Observations of four glitches in the young pulsar J1833–1034 and study of its glitch activity

Jayanta Roy,1* Yashwant Gupta1 and Wojciech Lewandowski2

1National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag 3, Pune 411 007, India
2Institute of Astronomy, University of Zielona Gora, Lubuska 2, 65-265 Zielona Gora, Poland

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ABSTRACT
We present the results from timing observations with the Giant Metrewave Radio Telescope of the young pulsar J1833–1034 in the Galactic supernova remnant G21.5–0.9. We detect the presence of four glitches in this pulsar over a period of 5.5 yr, making it one of a set of pulsars that show fairly frequent glitches. The glitch amplitudes, characterized by the fractional change of the rotational frequency, range from $1 \times 10^{-9}$ to $7 \times 10^{-9}$, with no evidence for any appreciable relaxation of the rotational frequency after the glitches. The fractional changes observed in the frequency derivative are of the order of $10^{-5}$. We show conclusively that, in spite of having significant timing noise, the sudden irregularities like glitches detected in this pulsar cannot be modelled as smooth timing noise. Our timing solution also provides a stable estimate of the second derivative of the pulsar spin-down model, and a plausible value for the braking index of 1.857, which, like the value for other such young pulsars, is much less than the canonical value of 3.0. PSR J1833–1034 appears to belong to a class of pulsars exhibiting fairly frequent occurrence of low amplitude glitches. This is further supported by an estimate of the glitch activity parameter, $A_g = 1.53 \times 10^{-15}$ s$^{-2}$, which is found to be significantly lower than the trend of glitch activity versus characteristic age (or spin frequency derivative) that a majority of the glitching pulsars follow. We present evidence for a class of such young pulsars, including the Crab, where higher internal temperature of the neutron star could be responsible for the nature of the observed glitch activity.

Key words: stars: neutron – pulsars: general – pulsars: individual: PSR J1833–1034 – supernovae: individual: G21.5–0.9.

1 INTRODUCTION
Besides the basic, smooth spin down of the neutron star due to the electromagnetic torque mechanism, pulsar timing studies also reveal the presence of irregularities in the rotation of the star, mainly of two kinds: timing noise which is characterized by continuous, random fluctuations in the rotation rate and glitches which are sudden increases in the rotation rate. These spin-up events are superposed on the long-term spin-down of the pulsar, and manifest themselves as sudden early arrival of the pulses. A recent work by Espinoza et al. (2011) reports a total of 315 glitches observed in 102 pulsars. The magnitude of the change in rotation frequency, $\Delta \nu$, during a glitch is typically in the range $10^{-10} < \Delta \nu/\nu < 10^{-5}$, and the fractional increment in the spin-down rate, $\Delta \dot{\nu}/\dot{\nu}$, is in the range $10^{-2} – 10^{-5}$.

The most plausible explanation for the sudden spin-up is the irregular flow of angular momentum from the faster rotating superfluid interior to the more slowly rotating solid crust of the neutron star as it slows down (Lyne, Pritchard & Shemar 1995). The current unified model for glitches is based on the superfluidity of the neutrons in a neutron star. The rotating superfluid in the neutron star carries angular momentum by forming quantized vortices. The spacing between the vortices is negligible compared to the radius of the neutron star. On the macroscopic scale, the flow pattern looks like uniform rotation. These quantized vortices in the neutron superfluid in the inner crust can get pinned to the lattice of heavy neutron-rich nuclei. The pinning is possible because the effective width of the vortex core is less than or comparable to the lattice spacing of the nuclei. The pinning force is related to the energy gain when vortices are pinned to the lattice. The vortices stay pinned in this manner until a stronger force unpins them from the lattice sites. These pinned vortices in the crustal nuclei are rotating slower than the surrounding superfluid. Due to this differential velocity, magnus forces that act radially outwards cause sudden unpinning and migration of vortices, which results in the transfer of angular momentum from the superfluid to the crust. This gives rise to a sudden speed-up of the solid crust, which manifests as a glitch in the timing behaviour of the pulsar. Anderson & Itoh (1975) were the...
first to make this connection between sudden unpinning of vortices and pulsar glitches. In the unpinned state, the superfluid moment of inertia is not coupled to the crust; hence, the effective moment of inertia of the crust decreases, which in turn increases the spin-down rate. Between glitches, the vortex lines undergo a slow, thermally activated process called vortex creep. The post-glitch relaxation is a process of recoupling of the vortices to another steady (pinned) state. Once the moment of inertia recovers due to this recoupling via repinning, the original extrapolated spin-down rate is restored. Thus, the observed sudden increase in the rotation rate, followed by exponential relaxation back to the extrapolated pre-glitch rotation rate, provides a useful probe of the neutron star interior.

