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ORIGINAL ARTICLE

Two decades of pulsar timing of Vela

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Abstract Pulsar timing at the Mt Pleasant observatory has focused on Vela, which can be tracked for 18 hours of the day. These nearly continuous timing records extend over 24 years allowing a greater insight into details of timing noise, micro glitches and other more exotic effects. In particular we report the glitch parameters of the 2004 event, along with the reconfirmation that the spin up for the Vela pulsar occurs instantaneously to the accuracy of the data. This places a lower limit of about 30 seconds for the acceleration of the pulsar to the new rotational frequency. We also confirm of the low braking index for Vela, and the continued fall in the DM for this pulsar.

Keywords Stars: neutron · Dense matter · Pulsars: individual (PSR B0833-45)

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1 Introduction

Mount Pleasant observatory, just outside Hobart in Tasmania, Australia, has a 14-metre dish that has been dedicated to tracking the Vela pulsar for two decades. This telescope is able to monitor the pulsar for eighteen hours every day, and therefore has caught many glitches 'in the act'. As a cross-check the older, but glitching, PSR 1644-4559 is observed for the six hours when Vela is set. There is no comparative dataset, and the conclusions we draw puts extremely tight conditions on the pulsar Equation of State (EOS) by placing a number of constraints on the models. An example of these would be that if the spin-up is very fast the crust has to have a low moment of inertia, therefore be very thin, and the coupling between the crust and the interior super-fluid has to be strong (see, for example, discussion of these issues in Epstein and Baym 1992 and Bildsten and Epstein 1989).

Three uncooled receivers are mounted at the prime focus of the 14-metre to allow continuous dispersion measure determination. Two are stacked disk, dual polarisation with central frequencies of 635 MHz and 990 MHz additional to a right hand circular helix at 1391 MHz. Bandwidths are 250 kHz, 800 kHz and 2 MHz respectively, limiting pulse broadening from interstellar dispersion to less than 1%. The output is folded for two minutes giving an integrated pulse profile of 1344 pulses. The backend to the 990 MHz receiver also has incoherent dedispersion across 8 adjacent channels allowing a study of individual pulses. Results from these systems have been reported, respectively, in McCulloch et al. (1990) and Dodson et al. (2002).

A new system, based on the PC-EVN VLBI interfaces Dodson et al. (2004). can produce TOA's with accuracy of the order of 0.1 ms every second (as opposed to every 10 seconds with the single pulse or 120 seconds with the multi-frequency systems). This interface is adapted from the Metsähovi Radio Observatories linux-based DMA, data collector, card designed for VLBI digital inputs. The two 40 MHz IFs from the 635 MHz feed provide the two polarisations, and the data are recorded in a continuous loop two hours long. This is halted by the incoherent dedispersion glitch

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Table 1 Parameters for the glitch of MJD 53193.092. The data fit is from MJD 53171 through to 53264 (mid-June to mid-September 2004). All significant figures are given. The model fitted consists of a permanent change in the rotation frequency and deceleration (denoted with a p subscript) and a number of temporary changes in rotation frequency (denoted with a n subscript) which decay on a timescale of τ

Parameters with reference to Epoch MJD 53193		
F/Hz	$\dot{\mathrm{F}}$/Hz s^{-1}	$\ddot{\mathrm{F}}$/Hz s^{-2}
11.1924472071183043	−1.555028E−11	5.27E−23
$\Delta\mathrm{F}_p$/Hz		$\Delta\dot{\mathrm{F}}_p$/Hz s^{-1}
2.2865E−05		−1.0326E−13
τ_n		$\Delta\mathrm{F}_n/10^{-6}$ Hz
1 ± 0.2 mins		54
00.23 days		0.21
02.10 days		0.13
26.14 days		0.16
DM		67.74 pc cm^{-3}

monitoring program. Coherent dedispersion is performed off-line, for the data segment covering the glitch.

