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Pulsar Timing Noise

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Abstract Pulsar timing techniques allow a pulsar's rotational, astrometric and binary parameters to be measured to high precision. Any features that remain in the timing residuals after fitting for the expected pulsar parameters are suggestive of unmodelled physics such as binary companions, free precession or glitch events. In this paper we provide an overview of the features observed in the timing residuals that collectively are referred to as "pulsar timing noise". We use results obtained from the literature and from the Jodrell Bank observatory archive of timing residuals.

Key words: pulsars: general

1 INTRODUCTION

The techniques behind pulsar timing have been described by numerous authors (see, for instance, Lorimer, & Kramer 2005). In brief, the procedure starts by converting the measured pulse arrival times at an observatory to the pulse emission time in the solar system barycentric reference frame. Pulsar timing residuals are then calculated; these represent the difference between the measured pulse phase and a predicted phase using a pulsar timing model. Terms corresponding to offsets in model parameters can subsequently be fitted to the timing residuals in order to improve the measurement of these parameters. A model that fully describes the physics behind the motion and the slow-down of the pulsar should produce timing residuals that are statistically equal to zero. However, for many pulsars the timing residuals show clearly identifiable features which generically have become known as "timing noise". Some of the features have previously been explained as being due to unmodelled planetary companions (e.g. Cordes 1993), free-precession (e.g. Stairs, Lyne & Shemar 2000) or glitches (Lyne, Shemar & Graham-Smith 2000).

The majority of analyses undertaken to characterise and understand pulsar timing noise have used relatively short data spans of $<$10 yr. We have undertaken a new analysis of the Jodrell Bank observations that span between 10 and 35 yr. A full write-up of this analysis is in preparation and will be published shortly. Here, we review the models that have been proposed for timing noise and provide an overview of the observations that are currently in the literature and those that we intend to publish soon.

2 PULSAR OBSERVING PROJECTS

Pulsars have been observed from many observatories worldwide over the past 35 yr. In terms of the sheer number of pulsars observed over the longest data spans, the Jodrell Bank observatory data set provides the most useful archive for studying pulsar timing noise. As described by Hobbs et al. (2004, hereafter Paper I) the Jodrell Bank archive now contains over 6000 yr of pulsar rotational history. The basic observational parameters for the pulsars with data spanning more than 10 yr were published in Paper I. These data have already been used to obtain a proper motion measurement for each pulsar. These proper motions were published in Hobbs et al. (2005) and highlighted the lack of evidence for a bimodal birth velocity distribution (see e.g. Arzoumanian, Chernoff & Cordes 2002). We hope that these same data will now provide new insight into the nature of timing noise.

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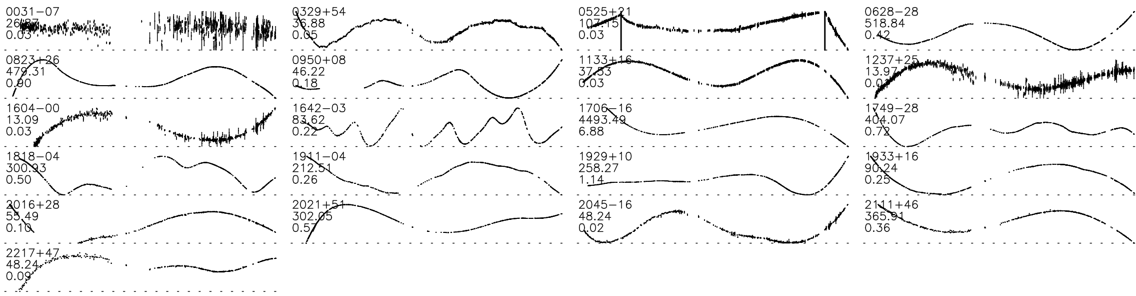

Fig. 1 The timing residuals for pulsars in the Jodrell Bank sample that have data spanning more than 30 yr. For each pulsar the abscissa represents 35 yr of observations and the residuals are individually scaled; the three labels on the left of each panel provide the pulsar's name, the range from the minimum to maximum residual (ms) and the same range scaled with the pulsar's rotational period.

