Session 8

Pulsar Timing

Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
Proceedings IAU Symposium No. 291, 2012
J. van Leeuwen, ed.

doi:10.1017/S1743921312023605

Timing noise and the long-term stability of pulsar profiles

Andrew Lyne
Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy,
University of Manchester, Manchester M13 9PL, UK
email: `agl@jb.man.ac.uk`

Abstract. It has recently been shown that there is a close correlation between the slowdown rates and the pulse shapes of six pulsars, and between the slowdown rates and the flux density of three others. This indicates that these phenomena are related by changes in the current flows in the pulsar magnetospheres. In this paper we review the observational status of these studies, which have now been extended to a total of 16 pulsars having correlated slowdown and pulse emission properties. The changes seem to be due to sudden switching between just two discrete magnetospheric states in the well-known processes of mode-changing and pulse nulling. We also address how widespread these phenomena are in the wider pulsar population.

1. Introduction

Timing noise is low-frequency fluctuation in the rotation-rate of pulsars and is evident in the timing residuals of all young and middle-aged pulsars. The basic properties of timing noise were reviewed recently by Hobbs *et al.* (2010) who presented the results of an analysis of the rotation of 366 pulsars. In summary, timing noise is seen as smooth changes in the timing residuals (and rotation frequency). The timing residuals are often asymmetric, with peaks and troughs having different radii of curvature; the variations are often quasi-periodic with timescales which are typically 1-10 years. For long, it was thought to arise from the fluid interiors of the neutron stars.

A breakthrough was made in 2006, when Kramer *et al.* showed that the timing noise in the long-term intermittent pulsar B1931+24 could be explained in detail by switching in the magnitude of the slowdown rate $\dot{\nu}$ betwen the "ON" and "OFF" emission states of the pulsar, indicating that changes in the current flow from the pulsar resulted in changes of both the radio emission and of the braking torque. The implication that changes in magnetospheric currents could alter pulsar emission properties as well as slowdown rate led Lyne *et al.* (2010) (hereafter LHKSS) to study the detailed pulse profiles of some of those pulsars having the largest amounts of timing noise. They demonstrated that six of these pulsars exhibited the well-known phenomenon of mode-changing, in which a pulsar switches abruptly between two stable profiles. Moreover, in all six pulsars, there was a high degree of correlation between the pulse shape and slowdown rate, the pulsars switching rapidly between low- and high-spindown rates.

Two years after the publication of LHKSS, we review the observational evidence for switched changes in magnetospheric states, both in intermittent pulsars and in mode-changing pulsars, and discuss the relationship between the two phenomena.

2. Intermittent pulsars

Many pulsars show intermittency in their radio emission, although usually the durations of the "ON" and "OFF" states are measured in seconds to hundreds of seconds,

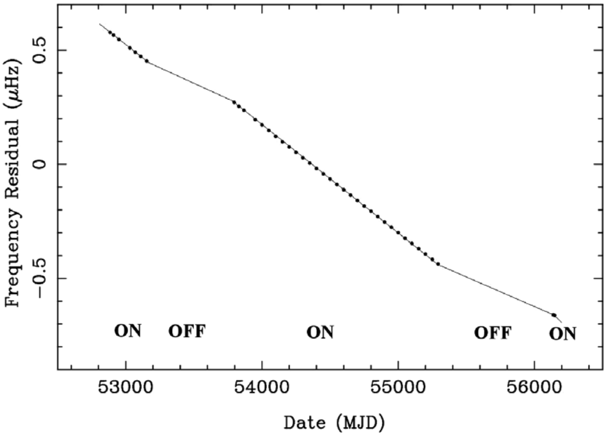

Figure 1. The rotational frequency evolution of PSR J1832+0029 (Lorimer *et al.* 2012).

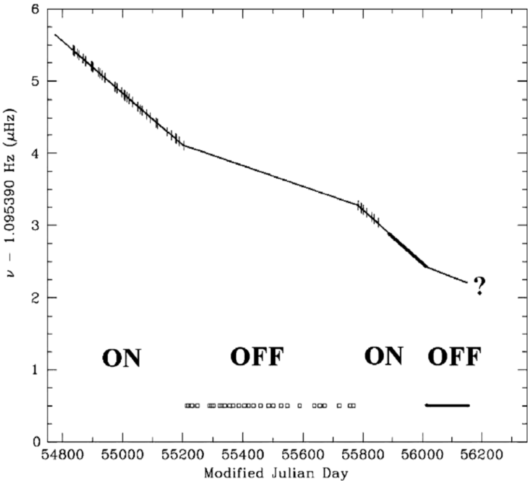

Figure 2. The rotational frequency evolution of PSR J1841−0500 (Camilo *et al.* 2012 and Lyne, priv. comm.).

timescales which are far too short to permit the determination of any change in slowdown rate between the states. This is the phenomenon of pulse nulling which has been known since shortly after the discovery of pulsars (Backer 1970).

