

## Sometimes a Pulsar!

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**Abstract** This paper reports on the discovery of a new population of transient neutron stars. This new class of pulsars is characterized by quasi-periodic bursting with a non-radiating or ‘switched off’ state, the duration of which exceeds the radiating ‘on’ state. There are currently four such objects known, the prototype being the isolated pulsar B1931+24 (J1933+2421). This pulsar emits radio radiation for approximately 4–10 days before switching off completely for between 30–40 days, hence it is only visible for  $\sim 10\% - 20\%$  of the time. It is therefore concluded from simple calculations, that many more of these objects must exist and this will have large consequences for the population estimates of neutron stars in our Galaxy. Further studies will provide information about the conditions necessary for radio emission.

**Key words:** stars: neutron — pulsars: general — Galaxy: general

### 1 INTRODUCTION

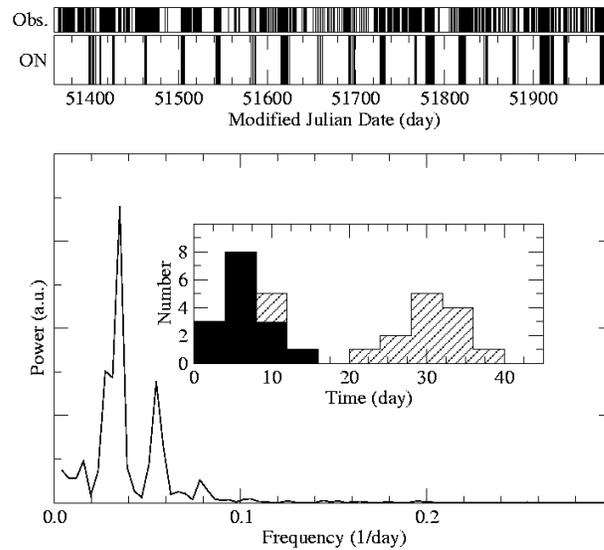
Pulsars, rapidly rotating neutron stars that emit radio emission, act as very accurate clocks. Their strong magnetic field lines help to stream radiation from its magnetic poles into beams, which is detected on Earth when this cone of emission crosses our line of sight. The intensity of single radio pulses that we can detect may differ from pulse to pulse, but generally forms a repeatable average profile. However, sometimes a pulse can drop in intensity to below one per cent of the mean pulse intensity, i.e. we receive no radio pulses on timescales of the order of a few pulse periods. This phenomenon is known as nulling (Backer 1970). Here, we report the existence of pulsars that ‘switch off’ their radio emission on much longer timescales, i.e. not on timescales of the order of a few periods, but of order of tens of days. This is the first time that such a phenomenon has been observed. It is not thought that this behaviour is an extreme case of nulling; the reason for this and other possible explanations for this observed phenomenon are discussed in Section 2.1. The nature of these objects, being visible for only a small proportion of the observation time, has significant consequences for the Galactic population estimates of neutron stars, as discussed in Section 3.

### 2 PSR B1931+24

The prototype for this new population of transient neutron stars, PSR B1931+24, was originally discovered with the Green Bank Telescope (GBT) in the USA, but its emission phenomenon was discovered with the 76-m Lovell Telescope at Jodrell Bank Observatory whilst timing observations were made for a large number of known pulsars. PSR B1931+24, a seemingly normal pulsar, on closer inspection appeared to exhibit some strange behaviour. This pulsar with a period of 813 ms (Stokes et al. 1985) and a period derivative of  $\dot{P} = 8 \times 10^{-15}$  (Hobbs et al. 2004), lies within the normal region of pulsars in the  $P-\dot{P}$ -diagram. The pulsar appears to be isolated with no stellar companion. Studying the observations which date back to 1986 October 18th, it was apparent that rather than emitting continuously, the pulsar ‘switches off’ its emission for approximately 30–40 days before ‘switching on’ for 4–10 days. Since 1998, the pulsar has been observed as frequently as twice a day. On one occasion it was caught switching off on a timescale of less than 10 s. Analysis of the pulsar profiles provides information about the dates when the pulsar appeared either in an ‘on’ or ‘off’ state, and gives some estimation of the length of this ‘on’ state.

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**Fig. 1** Time variation of the radio emission of PSR B1931+24. The top two bars show a 20 month interval of observation time and the times when PSR B1931+24 was in an ‘on’ state respectively. The bottom plot shows the Fourier Transform of the autocorrelation function of the mean pulse flux density obtained for the same 20 month interval, giving the power spectrum of the intensity. Inset: histograms of the durations of the ‘on’ (solid) and ‘off’ (hatched) states.

