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Radio pulsar variability

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Abstract. Pulsars are potentially the most remarkable physical laboratories we will ever use. Although in many senses they are extremely clean systems there are a large number of instabilities and variabilities seen in the emission and rotation of pulsars. These need to be recognised in order to both fully understand the nature of pulsars, and to enable their use as precision tools for astrophysical investigations. Here I describe these effects, discuss the wide range of timescales involved, and consider the implications for precision pulsar timing.

Keywords. pulsars: general

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1. Introduction

A textbook pulsar emits a beam of radio emission from just above its magnetic poles. The mis-alignment of the spin and magnetic axes then results in a light-house effect as the star rotates. Those pulsars whose radio beams cut across the Earth are observed as a string of sharp pulses in the signals detected by radio telescopes. The signal is straight forward to model with a simple slow-down law consisting (usually) of just spin frequency, its derivative and (if applicable) some binary parameters. The regularity of the signal means that these pulses act as the ticks of an extremely precise clock. Furthermore, pulsars are often to be found in extreme environments, which we are able to study by utilising this clock-like nature. The moniker of 'super clocks in space' is well earned.

A real-life pulsar deviates from the ideal in a number of ways. This is due to a number of instrumental, propagation and intrinsic effects, many of which are not well understood. In § 2 we discuss the wide range of variable behaviour observed in pulsar signals. In § 3 we consider how pulsars actually work before asking why this is of interest to pulsar astronomers in § 4. Finally, in § 5, we present conclusions and discussions.

2. What do we see?

The range of variability timescales in pulsars is remarkably wide, spanning all timescales on which it has been possible to measure. The fastest timescales to have been probed are nanoseconds. The voltage signals from radio telescopes are commonly Nyquist-sampled at rates of ~ 1 GHz, but usually this time resolution is traded for frequency resolution, and furthermore data is integrated in time to increase the signal-to-noise ratio (S/N). However, in the case of the Crab pulsar this is not necessary in order to detect a signal, and Hankins *et al.* (2003) have observed kJy pulses lasting 2 ns, showing that its well-known $\sim$ μs 'giant pulses' are in fact composed of a large number of such "shots". These shots appear to be the quanta of pulsar radio emission. They are not resolved — indeed, we might expect this, i.e. an intrinsic timescale of $\lesssim 100$ ps, given the uncertainty principle and the observations that pulsars emit over bandwidths of several tens of GHz (Maron *et al.* 2000; Camilo *et al.* 2007). The actual mechanism is unknown but the brightness temperature of $T_{\rm B} = 10^{37}$ K (for the Crab pulses) implies, using the well-known expression for the maximum possible brightness temperature $T_{\rm B,max} = 6 \times 10^9 N(\gamma - 1)$ K, a coherence factor of $N \approx 10^{27}/\gamma$. Clearly the mechanism is coherent, most likely involving particles emitting in bunches, a plasma instability or some kind of maser, but despite much effort (Ginzberg & Zheleznyakov 1970; Asseo *et al.* 1990; Lyutikov *et al.* 1999; Melrose 2004) the details are not known.

The duration of a time sample in most pulsar observations is usually $\gg 100$ ps so that a large number of shots are incoherently added within each time sample. The Poisson distribution of the shots then approaches that of a Gaussian, and it is common to model the pulsar signal as amplitude-modulated noise (Rickett 1975). This model is insufficient however, as single pulse studies show non-Gaussian variations on μs−ms scales, e.g. the “giant micropulses” seen in Vela by Johnston *et al.* (2001), and we see dramatic variations from one pulse period to the next, on ms−s scales, e.g. we see changes in intensity (by factors of $\gtrsim 10^3$), phase, pulse shape and the number of components.

Extremely organised behaviour is seen on second to minute timescales, in the form of sub-pulse drifting. Here, a ‘Joy Division plot’ reveals that the pulses drift periodically (both earlier and later) in pulse phase in regular ‘bands’ as a function of time with typical repetition periods of tens of spin periods. A standard explanation for this behaviour has been the “carousel model” (Ruderman & Sutherland 1975) where disparate emission spots above the stellar surface are induced to rotate by $E \times B$ drift. Lately however it has been shown that this model does not explain the drifting seen in PSR B0809+74 (Hassall *et al.*, in prep.). In a study of 187 pulsars, using the Westerbork Synthesis Radio Telescope, Weltevrede *et al.* (2006) showed that at least one third exhibited drifting.