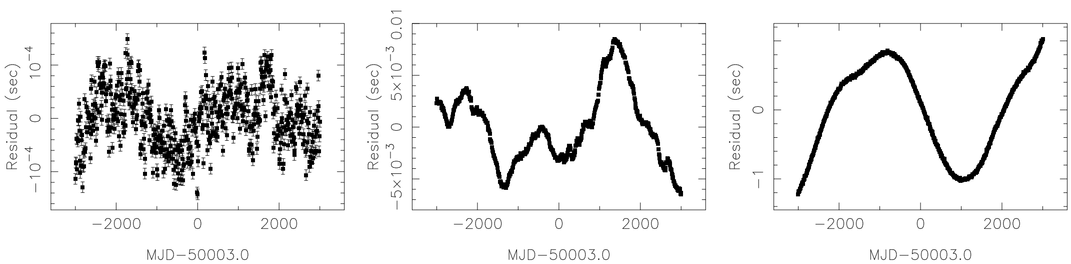

Fig. 2 Examples of timing residuals produced from a red-noise simulation with power-law indices of -1, -3, and -5 respectively.

We also note the large number of timing observations for young pulsars that have been obtained at the Nanshan observatory ($\sim$284 pulsars over a 10 yr data span), Haartebeestoek (30 pulsars over 15 yr) and at Parkes ($\sim$110 pulsars over 10 yr). Even though most of our current knowledge of timing noise has come from studies of young pulsars, recent high-precision timing experiments of millisecond pulsars show the effects of pulsar timing noise. The Jodrell Bank observations, to date, have not been sensitive to studying the timing noise of millisecond pulsars in great detail. However, the Parkes, Arecibo, Green Bank and Nancay observatories have been observing such pulsars with the best possible timing precision over the last $\sim$10 yr. Current limits from the Parkes Pulsar Timing Array project (see http://www.atnf.csiro.au/research/pulsar/psrtime) include root-mean-square (rms) timing residuals of $\sim$0.1 μs for PSRs J0437$-$4715, J1909$-$3715, and J1713$+$0747 and $\sim$1 μs for approximately 15 more millisecond pulsars. It is expected that these rms timing residuals will continue to improve with better instrumentation and calibration procedures.

As most of the results presented here are obtained using Jodrell Bank data we now provide a basic summary of the Jodrell Bank observing system. The observations are carried out at frequencies close to 410, 610, 910, 1410, and 1630 MHz. The signals are combined to produce, for every observation, a total intensity profile. Pulsar times-of-arrival (TOAs) are subsequently determined by convolving, in the time domain, the profile with a template corresponding to the observing frequency. The pulsar timing residuals are obtained by fitting a timing model to the TOAs using the PSRTIME pulsar timing software. For 18 pulsars we also combine the Jodrell Bank observations with early measurements from the NASA Deep Space Network (Downs & Reichley 1983).

3 CLASSIFYING PULSAR TIMING NOISE

Figure 1 shows many of the different features seen in the timing residual. These features can often be modelled by the least-squares-fitting of harmonically related sinusoids (see Paper I) which provides an analytic function to describe the timing residuals. This function can subsequently be used to 1) form the power spectrum, 2) search for local maxima and minima, 3) obtain a time-scale for the dominant timing noise feature from the auto-correlation function and 4) determine local gradients and radii of curvature. This technique fails for discrete changes in the timing residuals; for example at a glitch event. To study such features more complex techniques are necessary. We note that a simple "red"-noise simulator (i.e. modelled by summing many sinusoids with random phase, but with amplitudes specified by a given power-law spectrum, $P(f) = Af^{-\alpha}$) can reproduce many of the observed characteristics of pulsar timing noise (see Figure 2). However, many of the standard spectral techniques (e.g. the Lomb-Scargle periodogram analysis) fail in the presence of steep "red"-noise. For instance a standard periodogram analysis can obtain power-law indices, α, for red-noise power spectra, only if $\alpha > -2$. Techniques have been developed in order to produce accurate power-law indices in the presence of steep red-noise including the use of the CLEAN algorithm (D'Alessandro, Deshpande & McCulloch 1997), using Hahn window functions (Buchner; these proceedings) and Deeter polynomials (e.g. Scott, Finger & Wilson 2003). However, these techniques, to date, have proved difficult to apply to large numbers of pulsars automatically. Full mathematical treatment of red-noise processes is provided in Kopeikin (1997) and his subsequent series of papers.