2 The glitch in 2004

The glitch of 2004 occurred while the telescope was recording data. Unfortunately the coherent de-dispersion system was not running at that moment and the results obtained are more or less a repeat of those in 2000. The instantaneous fractional glitch size was 2.08×10^{-6}. This is the sum of the permanent and the decaying terms. The full details are reported in Table 1, after fitting with TEMPO (Taylor et al. 1970). A similar fast decaying term as reported in the 2000 glitch can be seen in the data after the usual model is subtracted, see Fig. 1, but it is only a few sigma above the noise. This usual model consists of permanent glitch components in the frequency and frequency derivate, and other components which are co-temporal jumps in frequency which decay away. A number of these are required to fit the data and the decay timescales are denoted with τ_n. Three decaying terms have been known for sometime and these make up the usual model. In Dodson et al. (2002) a forth short term component was identified. For a fuller discussion see that paper. In Fig. 1 the longer timescale terms are subtracted, and the residuals are plotted scaled against the RMS. Time zero is the intercept of the post-glitch model with the pre-glitch model, i.e. assuming an instant spin-up. The indication of a spin-up would be negative residuals, of which there is no sign. The positive residuals seen are modelled as a later

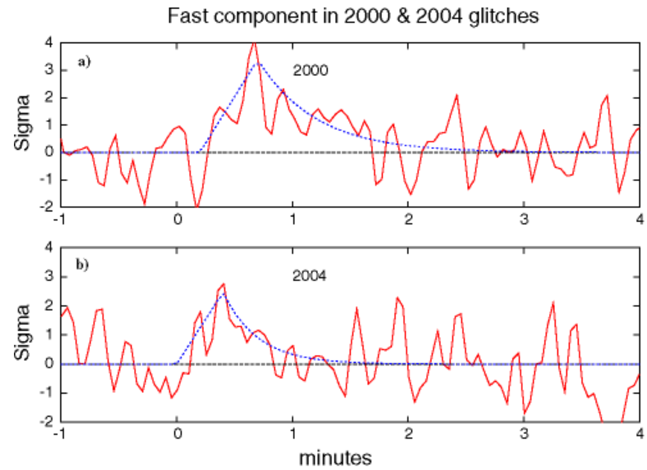

Fig. 1 The timing residuals after removing the long scale timing models, plotted as standard deviations, against the minutes relative to the assumed glitch epoch. The model of a later glitch epoch, and a very fast spin down, are overlaid. **a** is for 2000, **b** is for 2004

glitch epoch and a very fast decaying term. Figure 1a shows the glitch of 2000, where the signal was clearly above the noise, Fig. 1b shows the glitch of 2004, where the signal is barely above the noise. We present it as supporting evidence for the similar signal seen in the 2000 data, but we are unable to draw more detailed conclusions from such weak data.

3 Observations over the last twenty years

The 14-metre telescope has recorded single channel two minute folded data from July 10 1981 to October 1 2005, spanning 8857 days. It has recorded incoherently averaged ten second folded data from 1998. It observed on the day of a glitch for all ten events in that twenty year period. After upgrading to a full Az-Alt telescope in 1987 it was able to track the pulsar for 18 hours a day, and was therefore able to catch the very moment of the glitch in 1988, 1991, 2000 and 2004, as well as the first of the two in 1994. The two in 2000 and 2004 were with the incoherent single pulse system which is folded over ten seconds to give a good signal to noise. In all of these cases there is *no detectable spin up*. Figure 2 shows a montage of the recorded glitch events. Compare this to the stately, half day, spin up of the crab pulsar (Wong et al. 2001). The upper limit from the 2000 and 2004 de-dispersed data is that the spin-up occurs in less than 30 seconds. It is most unfortunate that, as yet, we have no observations with the coherent de-dispersion system, as these very fast spin up times measure directly the moment of inertia, and therefore the thickness, of the Vela pulsar crust (Epstein and Baym 1992). Figure 3 shows the fitted $\dot{\mathrm{F}}$ over the twenty years. As an independent check of the braking index calculation of Lyne et al. (1996) we applied their method (used on the JPL data from 1969 to 1994, nine glitches) to our data (1981 to