The pulsar J1833−1034 was independently discovered at the Giant Metrewave Radio Telescope (GMRT) (Gupta et al. 2005) and at Parkes (Camilo et al. 2006) and is associated with the Galactic supernova remnant (SNR) G21.5−0.9. This pulsar has quite a high spin-down luminosity that is amongst the top 10 of all the known pulsars in our Galaxy. The flux density measured at radio wavelengths is very low – the estimated mean flux density from the observations at 610 MHz is 0.65 mJy (Gupta et al. 2005). With a period of 61.86 ms and a period derivative of $2.02 \times 10^{-13}$ s$^{-1}$, it has a characteristic age, $\tau_c \approx 4.8$ kyr (Camilo et al. 2006), which makes it a fairly young pulsar. Existing studies indicate that younger pulsars are more likely to show glitches. About half of all known pulsars with $\tau_c$ less than $3 \times 10^4$ have exhibited glitches, but this fraction is much lower for the older population (Yuan et al. 2010). PSR J1833−1034 is thus a good candidate for the study of glitches. In this paper, we report the detection of multiple glitches from this pulsar using timing observations carried out at the GMRT at 610 MHz, and present a detailed study of its glitch activity. We also provide refined estimates of the timing parameters for this pulsar, including an estimate of the braking index. In Section 2, we explain the observations and data analysis techniques. Section 3 describes the detected glitches and their modelling in detail. In Section 4, we discuss the significance of our results. Summary and future scope are presented in Section 5.

2 OBSERVATIONS AND DATA ANALYSIS

The GMRT is a multi-element aperture synthesis telescope consisting of 30 antennas, each of 45 m diameter, spread over a region of 25 km diameter (Swarup et al. 1997). Though designed to function primarily as an aperture synthesis telescope, the GMRT can also be used as an effective single dish in an array mode by adding the signals from individual dishes, either coherently or incoherently (Gupta et al. 2000), for studying compact objects like pulsars. The radio signals at the observing frequency band, from both polarizations of the 30 dishes, are eventually converted to baseband signals of 16 or 32 MHz bandwidth, which are then sampled at Nyquist rate. These digitized signals are delay corrected and then Fourier transformed in an FX correlator to get spectral information. After fringe derotation, these dual polarization spectral voltage samples from all the antennas are added coherently in the GMRT Array Combiner (GAC), to produce the phased array outputs for each polarization. These are then converted to intensity, integrated to the desired time constant and recorded on disc for offline processing. The data are time stamped using a minute pulse signal, derived from the observatory’s Global Positioning System (GPS) receiver, which is embedded in the data stream.

The timing observations described here were carried out in the total intensity-phased array mode at 610 MHz. In this mode of operation, the array needs to be phased up before observing the target pulsars. This is achieved by recording the correlator data for a point-source calibrator, solving for the antenna-based gains and phases from these, and applying the phases as corrections to the output of the Fourier transform stage of the correlator. The array remains phased for up to a few hours and dephases due to slow changes in instrumental and ionospheric phases. When this happens, one needs to rephas the array to proceed with further observations.

Timing observations for PSR J1833−1034 were started around mid-2005, shortly after its discovery at the GMRT. In the beginning, after the initial, closely spaced observations that are needed to obtain the timing solution for a newly discovered pulsar, the observations were somewhat random and sparse in time. Since the occurrences of glitches are unpredictable and their relaxation time-scales can be quite short, regular monitoring is important for the detection and study of the glitches. From mid-2007, after the possible detection of the first glitch from this pulsar, a regular timing program was started, with observations roughly about 10 d apart, except for the GMRT maintenance intervals. Each observing epoch has a 90 min long scan on PSR J1833−1034, and a shorter scan of 5 min on PSR B1855+09, which acts as a control pulsar for validating the data quality and reliability of the time-of-arrival values (TOAs) from the newly established GMRT timing pipeline. The final data for each scan are total intensity values for each of 256 spectral channels (across a 16 MHz bandwidth), recorded with a sampling interval of 0.256 ms. The main observing parameters for a typical epoch are summarized in Table 1.

| PSR     | Period (ms) | Mean flux at 610 MHz (mJy) | Integration time (min) | $N_p$ | $(S/N)_{exp}$ |
|---------|-------------|----------------------------|------------------------|-------|--------------|
| B1855+09 | 5.36        | 16.8$^a$                  | 5                      | 55970 | 177          |
| J1833−1034 | 61.86     | 0.65$^b$                  | 90                     | 87293 | 32           |

$^a$ Extrapolated flux using the catalogued values at 400 and 1400 MHz. $^b$ Gupta et al. (2005).