Many techniques exist for measuring the "amount" of timing noise present in any given dataset. In this paper we use the σ_z stability parameter which is based on the Allan variance (Matsakis, Taylor & Eubanks 1997). Figure 3 shows the σ_z parameter at different time scales for a representative sample of four pulsars. It is clear that the youngest pulsars are less stable (i.e. show more timing noise) than older pulsars. Figure 4 contains the σ_z parameter measured at a ten-year timescale versus the pulsar period derivatives from the Jodrell Bank sample (note: the timing residuals for most millisecond pulsars in this sample are dominated by receiver noise and therefore the σ_z values provide an upper limit to the intrinsic pulsar stability).

Any attempt to classify pulsar timing noise is limited by 1) the TOA precision achievable and 2) the dataspans available. In Figure 5 we show the residuals that are obtained from a 5 yr section of data from PSR B0950+08 which are dominated by a cubic. The full 35 yr of data (right panel) is clearly dominated by an oscillatory component that is not detectable with data spanning less than ~5 yr. Nevertheless, even with these limitations in mind an approximate classification of the Jodrell Bank sample indicates that 38%

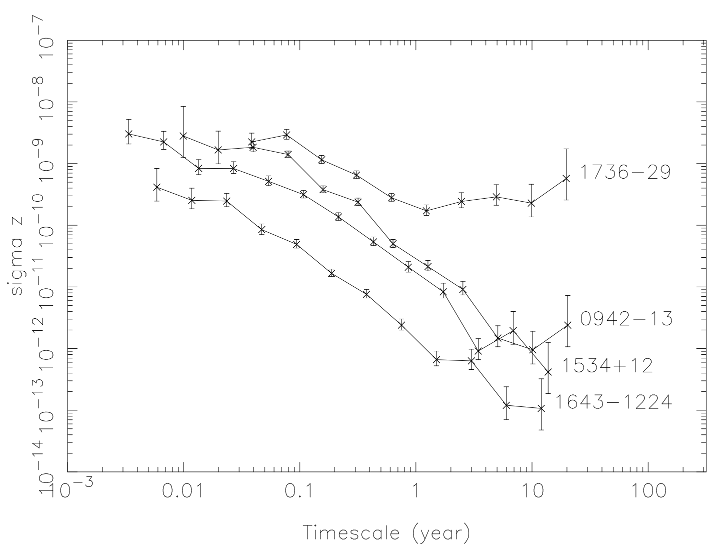

Fig. 3 The σ_z parameter for four pulsars plotted for different time scale.

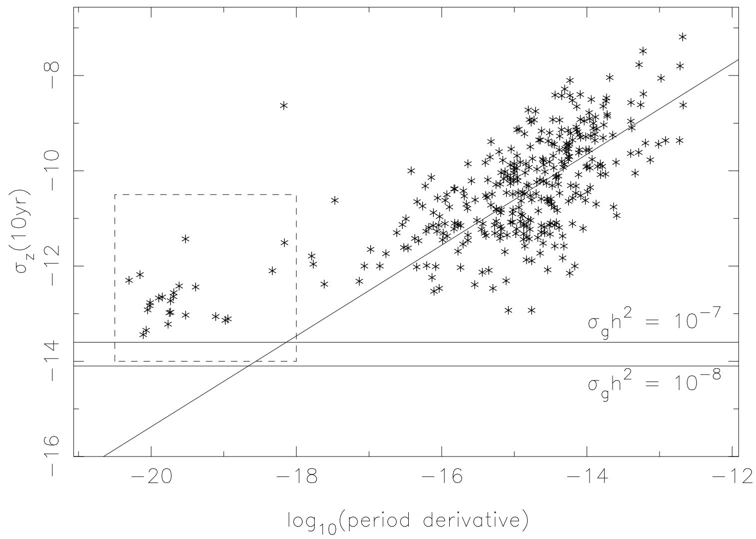

Fig. 4 The σ_z parameter measured over a 10 yr timescale versus the pulsar period derivatives. The millisecond pulsars (indicated within the dashed rectangle) provide only upper limits and the intrinsic pulsar timing noise is expected to be at a lower level. Two values of the σ_z parameter for a stochastic background of gravitational waves are overlaid.

