The ORT and the uGMRT Pulsar Monitoring Program : Timing Irregularities in Pulsars

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Abstract

Pulsars, extremely compact and highly magnetized rotating neutron stars, were observed to have high rotational stability. The spin evolution of pulsars is commonly affected by two irregularities: glitches and timing noise. Glitches are abrupt changes in the spin period of pulsars, while timing noise refers to any random fluctuations in the rotation of the pulsar. We present a summary of the timing results for a sample of pulsars monitored using the Ooty Radio Telescope and the upgraded Giant Metrewave Radio Telescope. Notably, we report a novel glitch verification methodology that can distinguish between a glitch and strong timing noise.

1. Introduction

Pulsar glitches are rare phenomena. Since the detection of the first glitch in 1969 [1], only around 680 glitches in about 220 pulsars have been observed [2]. Various models have been developed to explain this phenomenon [3], with the most successful model being based on the superfluid vortex pinning and creep mechanism. This model explains how internal superfluidity leads to differential rotation within the star by immobilizing vortex lines and pinning them to lattice nuclei and flux tubes in the outer core. The large amount of angular momentum thus produced is released abruptly, causing a spin-up of the crust, known as a glitch. Glitches can be classified into four categories based on their occurrence: conventional glitches, slow glitches, glitches with delayed spin-ups, and anti-glitches. Based on size, glitches can be categorized as either small or large [4].

Timing noise and glitches can often be easily confused. Timing noise is more random and less understood than glitches, primarily because studying it requires long timing baselines, during which noise due to variations in ionized interstellar medium can easily creep into the data and corrupt it, sometimes even manifesting as a small glitch. Therefore, it is crucial to look for solid evidence when reporting a glitch, as it might also be a manifestation of timing noise [5]. Additionally, it is possible that glitches and timing noise are produced by similar mechanisms.

The traditional glitch detection procedure does not account for any possible irregularity due to timing noise. An alternative to the traditional glitch analysis involves developing a semi-automated approach using a Hidden Markov Model (HMM) that incorporates both timing noise and glitches [6]. However, this model approximates timing noise as white noise in the torque derivative instead of following the red noise or power law spectra observed in most pulsars. We proposed and demonstrated an innovative glitch verification methodology that accounts for timing noise as a red noise process, as seen in most pulsars. This novel approach is designed to differentiate glitches from manifestations of timing noise.

This paper summarizes the outcomes of our monitoring program utilizing the Ooty Radio Telescope (ORT) [7] and the Upgraded Giant Metrewave Radio Telescope (uGMRT) [8]. The outline is as follows: Section 2 describes the observations, and various analysis techniques are discussed in Section 3. In Section 4, we explain the Gaussian Process realization. The results are provided in Section 5, and Section 6 presents the conclusions.

2. Observations

Regular observations for a sample of 24 pulsars are conducted using the uGMRT and the ORT to investigate timing irregularities in pulsars, since 2015. The sample consists of pulsars of different ages, that exhibit glitches of variable amplitudes [4]. We use two of India's largest radio telescopes for our observations.

The first telescope used is the ORT [7], a cylindrical paraboloid measuring 530m in length and 30m in width. It covers a declination range from –60° to +60°. Observations with the ORT are conducted at 326.5 MHz (central frequency) with a cadence ranging from 1 to 15 days.

The second telescope used is the uGMRT [8], an array comprising 30 fully steerable parabolic antennas, each 45 meters in diameter, extended over a baseline of 25 km. It covers a declination range from –53° to +90°. The uGMRT supports observations in the frequency range of 120–1460 MHz across four bands. We observe sources at the uGMRT with a cadence of 15–30 days.

3. Analysis

3.1 Timing Analysis

Pulsar timing involves matching the predicted times of arrival (ToAs) from a presumed model with the observed measurements from an average pulse. Traditional timing includes a timing model and ToAs. The ToAs are obtained by cross-correlating the average observed pulse with the template, while the timing model includes parameters such as pulsar frequency and its derivatives, dispersion measure, coordinates and proper motion of the star, parallax, and more. The parameters of the timing model are obtained by fitting the ToAs using a weighted least squares algorithm. A good timing solution yields whitened and minimized residuals. The pulsar timing software TEMPO2 [9] was used to perform the timing analysis.