On timescales of seconds to minutes, and even up to hours we see further organised behaviour in the form of ‘moding’ — the changing of the pulse profile to one of a small number of different profiles. If there is no detected radio emission from one of these ‘modes’ the phenomenon is commonly termed ‘nulling’. A quantitative analysis of the pulse amplitude distributions of a large number of pulsars has recently been performed by Burke-Spolaor *et al.* (2012). This work looked at the single pulse statistics of 315 pulsars with detectable single pulses in the High Time Resolution Universe survey. The authors classify the pulse amplitude distributions as either Gaussian (7 sources, 2%), log-normal (84 sources, 27%), multi-peaked (18 sources, 6%) or unimodal (24 sources, 8%). Unfortunately the majority (182 sources, 58%) did not fit within these classifications. While we might suggest testing for more complex distributions for the unclassified sources, this is not possible due to a paucity of detected pulses. Of the unclassified 182 sources, only 92 had more than 20 detected pulses during the 9-minute survey pointings, and a single pulse was all that was detected for 22 of the sources.

Moding is also observed on timescales of hours to weeks, or even months. The first realisation of this came when Kramer *et al.* (2006) discovered that PSR B1931+24 is detectable as a radio pulsar only for periods of $\sim 5 - 10$ days before ‘turning off’ and remaining undetectable for $\sim 25 - 35$ days in a quasi-periodic fashion. Crucially this moding is accompanied by a $\sim 50\%$ change in the spin-down rate, with $\dot{\nu}_{\rm hi}/\dot{\nu}_{\rm lo} = 1.5$. Since then two more “intermittent pulsars” have been reported — PSRs J1841−0500 (Camilo *et al.* 2012) and J1832+0029 (Lorimer *et al.* 2012). These sources have ‘on’ and ‘off’ timescales $\sim 20 - 30$ times longer than B1931+24 and spin-down rate ratios of 2.5 and 1.8 respectively. Lyne *et al.* (2010) presented results of several decades of Lovell Telescope observations of 17 pulsars where correlated quasi-periodic changes in $\dot{\nu}$ and pulse profile were clearly observed. The changes in spin-down rate ranged from 0.3% to 13%. More examples of such behaviour continue to be identified (see e.g. Karastergiou, these

Table 1. An incomplete list of the variability and evolutionary timescales of a pulsar. A plethora of interstellar medium timescales also exist which will also modulate the observed pulsar signal, as well any gravitational wave sources. † Here we use the term 'nulling', but 'moding', 'extreme pulse amplitude modulation' or a variety of similar terms could be used interchangeably.

Timescale	Name	Cause
ns	Radio quanta "shots"	Fundamental emission timescale
us−ms	Single pulse variations	?
ms−s	Pulse-to-pulse variations	?
s−min	Sub-pulse drifting	?
s−min	Nulling†	?
s−hrs	Extreme nulling	?
hrs−yrs	Quasi-periodic switching	Magnetospheric switching?
hrs−years	Orbital timescales	Orbital motion
$\sim 10^7$ years	NS cooling timescales	Thermal cooling
$\sim 10^7$ yr	Galactic Evolution, $(G\rho_{\rm MW})^{-1/2}$	Moving in Galactic potential
$10^3 - 10^7$ yr	Spin Evolution, $P/\dot{P}$	Loss of rotational energy

proceedings). We stress that it is not simply switching between two states that is seen in moding pulsars (see Fig. 5 from Burke-Spolaor & Bailes (2010) or Fig. 1 from Esamdin *et al.* (2012) for some excellent examples). Furthermore we note that such moding is seen on all timescales ranging from several years down to one rotation period (Keane & McLaughlin 2011). On the shorter time-scales changes in $\dot{\nu}$ cannot be measured — Young *et al.* (2012) point out that for modes persistent for less than a day spin-down rate switching of a few percent would never be detectable. The associated profile changes are also often quite subtle and obviously cannot be discerned from pulse-to-pulse variations when the persistence of the mode is less than the required duration to surpass the stable profile threshold (see § 4). *It would seem that switching between a number of stable states, often with some quasi-periodicity, is a generic feature of pulsars.*