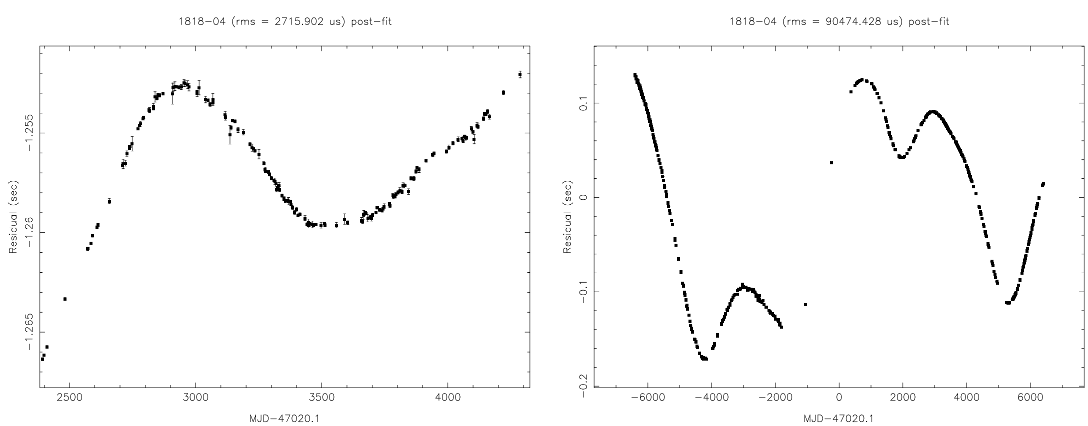

Fig. 5 The timing residuals for PSR B0950+08 obtained from a dataspan of 5 yr and 35 yr.

of the timing residuals show no features, 14% have cubic terms that correspond to a positive frequency second derivative, 10% correspond to a negative frequency second derivative, 2% have clear periodicities, 23% resemble smooth curves, but with no clear periodicity, 9% are dominated by glitch events and 4% are irregular. The cubic terms can be modelled by a second frequency derivative, however the braking indices obtained from these derivatives range from -2.6×10^8 and $+2.5 \times 10^8$ (see Paper I). These cubic terms are therefore not due to the intrinsic dipole braking of the pulsar and we therefore only fit for the first frequency derivative and consider any remaining features as timing noise.

The timing residuals for millisecond pulsars also show timing noise. Lommen (2002) presents the timing residuals for PSR B1937+21 which are dominated by a cubic term corresponding to a positive second frequency derivative. The removal of this cubic yields irregular timing residuals. PSR B1821$-$24 has been monitored at the Nancay observatory. Cognard et al. (1996) present their timing residuals which are also well-modelled by a cubic. They also note that as the pulsar-line-of-sight passes the Solar corona large systematic timing residuals are observed. More recently Cognard & Backer (2004) reported the detection of a very small glitch in this pulsar (the first glitch detected in a millisecond pulsar). The Australian Pulsar Timing Array Project is amongst a number of similar projects that aim to detect gravitational waves (GWs) by looking for small effects in the pulsar timing residuals. However, it has not been clear whether the effects of GWs will be too small to detect compared with the expected level of timing noise for these pulsars. The expected σ_z level for a stochastic background of GWs is plotted in Figure 4. Extrapolating the σ_z values from the non-millisecond pulsars predicts stabilities for most of the millisecond pulsars that are lower than the level expected for GWs. The timing residuals for such pulsars are therefore expected to be dominated by the GW signature. It is often useful to be able to predict the expected timing noise amplitude for a given pulsar. It is possible to show (Jenet, private communication) that the strongest correlation with the σ_z parameter is obtained from