3.2 Bayesian Analysis

Bayesian analysis is a statistical technique that uses Bayes' theorem to determine the posterior distribution of a set of parameters *X* given data *D* and a hypothesis *H*:

$$P(X|D,H) = \frac{P(D|X,H)P(X|H)}{P(D|H)}, \quad (1)$$

where, $P(D|X,H)$ is the likelihood, $P(X|H)$ is the prior, $P(D|H)$ is the evidence and $P(X|D,H)$ is the posterior. We utilized Bayesian analysis for model comparison and parameter estimation. The Bayes Factor, ratio of evidence, is used to select the best model. Jeffrey's scale has been used to examine the strength of evidence in favor of one model over another.

3.3 Timing Noise Analysis

Irregularities in the spin create a time-correlated stochastic function in the TOAs, known as achromatic red noise or timing noise. It exhibits a power spectrum where the power decreases with increasing frequency, written as,

$$P(f) = \frac{A_{\rm red}}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma} {\rm yr}^3, \quad (2)$$

where, $A_{\rm red}$ is the red-noise amplitude, γ is the power law index, and $f_{\rm yr}$ = 1.0 / yr, astronomical frequencies in Hz. In addition to Red Noise (RN), there are other sources of uncertainties, such as radiometer noise and pulse jitter, which result in white noise. These can be accounted for by scaling the ToA uncertainties as given below,

$$\sigma^2 = F^2(\sigma_r^2 + \sigma_Q^2). \quad (3)$$

Here, σ_r is ToA uncertainty, F is known as EFAC or radiometer noise and σ_Q is EQUAD, random fluctuations in the pulse profile. In timing noise analysis, we used four combinations of noise models:

I. EFAC
II. EFAC + EQUAD
III. EFAC + RN
IV. EFAC + EQUAD + RN

The number of Fourier modes plays an important role in noise analysis. The optimal number of Fourier modes is selected simultaneously with the model selection. We have used ENTERPRISE [10] to model the noise in pulsars.

4. The Gaussian Process Realization

The novel glitch verification technique uses the Gaussian Process (GP) realizations to identify true glitches and differentiate them from timing noise. The Gaussian process is the family of curves obtained in the timing noise analysis. To plot the GP realization curve, each value of red noise amplitude and spectral index, i.e., chains obtained from the timing noise analysis, is used. The median value of the posterior for $A_{\rm red}$ and γ will give the median curve; if one subtracts the median curve from the observed residuals, it results in the whitened residuals. For the GP realizations, we used a python package LA-FORGE [11].

The novel glitch verification methodology is as follows:

I. Identify probable glitches using the traditional glitch detection methodology.
II. Utilize Bayesian inference to model timing noise in the before-glitch and the after-glitch regions.
III. Reconstruct the GP realizations in the before and after-glitch regions using the results of noise analysis.
IV. Subtract the median GP realizations from the observed residuals, the residuals should be dispersed as white noise.
V. The real glitches are identified by a jump in the whitened residuals shortly after the glitch epoch.

5. Results

5.1 Glitches

In our recent results, we have reported the detection of five glitches in four pulsars [5]. The spin evolution of two glitches is newly reported. To date, we have detected 17 glitches in 8 pulsars since the beginning of the monitoring program (2015) [5, 12].

Here, we present the timing evolution of a glitch in the Vela pulsar (PSR J0835–4510), which occurred at MJD 59417.57(8). The spin evolution of the glitch is shown in Fig. 1. The fractional change in frequency is estimated as 1235(5) × 10^{-9}, and the fractional change in derivative of frequency is 8.0(7) × 10^{-3}.