However, the intermittent pulsar B1931+24 is typically ON for 1 week and OFF for about 1 month, permitting Kramer *et al.* (2006) to show that the ratio of ON- and OFF- slowdown values $\dot{\nu}_{\rm ON}/\dot{\nu}_{\rm OFF} = 1.5 \pm 0.1$, roughly consistent with an absence of all magnetospheric currents during the OFF phase, in accordance with the calculations of the braking effects of magnetospheric currents by Goldreich & Julian (1969).

Shortly after that publication, a second long-term intermittent pulsar was discovered (PSR J1832+0029) and reported to show similar large changes in in slowdown rate ($\dot{\nu}_{\rm ON}/\dot{\nu}_{\rm OFF} = 1.7 \pm 0.1$; Kramer 2008, Lyne 2009, Lorimer *et al.* 2012). Fig. 1 shows the measured values of rotation rate during the 10 years since its discovery. With rather poor statistics, the lengths of the ON and OFF states are typically many hundreds of days, compared with tens of days for B1931+24.

More recently, a third long-term intermittent object (PSR J1841−0500), also with timescales measured in hundreds of days, has been reported by Camilo *et al.* (2012).

Even though the statistics are also poor for this pulsar, it is clear that this has an even greater slowdown rate ratio ($\dot{\nu}_{\rm ON}/\dot{\nu}_{\rm OFF} = 2.5 \pm 0.2$; see Fig. 2).

3. Profile-switching pulsars

LHKSS studied those pulsars in the Jodrell Bank timing database which showed the largest amounts of timing noise, measured as the ratio of maximum to minimum values of slowdown rate. Seventeen examples are shown in Fig. 3. Pulsars typically have peak-to-peak values of about 1% of the mean, over a 4-orders-of-magnitude range of slowdown rates. Individual pulsars may have a factor of 10 times more or less than this. LHKSS found that six of the 17 pulsars showed pulse-shape changes which were correlated with these slowdown rate variations. Subsequent studies (Lyne *et al.*, in prep) have now shown that a further four of these 17 also have significant pulse-shape variations that are correlated with slowdown rate (PSRs B0919+06, B1642−03, B1826−17 and B1903+07) as well as two others (PSRs B1740−03 and B0105+65).

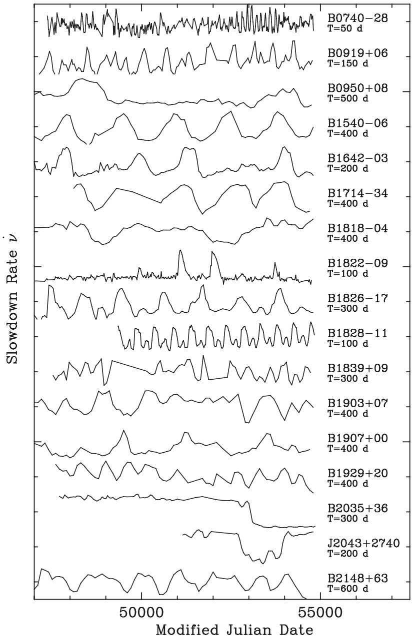

Figure 3. The slowdown rate ($\dot{\nu}$) of 17 pulsars (from Lyne *et al.* 2010).

A further striking example of correlated changes in pulse shape and slowdown is displayed by PSR J2047+5029, discovered at Westerbork in the 8gr8 survey (Janssen *et al.* 2009). At discovery, the observed profile showed a main pulse and an interpulse with an associated precursor having about 1/3 of the flux density of the main pulse (Fig. 4 top). However, when monitoring commenced at Jodrell Bank, the main pulse had reduced in intensity by a factor of about 10, so that it was then much weaker than the interpulse (Fig. 4 bottom). The pulsar has since changed from this “abnormal mode” back to the earlier “normal” mode. These changes were accompanied by changes in slowdown rate, which was larger when in the normal mode than in the abnormal mode, again consistent with the notion that the particles responsible for much of the normal-mode main-pulse radio flux density were also responsible for the increase in braking.

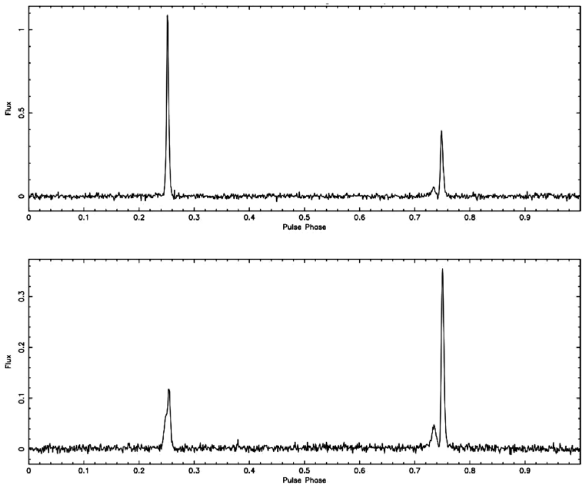

Figure 4. The profiles of the "normal" (top) and "abnormal" (bottom) states of PSR J2047+5029 (Janssen *et al.*, in prep.).