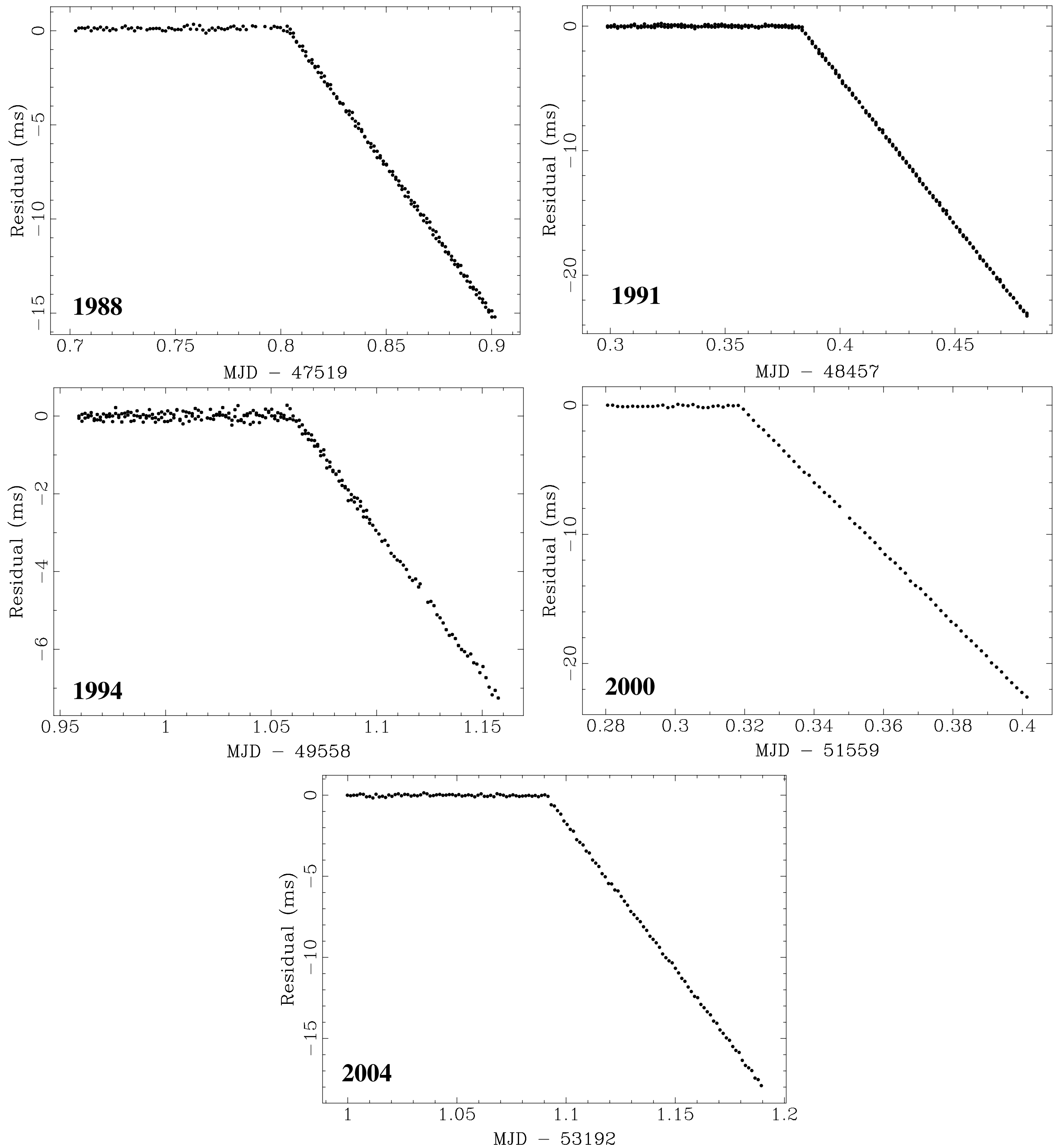

Fig. 2 Plots of all the glitches of Vela directly observed. The residuals are in milliseconds are plotted against time in days

2005, ten glitches). Here they assume that some months after the glitch the short term relaxations have decayed away, and the build-up of timing noise has not yet contaminated the rotation rate. Therefore by fitting $\ddot{F}$ to the slope $\dot{F}_{150}$, the deceleration 150 days after the glitch, the braking index, n, can be found from $F\ddot{F}\dot{F}^{-2}$. We find a braking index of 1.6 ± 0.1 for the data 150 days after the glitch. This is to be compared with the value Lyne et al. obtained by the same method of 1.5 ± 0.4. Lyne et al. improved on this value by extrapolating $\dot{F}$ back to the epoch of the glitch. We will report the full analysis, including this extrapolation, in a future paper.