In the offline processing, the recorded multichannel total intensity data are first dedispersed to remove the effect of interstellar dispersion on the pulse shape. The dedispersed time-series data are then synchronously folded using the topocentric pulsar period, obtained from the best existing model parameters (barycentric) for the concerned pulsar, after correcting for the observing time and location. The UTC corresponding to the middle of the observing session is used as the reference point for that particular epoch and it is derived from the analysis of the GPS pulse signal embedded in the data. The predicted topocentric periods are calculated using ‘polyc’ files produced by the pulsar timing program tempo.\footnote{See http://www.atnf.csiro.au/research/pulsar/psrcat}

For the control pulsar, the barycentric model parameters were taken from the Australia Telescope National Facility (ATNF; Manchester et al. 2005) pulsar catalogue;\footnote{See http://www.atnf.csiro.au/research/pulsar/tempo} for J1833−1034, these were obtained from the initial epochs of observations and refined at successive epochs, as required. The topocentric TOAs at each epoch are obtained by cross-correlating the average profile at that epoch with the highest signal-to-noise (S/N) profile from all the epochs used as a template. These are then converted into Solar system barycentric TOAs using the Jet Propulsion Laboratory DE200 Solar system model.
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**3 RESULTS**

We first discuss the timing results for the control pulsar and then present the results from the timing analysis of the target pulsar J1833–1034, using GMRT data spanning 2005 July 30 to 2011 January 11. The post-fit residuals obtained from the phase-connected timing solution for the control pulsar B1855+09 (shown in Fig. 2) over the full data span of 52 epochs yield a root-mean-square (rms) value of 15 µs. This is more than the theoretical, expected value ($\sigma_0$) of 3 µs, which is based on the expected S/N of 177 given in Table 1, and using $\sigma_{\text{TOA}} \sim W^{0.5}$ (where W is the pulse width and S/N is the expected signal-to-noise ratio of the average profiles). However, it matches well with the value expected for the achieved S/N (which has a maximum value of 35 in all the observing epochs). Nevertheless, our final 610 MHz timing residuals for PSR B1855+09 are worse off by a factor of 5 in rms from the 1420 MHz results obtained by Hobbs, Edwards & Manchester (2006).

In addition to S/N limitations, there can be effects of interstellar weather that can reduce the accuracy of the TOAs: the pulse arrival time at each epoch can have extra deviations due to propagation effects in the interstellar medium, which will be larger at the lower frequency. These effects verify, to first order, the proper working of the pulsar timing set-up at the GMRT.

In order to check for any low-level systematic effects in the timing residuals for this control pulsar, we investigated the changes in the rms value when adjacent residuals are averaged. For truly white-noise residuals, this rms value should decrease as the square root of the number of residuals averaged. Fig. 3 shows the results for this on a log–log plot, where the data points are found to match quite...
well with a slope of $-0.5$ (green dashed line). The overall post-fit residuals thus exhibit a white-noise behaviour and are likely to be free from any systematics. The averaging of post-fit residuals over 166 d (10 TOAs) achieves an rms value of 3 µs for B1855+09, which implies a long-term timing stability of one part in $4 \times 10^{12}$. The above results for the control pulsar establish the basic fidelity of the timing pipeline for the GMRT.

For PSR J1833–1034, since the S/N is typically significantly lower than that for the control pulsar, to check the data quality for timing purposes we show the distribution of TOA errors in Fig. 4. The bulk of the values are clustered in the range of 100–300 µs, with a small tail of larger values. This skew in the distribution is due to degradation of S/N at some epochs, possibly due to fading caused by interstellar scintillation. However, the achieved TOA uncertainties are still good enough to detect changes in the residuals of the order of several milliseconds due to the occurrence of glitches.

Starting with the initial timing observations for PSR J1833–1034, we are able to build up a phase-connected timing solution (shown in Fig. 5), till the epoch of 2007.2. From this 1.5 yr data span, we obtain a fairly good timing model for this pulsar, including a second frequency derivative (see the first row of Table 2), and the rms value of the residuals is around 174 µs. The reference epoch (MJD) for these measurements is set to the epoch which is the mid-point of our full data span (i.e. MJD of 545 75), for better comparison with the later models. The pulsar position used in the timing model is the one determined from the Chandra observations (Camilo et al. 2006). The position derived from our timing solution of 1.5 yr of phase-connected residuals is within the 3σ error bars of this X-ray position. We derive a braking index ($n = \ddot{\nu}/\dot{\nu}^2$) of 2.168(8) for this pulsar from this initial data span (see the last column of Table 2).