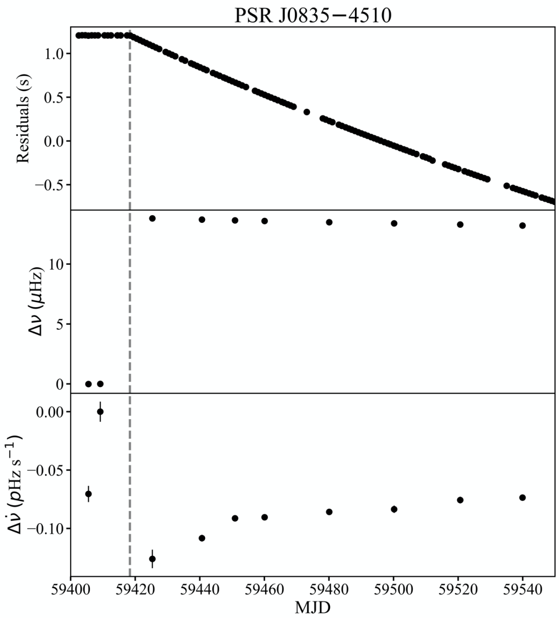

Figure 1. The spin evolution of the Vela pulsar near the glitch epoch, indicated by vertical line. The top panel show the residuals. The middle and the bottom panel show the evolution of frequency $\Delta\nu$ and its time derivative $\Delta\dot{\nu}$.

5.2 Timing Noise

We have reported timing noise for 20 pulsars, including seven new measurements and four before and after the glitch results [5]. Noise estimation is performed for the best model, obtained from the Bayesian model comparison among the four assumed models. Here, we present the posterior for the pre-glitch (Fig. 2) and the post-glitch (Fig. 3) regions for glitch in the Vela pulsar at MJD 59417.57.

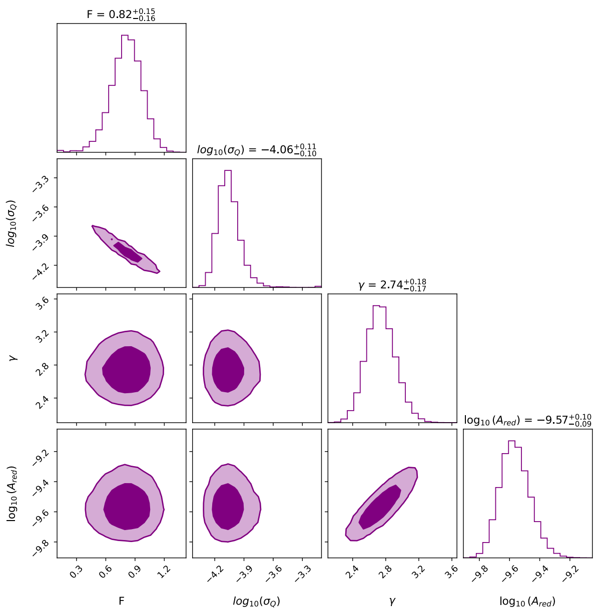

Figure 2. Pre-glitch timing noise posteriors for the Vela glitch at MJD 59417.57 with 68 and 95% credible intervals.

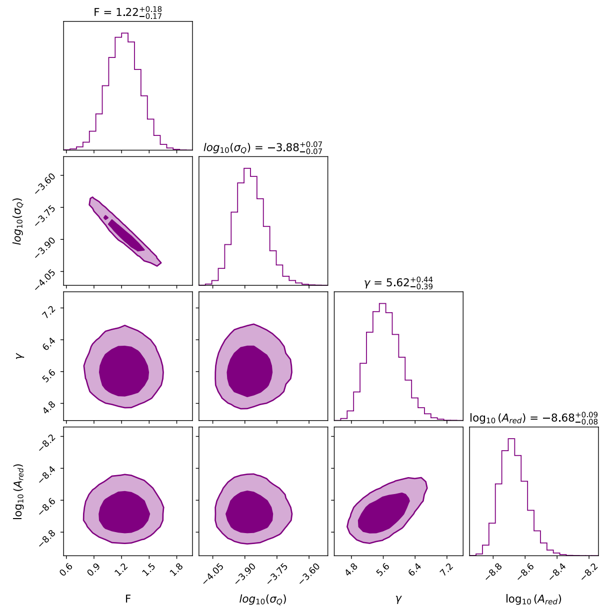

Figure 3. Post-glitch timing noise posteriors for the Vela glitch at MJD 59417.57 with 68 and 95% credible intervals.