$$\sigma_z(10\,\mathrm{yr}) \sim 0.71\log_{10}(P^{-0.72}\dot{P}). \tag{1}$$

4 PHYSICAL MODELS FOR PULSAR TIMING NOISE

Pulsar timing noise is not to be due to effects introduced by pulsar timing packages nor the observatories or receiver systems. Cordes & Helfand (1980) also concluded that timing noise is not correlated with height above the Galactic plane, luminosity nor pulse shape changes. Physical models for pulsar timing noise that exist in the literature can be divided into those intrinsic to the pulsar, orbital companions and those that are extrinsic. The models can, in some cases, be distinguished by studying the power spectra of the timing residuals or looking for correlations in the timing residuals between different pulsars. Here we summarise many of the theories that are presented in the literature with, if possible, a description of how each theory may be checked or disproved.

4.1 Intrinsic Models

Boynton et al. (1972) first suggested that the rotational irregularities might arise from a simple ‘random walk’ process that comprises of unresolved step functions in the pulse phase, spin frequency or frequency derivative. Random walks of these three types give rise to phase noise, frequency noise and spin-down noise respectively where the power law index, α, in the power spectrum of the residuals, scales as $\alpha = -2, -4$, and -6 for the three types of noise respectively. The Crab pulsar timing noise was shown to be consistent with a random walk in pulse frequency (Groth 1975) although more recent work (Scott, Finger & Wilson 2003) casts doubt on this conclusion. As summarised by D’Alessandro et al. (1995) detailed analysis of 45 pulsars suggest that the timing noise cannot always be modelled as simple random-walk processes, but may be also due to discrete jumps in one or more of the timing parameters. For five pulsars in their sample, the timing activity is neither due to a pure random walk process nor resolved jumps.

Various models are based on the superfluid interior of the neutron star affecting the pulsar rotation (e.g. Alpar, Nandkumar & Pines 1985; Jones 1990). It may be possible to prove (or disprove) such theories by studying the power spectra of the timing residuals. As shown by Alpa, Nandkumar & Pines (1985), the highest-frequency components to the power spectra allow a determination of whether vortex pinning regions that are characterised by short relaxation times ($<$1 d) are contributing to timing noise. Studying the low-frequency end allows one to search for noise originating in pure unpinning or mixed events in the weak pinning regions that are characterized by long relaxation times ($>$2000 days).

The sinusoidal features seen in the timing residuals for PSR B1828$-$11 have been explained as the effects of the neutron star undergoing free-precession (Stairs, Lyne & Shemar 2000). This is notable from the clear periodicities in the timing residuals and correlated pulse shape changes. Since the publication of Stairs, Lyne & Shemar (2000), PSR B1828$-$11 has undergone a further five oscillatory cycles (see Figure 6). However, a periodogram analysis clearly identifies the dominant periodicity reported earlier of $\sim$500 d with significant other periodicites at $\sim$1300 d and $\sim$2500 d. A further two pulsars, PSR B1642$-$03 and B1826$-$17 also show significant periodicities (see the lower panel in Figure 6) which may be due to free-precession; these will be fully analysed in our forthcoming paper.