Fig. 6 shows the timing residuals for the full data set (94 epochs spanning 5.5 yr) for this pulsar, relative to a simple slow-down model including the pulsar spin frequency and its first two derivatives. The best-fitting model parameters from this are listed in the second row of Table 2. The residuals, with a relatively large rms value of 15.4 ms, are clearly dominated by non-random, low-frequency timing noise effects. The amplitude of this timing noise is a strongly increasing function of the length of the data span. The effect of this timing noise probably not detected for the initial data span of 1.5 yr, as the fitting of the spin frequency and its two derivatives can mask most of the low-frequency trends. In these timing noise-dominated residuals of Fig. 6, the presence of glitches can be distinguished by sudden changes in the slope of the curve. Clear events are seen at 2007.2 and 2009.9, and less likely ones at 2007.9 and 2008.8, all of which are marked by arrows in Fig. 6.

The presence of a glitch is confirmed by taking relatively shorter stretches of data around the suspected glitch event, and doing a local timing fit to the TOAs, starting with a model for the data prior to the glitch. Sudden, systematic deviation of the residuals from a smooth behaviour is taken as the signature of the occurrence of a glitch (as seen in Figs 7–10). Detailed modelling is then carried out to estimate the glitch epoch, and the changes in frequency and frequency derivative at the glitch. The best possible value of the glitch epoch is estimated by minimizing the phase increment required to obtain a phase-connected solution over the interval around the glitch epoch (Janssen et al. 2006). The measurement uncertainty of the glitch epoch is obtained from the corresponding 3σ limit of the glitch phase increment parameter.

Starting with an initial timing model having $\nu, \dot{\nu}$ and $\ddot{\nu}$, we find that the first glitch (Fig. 7) occurred at MJD $= 514.69 (±7)$, with

![Figure 4. Distribution of TOA errors for PSR J1833–1034.](image)

![Figure 5. Timing residuals for the target pulsar PSR J1833–1034 from the first 1.5 yr of data, prior to the first detected glitch at $\sim$2007.2.](image)

### Table 2. Rotational parameters for PSR J1833–1034 from different timing solutions. The first row is for the timing solution from the initial 1.5 yr of data, before the first detected glitch. The second row is for the full 5.5 yr of data, without inclusion of any glitch models. The third row is for the full 5.5 yr of data, with glitch models fixed to the values derived from the piecemeal modelling of the glitches. The last row is for the solution from the global fit, including all four glitches (two free parameters each, with glitch epochs fixed to the values obtained from the piecemeal fittings) and four frequency derivatives. All errors are 1σ values.

| No. of glitches fitted | Ref. epoch (MJD) | Data span MJD | No. of TOAs | $\nu$ (s$^{-1}$) | $\dot{\nu}$ (10$^{-14}$s$^{-2}$) | $\ddot{\nu}$ (10$^{-25}$s$^{-3}$) | Residual (ms) | Braking index |
|----------------------|-----------------|---------------|-------------|----------------|-----------------|---------------|--------------|--------------|
| –                    | 545 75          | 535 81–541 64 | 22          | 16.159 357 125(2) | $-5.275 017(9)$ | 3.73(1)        | 0.174        | 2.168(8)     |
| –                    | 545 75          | 535 81–555 72 | 94          | 16.159 357 130 57(2) | $-5.275 071(99)$ | 3.6006(2)       | 15.4        | 2.0891(1)    |
| 4                    | 545 75          | 535 81–555 72 | 94          | 16.159 357 114 48(2) | $-5.275 072(91)$ | 3.632(2)        | 2.20        | 2.1041(1)    |
| 4                    | 545 75          | 535 81–555 72 | 94          | 16.159 357 113 36(3) | $-5.275 113(0)$ | 3.197(1)        | 0.512        | 1.8569(6)    |
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Figure 6. Residuals from the full 5.5 yr of data without modelling of any glitch event, showing strong signature of timing noise, as well as evidence for glitches – these are typically seen as sudden negative changes in the slope of the residuals, and the suspected locations are indicated by arrows. The detection and modelling of these glitches are explained in detail in the text and illustrated in Figs 7–10.