The DM, which we can deduce from the multiple frequencies observed, continues to fall as reported in Hamilton

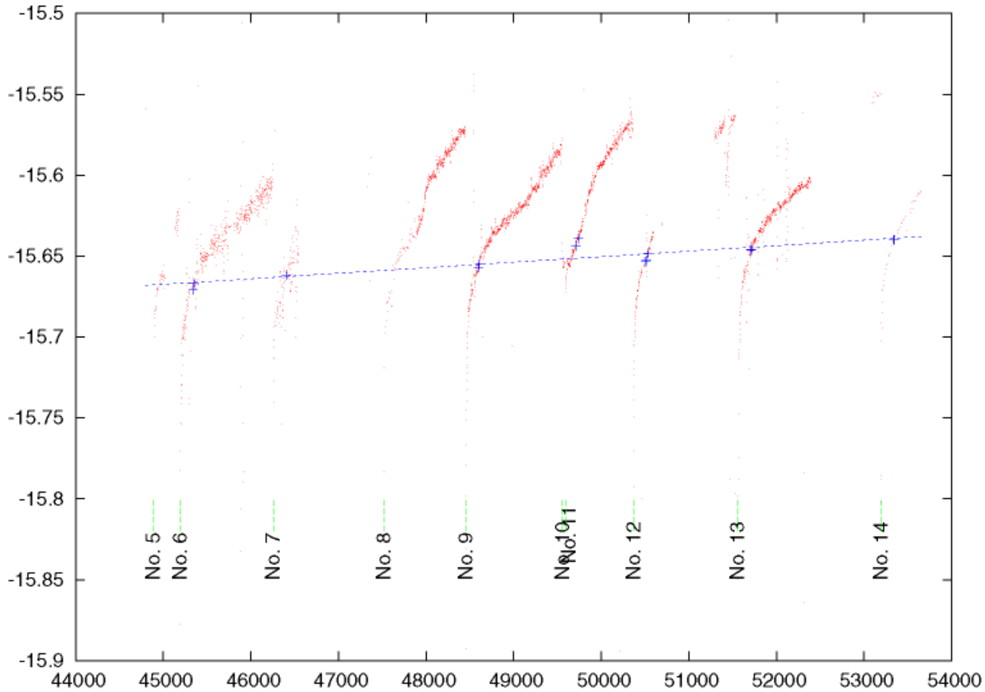

Fig. 3 Solutions for $\dot{F}$ over twenty years, with the $\dot{F}_{150}$ marked and the fitted slope for $\ddot{F}$ overlaid

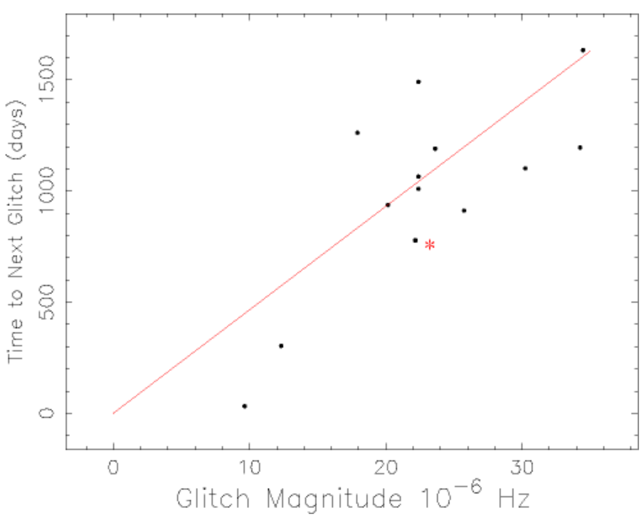

Fig. 4 Plot of the time to the next glitch vs glitch amplitude c.f. (Middleditch et al. 2006, Fig. 7), showing the weak correlation for the Vela pulsar compared to that of PSR 0537-6910. Marked with a *red star*, but not included in the fit, is the glitch of August 2006 (Flanagan and Buchner 2006)

et al. (1985). At the epoch of 53 193 it was 67.74 pc cm^{-3} and is falling by 4.3 pc cm^{-3} per century.

We don't see the strong correlation between glitch size and time between glitches in our data, as reported for PSR0537-6910 (Middleditch et al. 2006) recently. The best linear fit through the origin gives 46.5 days μHz^{-1}. The data are shown in Fig. 4.

4 Conclusions

The Vela pulsar has been timed for more than twenty years, and continues to provide new insights into the pulsar EOS by, for example, providing very low limits for the spin-up time and therefore the crust thickness. There is clearly a need to observe a glitch with higher sensitivity and time resolution to investigate both the fast decay term and to detect the spin-up. Both of these values relate directly to the pulsar EOS and will provide rich fodder for theoretical analysis by allowing the measurement of the moment of inertia of the crust. These observations could be made with the 14-metre telescope and the enhanced back-end if dedicated observing is continued. If the observation program is terminated then this effect is a ripe target for the next generation of pulsar telescopes that could monitor a large number of targets simultaneously with new beam forming techniques.

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