Of course we must not forget that the emitted broadband signal from a pulsar is subject to the transfer function of the interstellar medium (which is also time variable on a number of scales) and that of the telescope-receiver system itself (which will also have a number of systematic contributions). There is an equally long list of these effects which must be accounted for in modelling the pulsar signal but which I will not elaborate upon here (but see e.g. Cordes & Shannon 2010). Table 1 gives an incomplete list of timescales on which pulsars are known, or expected, to be variable.

3. How do they work?

Assuming that the propagation and instrumental effects can be understood (whether or not they can be removed) there are still a wide range of transient behaviours seen in pulsars. This leads us to a big question: *How do we get erratic radio emission from a PSR with a particular timescale, and periodic switching?*

For force-free magnetospheres (see below) it has been shown that a number of stable solutions exist with the closed magnetosphere not necessarily extending to the light cylinder radius (Contopoulos *et al.* 1999; Spitkovsky 2006). It has further been shown that perturbing these solutions can result in a rapid switch from one magnetospheric configuration to another (Contopoulos 2005). However, these perturbations are put in 'by hand' and the underlying reason for the switching remains unknown. Furthermore, why this would occur with a periodicity is unknown. That the switching is quasi-periodic,

Table 2. Some of the important questions regarding pulsar magnetospheres and the status of the force-free solutions (see e.g. Li; Spitkovsky, these proceedings).

Question	Status
Stable magnetosphere with dE/dt> 0?	Yes
Why force-free?	Don't Know
2+ stable solutions possible?	Yes
Switching between configurations?	Mechanism unknown
Switching with (quasi-)periodicity?	No
Braking index predictions?	Many ($n \neq 3$)
Radio emission explained?	No
Gamma-ray emission explained?	Realistic lightcurves

rather than strictly periodic, must also be explained. Recently Seymour & Lorimer (2012) have suggested that the quasi-periodicity resembles that seen on "the route to chaos" and detect chaotic behaviour in PSR B1828−11, one of the Lyne *et al.* (2010) sample. The timescales for the erratic behaviour are wide (see Table 1), so much so that it is difficult to see what the decisive variables are. If the moding is simply a result of the magnetospheric switching (Timokhin 2010) the timescales for both phenomena are obviously one and the same. This raises the question of whether pulsars with large pulse-to-pulse modulation on much faster timescales than the intermittent pulsars are changing magnetospheric configuration constantly. This would suggest a picture of highly unstable and frequent fast changes on the scale of the entire magnetosphere. If this is not what is occurring in these cases it is unclear on which timescales this ceases, as there seems to be a continuum of moding/switching timescales observed (Keane 2010a). We are forced to abandon our big question entirely in favour of a more tractable one: *What does a PSR magnetosphere even look like?*

There are two approaches to answering this question — the first is to solve Maxwell's equations for a rapidly-spinning strongly-magnetic highly-conductive ball; the second is to try to determine the geometry of the system from observations of the polarisation characteristics of pulsar emission. Both of these approaches should result in the same answer, but both are fraught with many difficulties. Here I briefly describe the first approach, but refer the reader to the works of Radhakrishnan, Cooke, Kramer, Karastergiou, Johnston, Weltevrede, Rankin, Wright and Noutsos for information on the geometrical approach. When calculating Maxwell's equations in the vicinity of the neutron star it is found that there are trapping surfaces for charges of opposite sign above the poles, and in the equatorial plane. Particles get ripped from the stellar surface and are simply trapped in these 'electrospheres' with no pulsar-like behaviour (see e.g. Fig. 2.4, Keane 2010b). One then would assume that either the initial conditions do not represent reality, i.e. in the violent supernova explosion wherein the neutron star was born there was abundant plasma provided from the offset so that the electrosphere scenario never arises, or, that the electrosphere solution is in fact unstable (e.g. to the diochotron instability, see Spitkovsky, these proceedings) and breaks down after some time. Regardless of the reason some authors have pressed on assuming "a sufficiently large charge density whose origin we do not question" (Contopoulos *et al.* 1999) and solved "the pulsar equation" (Michel 1973) for the first time. The results of this work show current flows in the magnetosphere coincident with the 'gap regions' for emission derived by the geometric approach so that it seems that progress is being made towards understanding pulsar magnetospheres. Table 2 summarises some of the knowns and unknowns.