Figure 7. Timing residuals illustrating the first glitch event at \( \sim 2007.2 \). This initial model is obtained from fitting \( \nu, \dot{\nu} \) and \( \ddot{\nu} \) to TOAs from 2005.5 up to the suspected epoch of the glitch. The final model yields a glitch with a fractional change in the rotational frequency of \( 3.34 \times 10^{-9} \), localized in time to the interval marked by the dotted lines.

Figure 8. Timing residuals illustrating the second glitch event at \( \sim 2007.9 \). This initial model is obtained from fitting \( \nu, \dot{\nu} \) and \( \ddot{\nu} \) and the glitch model for the first glitch to TOAs from 2005.5 up to the suspected epoch of the glitch. The final model yields a glitch with \( \Delta \nu / \nu \) of \( 1.00 \times 10^{-9} \), localized in time to the interval marked by the dotted lines.

Figure 9. Timing residuals illustrating the third glitch event at \( \sim 2008.8 \). This initial model is obtained from fitting \( \nu, \dot{\nu} \) and \( \ddot{\nu} \) over the first 130 d shown here, with \( \ddot{\nu} \) held constant at the value obtained from the fit to the first 1.5 yr of data. The final model yields a glitch with \( \Delta \nu / \nu \) of \( 1.6 \times 10^{-9} \), localized in time to the interval marked by the dotted lines.

A fractional change in the rotational frequency \( (\Delta \nu / \nu) \) of \( 3.34 \times 10^{-9} \). The modelling for this glitch includes 26 TOAs observed over 824 calendar days, of which there are 236 d of data after the glitch event. Fig. 8 shows the second glitch event, which is best fit by a fractional increase in rotational frequency of \( 1.00 \times 10^{-9} \) at MJD = 544 23 (+9). As we have a fairly good timing model for the first 1.5 yr (including the first glitch event), without any timing noise effects, the pre-glitch interval for this second glitch includes all of these TOAs over 842 calendar days, with a pre-fit model of \( \nu, \dot{\nu}, \ddot{\nu} \) and the derived parameters of the first glitch. There is a third glitch (Fig. 9) detected at MJD = 547 50 (±1) with a fractional change in the rotational frequency of \( 1.6 \times 10^{-9} \). The last glitch event (Fig. 10) observed at MJD = 551 42 (±2) yields a fractional change in the rotational frequency of \( 6.9 \times 10^{-9} \). In order to minimize the effects of timing noise, the pre-glitch interval for the third glitch includes TOAs over 130 d and the fourth glitch includes TOAs over 152 d, with the pre-fit model having \( \nu, \dot{\nu} \) and \( \ddot{\nu} \). But since the pre-fit data span over smaller intervals, the fit uses \( \nu, \dot{\nu} \) as free parameters, with \( \ddot{\nu} \) kept constant to the value derived from the initial 1.5 yr of data. The inclusion of TOAs over larger spans increases the influence of timing noise, where the residuals depart from the simple spin-down model with \( \nu, \dot{\nu} \) and \( \ddot{\nu} \), making it harder to detect the glitches accurately. There are also small changes in the slow-down rate, of the order of \( 10^{-9} \), observed at the glitch epochs. The new timing models, after inclusion of the glitch parameters, yield phase-connected timing residuals with rms values of 177 \( \mu s \), 216 \( \mu s \), 227 \( \mu s \) and 1.5 ms, respectively, for the four cases.

It is sometimes possible that, for data that are relatively sparsely sampled and have significant amount of timing noise (both of which are somewhat true for the present case), there can be large deviations in residuals with respect to the basic spin-down model of \( \nu, \dot{\nu} \) and \( \ddot{\nu} \), which may mimic glitch-like behaviour. In order to discriminate between the effect of timing noise and genuine glitches, we investigated the pre-fit and post-fit residuals around the glitch epochs by fitting with higher frequency derivatives without inclusion of any glitch model. For example, for the case of TOAs spanning over the first 936 d (including the first and the second glitch), the rms value for the post-fit residuals is 216 \( \mu s \) (shown in Fig. 11). The model includes two glitches and a spin-down model with \( \nu, \dot{\nu} \) and \( \ddot{\nu} \), which
amounts to nine free parameters. The same span of TOAs can also be fitted with a model having $v$ and eight frequency derivatives, without inclusion of any glitch models, which also amounts to nine free parameters, as for the model with glitches. The post-fit residuals are noticeably suppressed. The glitch parameters are not very different from those obtained from the piecemeal fits. The results from this model are summarized in the fourth row of Table 2 and the final glitch parameters are given in Table 3.