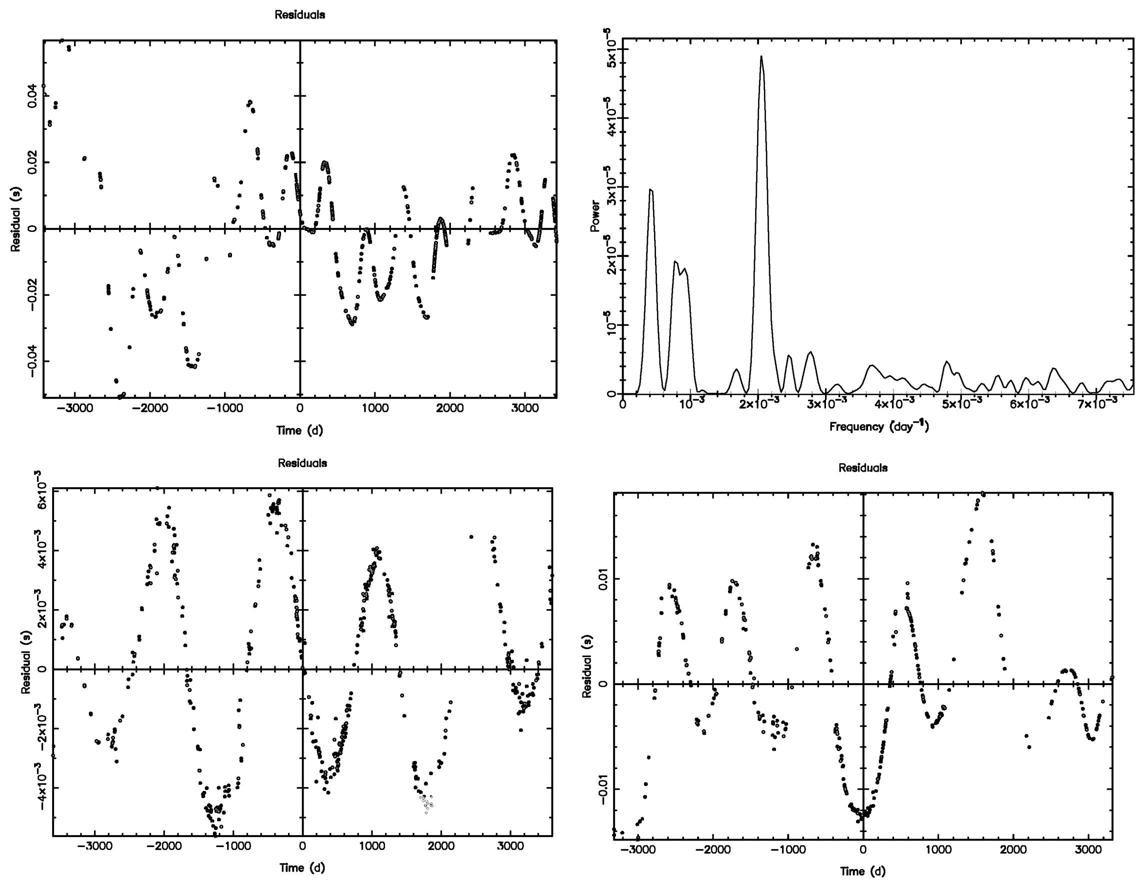

Fig. 6 (upper panel) The timing residuals (after a cubic term has been removed) and the Lomb-Scargle periodogram for PSR B1828−11.

Pulsars are known to have strong magnetic fields. Variations in the outer magnetospheres of pulsars that gives rise to changes in the braking torque will lead to a random walk in rotational frequency. However, Cheng (1987) showed that even for pulsars with stable outer magnetospheres the low-frequency component of timing noise could come from sudden changes of the braking torque arising from pertubations caused by microglitches. Candidates for such processes include those with excess noise power at low freqencies and blue (or white) noise at high frequencies.

4.2 Orbital Companions

Many pulsars are known to be in binary systems and PSR B1257+12 is known to have at least three planetary companions. Any unmodelled companions will produce orbital effects that can be determined by searching for periodic signals in the timing residuals (e.g. Bailes, Lyne & Shemar 1993; Cordes 1993). As pointed out by Gong (these proceedings), it may be possible for the Keplerian orbital parameters to be undetected, but over long dataspans long-term post-Newtonian effects such as the advance of periastron may be detectable. The effects of an asteroid-belt (or any cloud of particles around a pulsar) will also produce “timing-noise”-like behaviour. Recently, is has been shown that it may be possible to disprove such a model for timing noise by studying the ensemble averaged correlation between pairs of pulsars (Jenet, private communication).

4.3 Extrinsic Models

It is also expected that terrestrial clock errors, inaccuracies in the solar system ephemeris and even gravitational waves will be affecting pulsar timing residuals. However, for these effects, the observed features in the timing residuals will be correlated between different pulsars: for clock errors all pulsars will be correlated, a dipolar signature will be found for inaccuracies in the planetary ephemeris and for gravitational waves the zero-lag correlation between different pulsars versus the angle between the pulsars on the sky has a well-determined form (Jenet et al. 2005).

5 CONCLUSIONS

We have provided a basic overview of the features seen in the timing residuals of both the young and the millisecond pulsars. Full details of the Jodrell Bank dataset will be presented shortly in another paper.

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