It is obvious from the top two bars in Figure 1 that there exists some quasi-periodicity in the ‘on’/‘off’ states of this pulsar. Performing a Fourier Transform of the autocorrelation function of the data reveals a peak in frequency (1/day) close to 0.03, corresponding to the 35 day quasi-periodicity (Kramer et al. 2006). The two further harmonics reflect the narrow duty cycle of the ‘on’-pattern. A Lomb-Scargle periodogram analysis gives the same periodicity, and initial wavelet analysis performed on the total data set shows that this quasi-periodicity appears to be drifting between 30 and 40 days. Simultaneous observations taken with the Lovell and Arecibo telescope in Puerto Rico at frequencies in the range 430–1,400 MHz show that this phenomenon is broadband in nature. From this analysis it is clear that this pulsar remains in an ‘off’ state for approximately 90% of the time.

## 2.1 What is causing this quasi-periodicity?

What causes this pulsar to switch on and off is not known. The pulsar is found to be an isolated pulsar, no companion star is blocking the emission. An initial thought was that this effect was similar to nulling. However, this usually occurs for a few pulse periods only and not on the timescales seen here of tens of days. Another argument is that there are no nulls during an individual ‘on’ phase, the pulsar being consistent when ‘on’. Another possibility is that it could be due to precession, which is an effect by which the pulsar undergoes a slow periodic wobble, thus moving the beams of radio radiation out of our line of sight. Taking the pulse profiles from different ‘on’ epochs, whose durations are known to within half a day either side of the epoch, the pulse profile was investigated for any changes. A normalised average pulse from the first three days of the ‘on’ epoch was compared to a normalised average of the middle and final three days of one epoch to look for signs of any profile changes which would indicate the presence of a precession effect. For each of the ‘on’ epochs studied, there was no significant profile change and thus precession as an explanation for this observed phenomenon can be ruled out. Also, the timescale of switching, less than 10 s, is certainly too fast for precession to be the cause. Hence this effect is thought to be linked intrinsically to the emission mechanism instead.

### 3 IMPLICATIONS FOR GALACTIC POPULATION STUDIES

The nature of this object, being visible for only a small proportion of the observation time, has significant consequences for the Galactic population estimates of neutron stars. Simply taking PSR B1931+24, which is ‘off’ for approximately 90% of the time means you have a one in ten chance of observing this type of object once, coupled with a one in ten chance of confirming this object, leads to the conclusion that at least 100 times more such neutron stars should exist in our Galaxy than previously assumed. Selection effects play a major role in the detection of these objects, such as RFI and the difficulty in discriminating weak signals from terrestrial interference and noise, thus this value is a lower limit.

### 4 NEW MEMBERS FROM THE PARKES MULTIBEAM PULSAR SURVEY

As previously stated, statistically many more of these objects should exist. The data of the Parkes Multibeam Pulsar Survey was searched for any new members of this new class of pulsars, as it is the most successful pulsar survey to date, finding over 750 pulsars so far (Faulkner et al. 2004). The survey used the 64-m telescope at Parkes with a 13 beam receiver operating at a central frequency of 1,374 MHz with a bandwidth of 288 MHz. It uses a filterbank system for each beam giving  $96 \times 3$  MHz channels. Observations were performed at a wavelength of 20 cm with 100- $\mu$ s sampling.

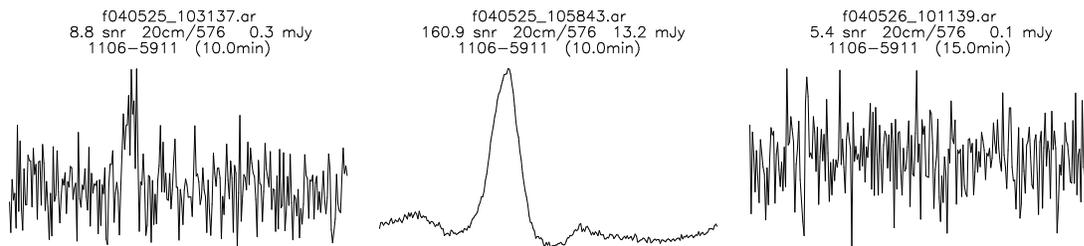
It was found that PSR J1107–5907 exhibits three different states of emission, a completely ‘off’ state, a weak state with a narrow profile and a very strong ‘on’ state with a wide profile, as shown in Figure 2. When the pulsar is in this bright state, its strength rivals that of Vela. This pulsar has a period of 253 ms and an unusually small period derivative of  $\dot{P} = 1.13(6) \times 10^{-17}$ . Coupled with a large characteristic age of 354 Myr, this pulsar lies in an interesting transition region between normal and recycled pulsars on the  $P$ – $\dot{P}$ –diagram.