Finally, to obtain a global model for the entire data span, we have compared the following three approaches: (i) taking the models for the four glitches obtained from the piecemeal fits to the individual glitches as fixed and then fitting for $v$, $\dot{v}$ and $\ddot{v}$ over the entire data span; (ii) a fit to the full data span using $v$ and up to 12 frequency derivatives (the maximum allowed by tempo) without any glitch models included and (iii) a global fit for four glitches, $v$ and first four frequency derivatives, to achieve the same count of 13 free parameters as in case (ii) – each glitch contributes two free parameters (spin-frequency increment and change in the spin-down rate), as the glitch epochs are fixed to the values obtained during the piecemeal fittings, by minimizing the phase increment at the glitch epoch. Case (i) gives the residuals shown in the middle panel of Fig. 13, with an rms value of 2.2 ms, and fairly smooth behaviour with large swings, typical of timing noise. Results from this fit are given in the third row of Table 2. Case (ii) gives the residuals shown in the top panel of Fig. 13. Though the rms value is 1.4 ms, the variations of the residuals show sudden, large jumps (as at the epoch of the first glitch) and also sharp, cuspy variations (as at the epoch of the fourth glitch). For case (iii), global fits with all four glitches (using the results from the piecemeal fits as the starting pre-fit model) and increasing number of frequency derivatives were tried, and the following was found: for four glitches plus $v$, $\dot{v}$ and $\ddot{v}$, the residuals are 1.2 ms and the behaviour is qualitatively similar to case (i); for the case of two more derivatives added to achieve the same number of 13 degrees of freedom as it was for case (ii), the residuals (shown in the bottom panel of Fig. 13) reduce significantly to 0.5 ms and also the slow, large fluctuations typical of timing noise are noticeably suppressed. The glitch parameters are not very different from those obtained from the piecemeal fits. The results from this model are summarized in the fourth row of Table 2 and the final glitch parameters are given in Table 3.

From the above, we argue that the best timing model is that given by a global fit of four glitches and five spin frequency terms, which gives the best global fit to the data and reduces the residuals to a minimum. The attempt to fit the TOAs with a pure timing noise model having large number of derivatives does not give acceptable results: both for localized fits to data sets that span individual glitches and for the global data set. For such cases, the rms value of the residuals is larger and/or the residuals show uncharacteristically large, abrupt changes. We take the results from this fit as the final timing model for this data set. These results are summarized in the last row of Table 2 and in Table 3.

Now in order to measure the amount of timing noise present in this pulsar, we have used the definition given by Arzoumanian et al. (1994),

$$\Delta_8 = \log_{10} \left( \frac{1}{6v} |\dot{v}| t^3 \right),$$

(6)

where the spin frequency, $v$, and its second derivative, $\ddot{v}$, are measured over a $t = 10^8$ s interval. We have used first 3.16 yr of data for PSR J1833–1034 to estimate the value of $\Delta_8$ as 0.5, which follows the correlation between timing noise and spin-down rate, i.e.
the younger pulsars with larger spin-down rate exhibit more timing noise than older pulsars, seen by Arzoumanian et al. (1994) and later by Hobbs, Lyne & Kramer (2010).

The value of the braking index determined from the final global fit is 1.8569(6). This braking index is much less than 3, which is in general agreement with the values obtained for other young pulsars having reliable estimates for this quantity. For example, for the Crab pulsar, $n = 2.509(1)$ (Lyne, Pritchard & Smith 1988, 1993), for PSR J1846–0258, $n = 2.65(1)$ (Livingstone et al. 2006), for PSR B0540–69, $n = 2.140(9)$ (Livingstone, Kaspi & Gavriil 2005), for PSR B1509–58, $n = 2.837(1)$ (Kaspi et al. 1994) and for PSR J1119–6127, $n = 2.684(2)$ (Weltevrede, Johnston & Espinoza 2011). A value of $n < 3$ indicates that a simple magnetic dipole model does not completely explain the spin-down evolution of pulsars. Particle outflow in the pulsar wind can also carry away some of its rotational kinetic energy.