Table 1. Timing noise slowdown rate ratios ($\dot{\nu}_1/\dot{\nu}_2$) and emission changes in 16 pulsars.

PULSAR	$\dot{\nu}_1/\dot{\nu}_2$	**Emission Change**	**Reference**
J1841−0500	2.5	Deep null	Camilo *et al.* (2012)
J1832+0029	1.7	Deep null	Lorimer *et al.* (2012)
B1931+24	1.5	Deep null	Kramer *et al.* (2012)
B2035+36	1.13	28% change in W_{eq}	Lyne *et al.* (2010)
B1740−03	1.13	70% change in component ratio	This paper
B0105+65	1.11	30% change in W_{eq}	This paper
B1903+07	1.07	10% change in W_{10}	This paper
J2043+2740	1.06	100% change in W_{50}	Lyne *et al.* (2010)
B1822−09	1.033	100% change in precursor/interpulse	Lyne *et al.* (2010)
J2047+5029	1.030	90% change in main pulse	Janssen *et al.* (in prep)
B1642−03	1.025	20% change in cone/core	This paper
B1540−06	1.017	12% change in W_{10}	Lyne *et al.* (2010)
B1828−11	1.007	100% change in W_{10}	Lyne *et al.* (2010)
B1826−17	1.007	10% change in cone/core	This paper
B0919+06	1.007	30% change in component ratio	This paper
B0740−28	1.007	20% change in W_{75}	Lyne *et al.* (2010)

In total there are now 16 pulsars with established synchronised changes in the radio emission and the slowdown rate. The properties of these pulsars are summarised in Table 1, in decreasing order of the magnitude of the timing noise, measured as the ratio of the maximum and minimum slowdown rates.

4. The nature of the switching

The time sequences of slowdown rates shown in Fig. 2 are usually bounded by well-defined maximum and minimum levels, each extreme level being identifiable with a characteristic emission profile or flux density. As reported by LHKSS, each pulsar is usually seen to switch abruptly between these extreme states. The fact that the patterns in Fig. 2 are generally smooth and do not display abrupt switching behaviour was demonstrated to arise from changing statistical properties of the mode-changing phenomenon, and the observed profile shape parameter is determined by the proportion of time spent in the two modes. This is most clearly illustrated in Fig. 5 which shows a number of 8-hour observations of PSR B1828−11 chosen at different phases of the 500-day oscillating

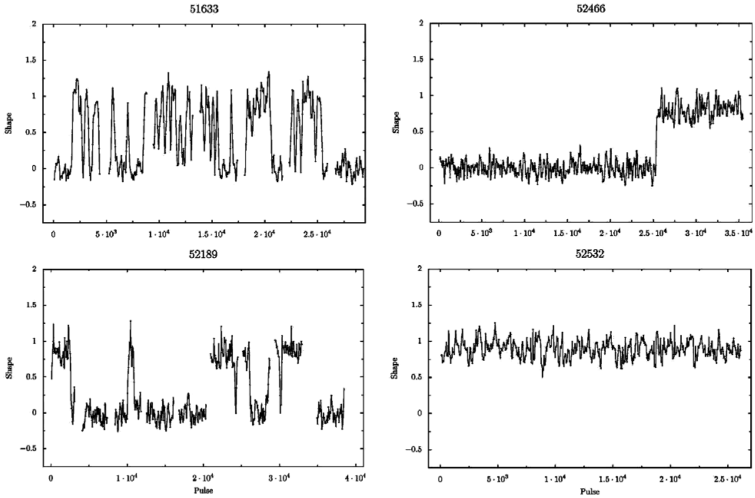

Figure 5. Four 8-hour time-sequences of the profile state of PSR B1828−11, taken at four different phases of the 500-day oscillation seen in Fig. 3 for this pulsar. Although the switching timescale may be short, the fraction of time spent in one state or the other changes slowly (Stairs *et al.* in prep.)

pattern displayed by this pulsar in Fig. 3. We note that although pulse nulling and profile mode-changing was first observed in 1970 (Backer 1970; Backer 1970a), the following four decades have seen no study of the stability of the statistics of nulling or mode-changing.

