch is triggered by a broken plate (Akbal et al. 2015; Gügercinoğlu & Alpar 2019; Liu et al. 2024), this broken plate could only affect the region of the polar cap where the trailing peak is emitted.

If the widening of the pulse is only due to a change of the inclination angle  $\alpha$  between the magnetic and rotational axes, Rankin (1990) calculated that  $W_{50}$  is linked to them as

$$W_{50} = 2.45^\circ \frac{P^{-1/2}}{\sin\alpha}. \quad (8)$$

According to this, the change in  $W_{50}$  of  $1.3(5)^\circ$  during the glitch corresponds to  $\Delta\alpha \sim 4.8^\circ$ . This value is quite high compared to the  $\Delta\alpha \sim 0.08^\circ$  inferred for PSR J1048–5832 by Liu et al. (2024). Given that the  $\Delta\alpha$  value is too large, we conclude that the widening of the pulse is not solely linked to a change in the inclination angle but also to pure magnetospheric changes.

We can confirm that the  $\Delta\alpha$  obtained before is invalid using the equations for the vortex creep model presented in Liu et al. (2024). The persistent shift in the spin-down rate is the following (Eq. (9)):

$$\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,total}}} = \frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,shift}}} + \frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,trap}}}, \quad (9)$$

where  $\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,trap}}}$  is the persistent step in the spin-down rate given by the formation of new vortex traps and  $\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,shift}}}$  is the contribution to the persistent change in the spin-down rate given by the change in the inclination angle between the magnetic axis and the rotational axis. Using Eq. (9) and that  $\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,trap}}} \geq 0$ , we obtain

$$\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,total}}} \geq \frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,shift}}}, \quad (10)$$

where (Zhao et al. 2017)

$$\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,shift}}} = \frac{\sin(2\alpha)\Delta\alpha}{1 + \sin^2(\alpha)}. \quad (11)$$

From Table 1, we obtain that the persistent change in the spin-down rate is  $\frac{\Delta\dot{\nu}}{\dot{\nu}_{\text{per,total}}} \sim 7 \times 10^{-4}$ . Therefore,  $\Delta\alpha \leq 0.05^\circ$ , which is a value similar to the one obtained by Liu et al. (2024). This way we conclude that the widening of the pulse is not only the result of a change in  $\alpha$ .

In summary, our results highlight the complexity of the interaction between the internal dynamics of the superfluid and the magnetospheric evolution in PSR J0742–2822 (Lyne et al. 2010; Keith et al. 2013; Dang et al. 2021; Shaw et al. 2022b). We demonstrate that the 2022 giant glitch clearly affected the magnetosphere of the pulsar and, consequently, both the oscillations in  $\dot{\nu}$  and the variation in the pulse profile were significantly altered. The reduction in red noise (Zubieta et al. 2024) and the decrease in the standard deviation of  $\dot{\nu}$  after the 2022 glitch suggest that the system stabilised after the glitch. In addition, the detection of a transient profile during the recovery period after the glitch raised may provide insight into the underlying mechanisms of glitches and their associated recovery processes.

Finally, we emphasise the need for long-term continued monitoring of glitching pulsars such as PSR J0742–2822 to better understand the link between glitches and magnetospheric changes. Given that this is the first time that an abrupt change in the pulse profile of PSR J0742–2822 was detected after the glitch, and that this is the largest glitch in this pulsar so far, we speculate that the size of the changes in the magnetosphere are proportional to the size of the glitch.

## 6. Conclusions

For this work we studied the rotational and pulse profile evolution of PSR J0742–2822 between MJD 58810 and MJD 60149, including the 2022 giant glitch on MJD 59839, based on high-cadence observations of the pulsar performed with the IAR radio telescopes. We find that both the rotational behaviour and the emission profile of the pulsar significantly changed after the glitch.

The oscillations of  $\dot{\nu}$  around the simple rotational model of the pulsar and the pulse profile emission are phenomena thought to be driven by the pulsar magnetosphere. Considering that we find they change after the glitch, it follows that either the magnetosphere is sensitive to changes in the superfluid interior of the star, or that the superfluid plays a more direct role in the behaviour of the frequency derivative, and the pulsar emission mechanism.

Furthermore, we also find a state transition in the magnetosphere coincident with the recovery timescale of the glitch, reinforcing the premise of a coupling between the magnetosphere and the superfluid interior of the star. Such conjecture is also strengthened by the fact that, before the glitch, oscillations in the frequency derivative occur at four different timescales, while after the giant glitch the oscillations damp significantly, experiencing a single quasi-periodicity, with a much lower amplitude. This suggests that multiple regions inside the neutron star are responsible for the braking torque. Such regions decouple during the glitch and begin to re-couple again at different timescales. Future real-time glitch observations, combined with detailed analyses of pulse profile and rotational dynamics, could provide more insights into the relation between pulse-profile evolution and internal processes in neutron stars.

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