PSR J1717–4054 was detected strongly twice during Parkes Multibeam Pulsar Survey observations at two different positions in an adjacent beam. This indicates that the pulsar has entered the telescope through the beam side-lobes and thus is an extremely strong source. Also, the pulsar has been seen switching off on a very short timescale of less than a second, indicating that this switching off process cannot be due to some obscuring companion star as a more gradual switching off would have been seen. Looking at the data it seems that this pulsar is only ‘on’ for less than 20% of the time.

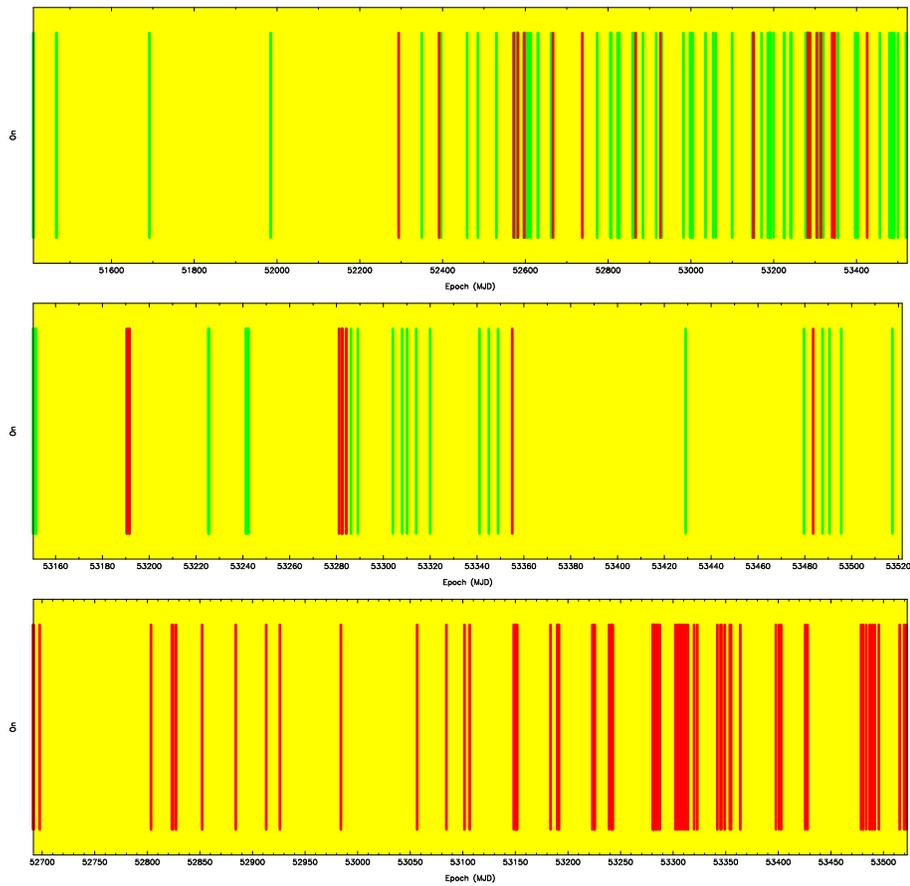
Indeed, it was noticed that three other pulsars showed similar quasi-periodic bursting behaviour to B1931+24, namely PSRs J1634–5107, J1717–4054 and J1107–5907. A similar analysis to PSR B1931+24 was performed to determine any possible quasi-periodicities, see Figure 3 (O’Brien et al. 2007).

PSR J1634–5107 also switches ‘off’ for long periods and appears to come ‘on’ with a periodicity of approximately 10 days. This pulsar, like B1931+24, has a strong ‘on’ state and a completely ‘off’ state (Duke 2004).

Similar spectral analysis was done on these three pulsars and graphs showing the relative ‘on’/‘off’ periods can be seen in Figure 3. Further analysis is needed on these pulsars to establish timescales of the ‘on’/‘off’ states and will be reported elsewhere.



**Fig. 2** Three emission states of PSR J1107–5907. The pulsar was observed, on May 25th, in a weak but clearly detectable state at UT 10:31 before it switched to a very bright state at UT 10:58. One day later, May 26th, the pulsar was not detected at all over a period of several hours.



**Fig. 3** Plots showing the time of observations (grey) and detections (black) for PSRs J1634–5107, J1717–4054 and J1107–5907 respectively.

**Acknowledgements** This work was funded by the Particle Physics and Astronomy Research Council (PPARC) in the UK. DRL is a University Research Fellow funded by the Royal Society. We are grateful to all colleagues that took part in the Parkes Multibeam Pulsar Survey. The Parkes telescope is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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