4 DISCUSSION

Our timing study of the young pulsar J1833–1034 associated with the Galactic SNR G21.5–0.9 shows clear evidence of frequent glitches in the pulsar’s rotational history. We find as many as four glitches over the observing span of 5.5 yr. Compared to the typical range of glitch amplitudes mentioned in Section 1, the fractional changes in the rotational frequency seen for this pulsar are relatively small, ranging from $1 \times 10^{-9}$ to $7 \times 10^{-9}$. This behaviour is similar to the Crab pulsar, which shows $\Delta \nu/\nu \sim 10^{-8}$, whereas the Vela pulsar exhibits larger glitches, generally with $\Delta \nu/\nu > 10^{-6}$. As the amplitude of a glitch is related to the amount of stress built up in the pinned vortices, one might expect some correlation between the amplitude of glitches and the interglitch interval. Pulses that have small amplitude glitches do tend to show smaller interval between glitches [as observed for PSR J0537–6910 by Middleditch et al. (2006) and for PSR B1642–03 by Shabanova (2009)], and this is borne out in the case of PSR J1833–1034 as well. Clearly, this pulsar falls under the category of pulsars that exhibit relatively frequent, but low amplitude glitches.

PSR J1833–1034 also shows small but permanent changes in the slow-down rate at the glitches, and the typical fractional change of $\dot{\nu}$ is a few parts in $10^{-5}$ (Table 3). These small increases in $|\dot{\nu}|$ are thought to be due to the decrease in the effective moment of inertia of the crust, which includes all components of the star dynamically coupled to the crust. Decoupling of the superfluid moment of inertia during the unpinning state reduces the entire moment of inertia of the star. However, for the third and fourth glitches, we observe a decrease in $\dot{\nu}$. This sign change of $\dot{\nu}$ may imply a small increase in the moment of inertia or a small decrease in spin-down torque at the time of the glitch.

We did not detect any exponential recovery or decay with time after the glitches in our data, for either the change in rotational frequency or its derivative. This may imply that there are only permanent changes in the rotational parameters when this pulsar glitches. However, there is also a possibility that this may be due to the fact that our sampling interval for the timing properties of this pulsar – about a week to 10 d – is somewhat coarser than what may be required to adequately sample the expected decay time-scale for

| Glitch epoch (MJD) | Date       | Fit span (MJD) | $\Delta
\nu/\nu$ ($10^{-9}$) | $\Delta
\nu/\nu$ ($10^{-5}$) |
|------------------|------------|----------------|-----------------------|-----------------------|
| 541 69 (±7)      | 2007 March 5 | 535 81–544 05  | 3.11(5)               | 1.4(2)                |
| 544 23 (±9)      | 2007 November 12 | 535 81–545 17 | 1.09(6)               | 4.0(3)                |
| 547 50 (±15)     | 2008 November 11 | 546 20–548 85  | 3.55(6)               | 9.7(2)                |
| 551 42 (±2)      | 2009 November 6  | 549 90–555 72  | 7.50(8)               | 9.9(2)                |
such low-amplitude glitches. For example, in the case of the Crab pulsar, for glitches with an amplitude of the order of \( \sim 10^{-8} \), the exponential decay time-scale is of \( \sim 10^4 \) d (Wong, Backer & Lyne 2001). Such time-scales would be hard to detect in our timing data, and would need a much more intensive campaign of observations.

For the general pulsar population, it is found that glitches with small \( \Delta \nu \) also have small changes in \( |\dot{\nu}| \). This is shown in Fig. 14, using the data base of the glitch table in the ATNF pulsar catalogue, where a clear correlated trend can be seen. Our results of the glitch parameters for PSR J1833–1034 show that this pulsar follows this trend quite well.

The level of strength and frequency of occurrence of glitches in a pulsar can be quantified by the glitch activity parameter, \( A_g \), defined as the mean change in frequency per unit time owing to glitches (Lyne 1999):

\[
A_g = \frac{1}{T} \sum \Delta \nu_g,
\]

where \( \Delta \nu_g \) is the total increase of the frequency owing to all the glitches over an interval of \( T \). Glitches are considered as events of angular momentum transfer from the superfluid interior to the crust of the neutron star. The same rate of angular momentum transfer can be achieved with frequent small glitches or occasional larger ones. The glitch activity parameter combines the amplitude and frequency of angular momentum loss due to glitches over the interval of \( T \). \( A_g \) is relatively insensitive to the additional discovery of smaller glitches as the quality of a given data set improves, and hence it can be used as a long-term indicator of glitch effects (Wong et al. 2001). We find \( A_g = 1.53 \times 10^{-15} \text{s}^{-2} \) for PSR J1833–1034.