5.3 Differentiating glitches from timing noise : GP realization

We have created a unique verification glitch methodology that can distinguish between a strong timing noise and a glitch [5]. To plot the GP realizations, we use the timing noise parameters obtained from the noise analysis for the Vela glitch, as shown in Figs. 2 and 3. The GP realizations with the observed data for the pre-glitch and post-glitch regions are given in Fig. 4. The top plot displays the observed residuals alongside the median GP realization. The bottom plot illustrates the subtracted data obtained by subtracting the GP realization form the observed residuals.

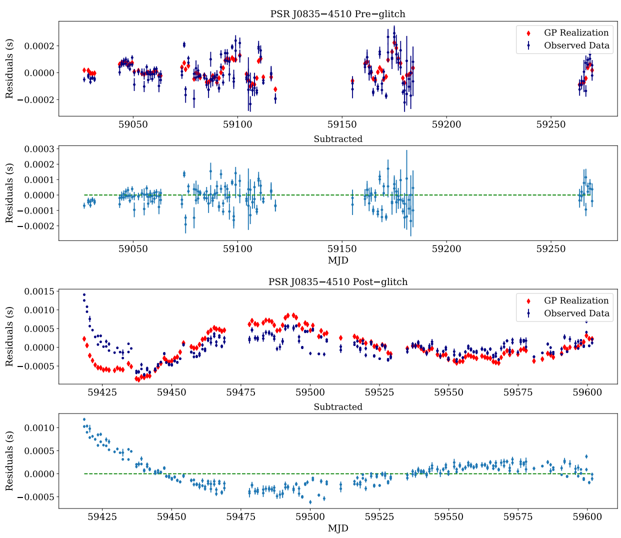

Figure 4. Post-glitch timing noise posteriors for the Vela glitch at MJD 59417.57 with 68 and 95% credible intervals.

In a glitch, we anticipate observing a jump in the post-glitch region after eliminating the timing noise. We applied the glitch verification methodology to two events: (i) the Vela MJD 59417.57 and (ii) J1847–0402 MJD 59883(6). Fig. 5, illustrate the results with a clear signature of the Vela MJD 59417 glitch while an absence of glitch-like structure in J1847–0402.

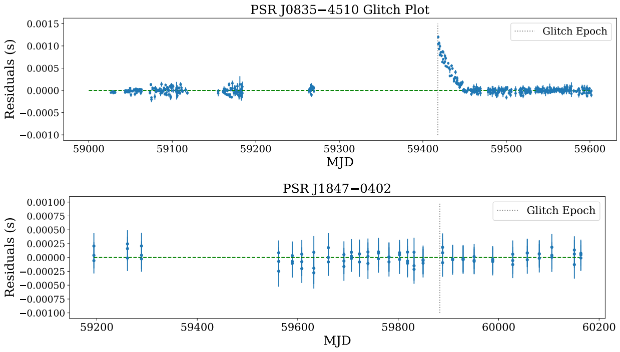

Figure 5. The residuals obtained after subtracting the GP realizations from the timing residuals for the Vela pulsar (revealing the clear signature of a glitch) and for PSR J1847–0402 (showing an absence of glitch-like structure).

6. Conclusion

Timing noise and pulsar glitches probe the interiors of neutron stars. Our findings include timing noise measurements for 20 pulsars, the detection of five glitches, and the novel glitch verification methodology designed to differentiate glitches from timing noise.

The continuous increase in reported glitches may illuminate various correlations that are not yet well understood, providing more information about the mechanisms responsible for these occurrences. Therefore, it is crucial to report only genuine glitches. Approximately one-third of all reported glitches have relatively small amplitudes, suggesting that many of these could be attributable to strong timing noise in pulsars. Hence, updating the glitch analysis methodology and implementing our novel glitch verification approach are essential to ensure that any considered glitch is real and not merely a manifestation of timing noise.

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