5. The relationship between nulling and mode-changing

The processes of nulling and mode-changing are similar in many ways. Both are switched phenomena between (usually) two discrete emission states. They both have similar large ranges of timescales and both have a major synchronisation with the spin-down rate of the pulsar. They are both understood in terms of changes in magnetospheric particle currents. The natural conclusion is that nulling is probably an extreme form of mode-changing. This view is supported by a few cases in which an apparently nulling pulsar has been found to have low-level emission in the null state. One such example is PSR B0826−34 shown in Fig. 6, in which integration of the data during apparently "null" episodes shows pulsed emission at a level of about 2% of the un-nulled pulses.

Perhaps one telescope's nulling pulsar is a larger telescope's mode-changing pulsar !

6. Conclusions

Pulsar magnetospheres switch between a small number of discrete states, usually two, each of which corresponds to an apparently quasi-stable magnetospheric configuration. It seems that changes in magnetospheric current flows between these states cause variations in both the emission beam snd the slow-down rate. This is supported by the general observation that the larger slowdown-rate is nearly always associated with enhanced emission, particularly of the pulsar "core" emission. I have no understanding of why there are these discrete states, or of the origin of the multi-year quasi-periodicities that modulate the statistical properties of the states. Free-precession of the neutron star and orbiting asteroids have been proposed, but any links are obscure.

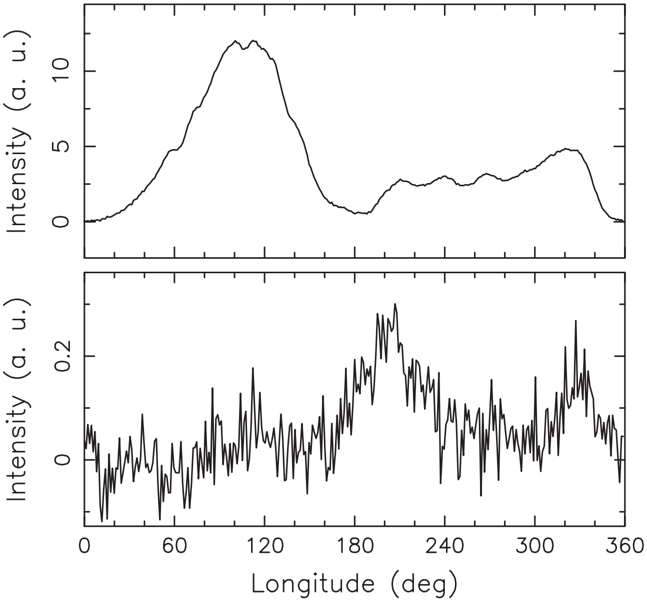

Figure 6. The integrated "normal" (top) and "abnormal" (bottom) profiles of PSR B0826−34 at 1374 MHz (from Esamdin *et al.* 2005).

Finally, it must be emphasised that these phenomena are widespread. The majority of pulsars of young and intermediate characteristic age display detectable timing noise. The studies of profiles described here have mostly been of those pulsars which have the largest fractional changes in slowdown rates and hence may be expected to suffer the greatest magnetospheric changes and corresponding variation in emission properties. In fact, 12 of the 19 pulsars with largest timing noise show correlated emission variations. Most of the remaining 7 have much poorer signal-to-noise ratio, making the precise determination of pulse shape changes challenging. The changes expected in less timing-noisy pulsars are likely to be much more subtle and a challenge to detect. At present, there is no reason to doubt that all timing noise has its origin in switched magnetospheric states.

References

Backer, D. C. 1970, *Nature*, 228, 42

Backer, D. C. 1970a, *Nature*, 228, 1297

Camilo, F., Ransom, S. M., Chatterjee, S., Johnston, S., & Demorest, P. 2012, *ApJ*, 746, 63

Esamdin, A., Lyne, A. G., Graham-Smith, F., Kramer, M., Manchester, R. N. & Wu, X. 2005, *MNRAS*, 356, 59

Goldreich, P. & Julian, W. H. 1969, *ApJ*, 157, 869

Hobbs, G., Lyne, A. G., & Kramer, M. 2010, *MNRAS*, 402, 1027

Janssen, G. H., Stappers, B. W., Braun, R., van Straten, W., Edwards, R. T., Rubio-Herrera, E., van Leeuwen, J., & Weltevrede, P. 2009, *A&A*, 498, 223

Kramer, M., Lyne, A. G., O'Brien, J. T., Jordan, C. A., & Lorimer, D. R. 2006, *Science*, 312, 549

Kramer, M. 2008, *40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, American Institute of Physics Conference Series*, 983, 11

Lorimer, D. R., Lyne, A. G., McLaughlin, M. A., Kramer, M., Pavlov, G. G., & Chang, C. 2012, *ApJ*, 758, 141

Lyne, A. G. 2009, *Astrophysics and Space Science Library*, 357, 67

Lyne, A., Hobbs, G., Kramer, M., Stairs, I., & Stappers, B. 2010, *Science*, 329, 409