Fig. 15 shows the range of known values of \( A_g \), as well as its dependence on \( |\dot{\nu}| \), for a collection of 32 pulsars. The data are mostly from the literature (circles), except for a few points (triangles for B0611+22, B1853+01 and B0540–69) which are from unpublished results from observations at the Torun Radio Telescope by one of us (WL). The literature references are as follows: Lyne et al. (2000) (B0833–45, B1325–43, B1535–56, B1641–45, B1727–33, B1736–29, B1758–23, B1800–21, B1823–13, B1830–08, B1859+07, B2224+45, B0055+54, B0155+21 and B1737–30); Wang et al. (2000) (B0833–45, B1046–58, J1105–6107, J1123–6259, B1338–62, B1341–67; B1357+16, B1641–45, B1727–33, B1736–29, B1758–23, B1800–21, B1823–13, B1830–08, B1859+07, B2224+45, B0055+54, B0155+21 and B1737–30); S. Zhang et al. (2000) (B0833–45, B1046–58, J1105–6107, J1123–6259, B1338–62, B1341–67; B1357+16, B1641–45, B1727–33, B1736–29, B1758–23, B1800–21, B1823–13, B1830–08, B1859+07, B2224+45, B0055+54, B0155+21 and B1737–30); Middleditch et al. (2006) (J0537–6910) and Livingstone et al. (2006) (J1846–0258). Though there is some scatter present, for a majority of pulsars there is an overall trend of increasing \( A_g \) with increasing \( |\dot{\nu}| \). This trend is mirrored in a plot of glitch activity versus characteristic age, as shown in Fig. 16: glitch activity is higher for younger pulsars with characteristic age \( \sim 10^4 \) kyr, and as the characteristic age increases, the activity falls off. These effects could be due to the fact that the flow of the angular momentum from the interior decreases with age (or increases with \( |\dot{\nu}| \)). There are a few pulsars with relatively higher values of \( |\dot{\nu}| \) (or relatively smaller values of characteristic age) that have somewhat lower values of \( A_g \), and hence lie off the main curve. Detailed investigation shows that these are a group of very young pulsars (i.e. low characteristic age), such as the Crab, PSR J1119–6127, PSR B1800–21, PSR J1846–0258 and PSR B0540–69. We find that our young pulsar J1833–1034 fits in very well with this group.

Glitches are thought to be caused by the release of stress built up during the regular spin-down of the pulsar. This stress on the pinned vortices in the superfluid interior gets released to the solid crust by a collective unpinning of many vortices. This unpinning process results in a sudden spin-up of the crust due to this
discontinuous transfer of angular momentum from the interior, which in turn is manifested in a change in observed pulsar frequency. Frequent, low-amplitude glitches imply that the release of the built-up stress happens in a more uniform and continuous manner than for pulsars which show few, large-amplitude glitches. In other words, for the younger pulsars with larger slow-down rates, the flow of the angular momentum from the interior seems to be a smoother process. According to McKenna & Lyne (1990), the higher internal temperature associated with the younger neutron stars might prevent the build-up of larger stresses. In such cases, stresses on the pinned vortices get relieved by the thermal drift of the vortices from one pinning site to another in a gradual fashion, resulting in frequent low-amplitude glitches. Hence, such pulsars may constitute a distinct class of glitching pulsars: younger pulsars with lower glitch activity and higher internal temperatures. These relatively young pulsars may evolve towards the normal trend (i.e. towards right in Fig. 16) as they age.

5 SUMMARY AND FUTURE SCOPE

In this paper, we have presented results for four glitches detected in PSR J1833–1034, from 5.5 yr of timing observations at the GMRT. These glitches show a fractional change of the rotational frequency ranging from $1 \times 10^{-9}$ to $7 \times 10^{-9}$, with no evidence for any appreciable relaxation of the rotational frequency after the glitches. The fractional changes observed in the frequency derivative for this pulsar are of the order of $10^{-5}$. This pulsar appears to belong to a class of pulsars exhibiting fairly frequent occurrences of low-amplitude glitches. We calculate the glitch activity parameter for PSR J1833–1034 to be $1.53 \times 10^{-15}$ s$^{-2}$, which puts it in a special class of young pulsars like the Crab, and offset from the normal trend of glitch activity versus characteristic age (or spin frequency derivative) that a majority of the glitching pulsars follow. This could be related to the thermal history of young neutron stars.

The final timing solution obtained after modelling of the glitches provides reliable estimates of the second derivative of the spin-down model for PSR J1833–1034. The resulting braking index of 1.856(6) is much less than the canonical value of 3, as also found for other young pulsars, supports the claim that pure dipole braking does not provide the full picture for pulsar spin-down.

With the aid of the high time resolution and coherent dedispersion capabilities of the new GMRT Software Backend (GSB; Roy et al. 2010), we aim to search for giant pulse (GP) emission from other young pulsars, supports the claim that pure dipole braking does not provide the full picture for pulsar spin-down.

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