4. Who cares?

"I don't care, I just want to do timing." Anonymous.

Some astronomers may not be very concerned with how pulsars actually work, and only interested in pulsars for their use as clocks, e.g. to use in pulsar timing arrays (PTAs). In this case the only question that matters is whether or not pulsar profiles are stable for typical PTA observations. Fortunately this can be measured, and one such method involves calculating ρ, the cross-correlation coefficient of the observed pulse profile with a template profile. If $1-\rho \propto N^{-1}$, where N is the number of periods folded into the observed profile, then the profile is stable (Liu *et al.* 2012). Longer integrations improve the profile's S/N only and not its stability. While the value of N where the exponent transitions to -1 denotes the stability timescale, different exponents reveal other timescales at work, e.g. nulling/moding timescales if present (Keane 2010b). Although the stability of pulsar profiles is implicitly assumed† in pulsar timing, it is not clear whether this has been systematically confirmed for all PTA pulsars. The received wisdom is that 10^4 periods gives you a stable profile but Liu *et al.* (2012) found this to be dependent upon the pulsar with values of up to 10^5 periods required in some cases. It is important to note that a high S/N does not imply stability (based solely on S/N we can time pulsars using their single pulses, but this is not *precision* pulsar timing, see Keane *et al.* (2011) for details).

If one used pulsar profiles which were not stable then there would be no justification for expecting a good fit to the timing model, with $\chi^2_{\rm red} = 1$. Oddly enough there is a practice (which is admittedly dying out) to assume that the best fit model, i.e. the one with the lowest $\chi^2_{\rm red}$ value, is the correct model, and to then scale the errors so as to make $\chi^2_{\rm red} = 1$. The errors in this case are scaled by an 'EFAC' quantity. This is very bad practice for several reasons (see § 3.2.1 of Andrae (2010) for more details), e.g. it assumes that: the error distribution is Gaussian; the model is linear in all of its parameters; the model used is correct (also completely negating the point of using the chi-squared *test*).

Pulse jitter is another contribution to errors in pulse time-of-arrival measurements which is usually ignored. Jitter is only evident in pulsar profiles when the S/N of single pulses are $\gtrsim 1$. Currently, for PTA sources, this is only relevant for PSR J0437−4715. For SKA-era sensitivity this must be accounted for in all PTA pulsars, but fortunately this is possible, as has been demonstrated for J0437−4715 (Liu *et al.* 2012).

5. Conclusions & Discussion

Pulsar emission and rotation is variable on a wide range of timescales. It is vital to gain a full understanding of these things in order to (a) understand pulsars; and (b) perform precision pulsar timing. The author's bias suggests to him that it may be difficult to achieve the latter with first making significant inroads into achieving the former. For example the observed behaviour (described in § 2) suggest a number of questions which the pulsar timing community should be thinking about: Is there any reason why there would not be (perhaps periodic or quasi-periodic) spin-down rate switching occurring in many/all pulsars? Is there any reason why there would not be (perhaps periodic or quasi-periodic) spin-down rate switching in many/all millisecond pulsars? Are there other (perhaps deterministic) timing instabilities yet to be identified? The planned upcoming studies of large pulsar timing databases (S. Johnston, private communication) will no

† It is assumed that the observed profile is a shifted scaled version of a smooth (sometimes analytic) template with additive noise.

doubt shed valuable light on what the answers to these questions are, and bring us a few steps closer to understanding those super clocks in space.

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