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# Timing Noise analysis of HartRAO pulsars: Possible mode switching in the magnetosphere of PSR J1326-5859

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Timing noise in long-term pulsar timing residuals is challenging our understanding of the present pulsar model and forms part of several key science projects, including the detection of GWs and the development of next-generation instruments for pulsar astronomy. We investigate the timing noise phenomena in PSR J1326-5859 that was observed with the 26m HartRAO radio telescope for several decades. One explanation for timing noise is mode switching in the magnetosphere of the pulsar. In this paper we investigate the possible mode switching seen in the spin-down evolution and the pulse shape parameters of PSR J1326-5859. We also search for possible correlations between the parameter data sets.

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## 1. Introduction

Pulsars are considered to be stable cosmic clocks [1], however long-term and single pulse observations reveal that our theoretical picture of pulsars is incomplete. Pulsar timing is becoming ever more complex and accurate with modern receivers, backends and processing algorithms. The phenomena of timing noise as seen in some of the long-term pulsar timing residuals are challenging the current pulsar models and some novel ideas are being put forward to challenge the concept of timing noise [2, 3, 4], these include: linking timing noise to activities in the magnetosphere of the pulsar and ultimately to fundamental processes such as precession and the pulsar emission mechanisms. Resolving timing noise as a limiting noise factor can ultimately influence the accuracy of pulsar timings arrays [5]. The process of modeling timing noise can help us to improve the current pulsar model.

Recent observations [6] suggest some pulsars that show quasi-periodical timing noise structures in timing residuals display the phenomena of sharp changes in their spin-down that could also be accompanied by changes in the pulse profiles. It has been pointed out in [3] that some of the pulsars reported in [6] show systematic and recurring switching (e.g. PSRs B1540-06, B1642-03, B1826-17 and B1828-11) and that it could be linked to other dynamical phenomena such as precession and glitching.

In this paper we investigate the possible mode switching seen in long-term timing residuals of PSR J1326-5859 and we try to link the observations to possible models.

## 2. Calculating the spin-down evolution of PSR J1326-5859

To calculate the spin-down evolution ($\dot{\nu}$) of PSR J1326-5859, we reconstructed the timing noise signature using a Gaussian process made available in the form of the Gaussian Process in Python (GaPP) code [7], similar work was done and initialized by [4]. This type of fitting procedure ensures that the second derivative of the reconstructed signature is calculated in a natural way without the dependence of assumptions such as step length, see Fig. 1. A list of residuals and times of arrival (TOA) errors was produced for the total data set using the TEMPO2 code [8]. These residuals and TOA errors serve as input for the GaPP code. It must be noted that the reconstructed Gaussian signature retains the attribute of being n-times differentiable.

One important part of the Gaussian process is the optimization of the step length ($l$). The parameters for the Gaussian process were optimized to be $l = 232$ days and $Var(x) = 2.8 \times 10^{-2}$. The calculation of these parameters were done by keeping in mind the TOA errors associated with the data. The errors associated with the data influence the optimization process of the step length in the kernel:

$$k(x,x') = \sigma^2 \exp\left(-\frac{(x-x')^2}{2\ell^2}\right). \tag{2.1}$$

Here $(x,x')$, $\sigma^2$ and $l$ represent two neighboring points, the variance and the step length of the Gaussian kernel.

PoS(HEASA2015)030

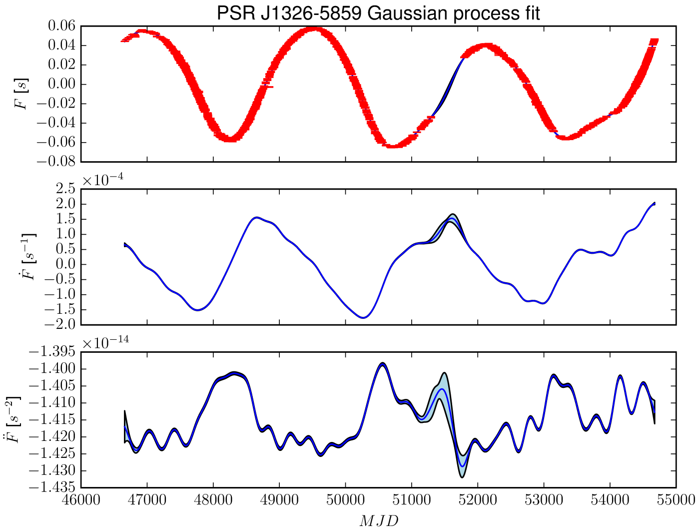

**Figure 1:** Timing residuals of PSR J1326-5859 showing a timing noise signature that is quasi-periodic, together with the first and second derivatives. The break in the residuals (MJD 51300-51700) was due to telescope maintenance. The light tinted band represents the error band. The scaling of $\dot{\nu}$ arises through the process of partial derivatives with time, see [4].

## 3. Interpreting the spin-down evolution of PSR J1326-5859

The timing noise signature seen in PSR J1326-5859 is unlike the near perfect periodical timing residuals that are predicted by models of precession or binary companions. However, it remains a premature assumption that precession [3] does not participate in the observed mode switching of pulsars [6].

The second derivative of the Gaussian reconstructed quasi-periodical timing residuals leads to abrupt mode switching that can be seen in the spin-down evolution of PSR J1326-5859, see Fig.1. There exists a clear change in the spin-down evolution after MJD $= 51000$. To better understand the variations seen in the spin-down evolution ($\ddot{\nu}$) of PSR J1326-5859, we performed a Ricker wavelet (Mexican hat wavelet) analysis on the data, see Fig.2. Using the wavelet spectra, we see a dominant variation present in most of the data set that is seen as the red, yellow and light blue contours. Wavelet analysis decomposes a time series (the data) into time/frequency space simultaneously. One gets information on both the amplitude of any periodic signals within the data, and how this amplitude varies with time. The wavelet analysis algorithm will typically produce contours that span the whole data set if any periodical variations are hidden in the data set.

Mode switching in the magnetosphere of the pulsar can also be linked to changes in the average pulse profile due to changes in the emission mechanisms (see PSRs J2043+2740, B2035+36, B1828-11, B0740-28, B1540-06 and B1822-09 in [6]). Unfortunately, no high resolution temporal stacking of the pulses could be achieved due to the low signal to noise ratio of the integrated pulses (PSR J1326-5859 is a 10 mJy source). To achieve the desired temporal stacking resolution, we will need average pulse profiles from more sensitive radio telescopes. Furthermore, extra timing

PoS(HEASA2015)030

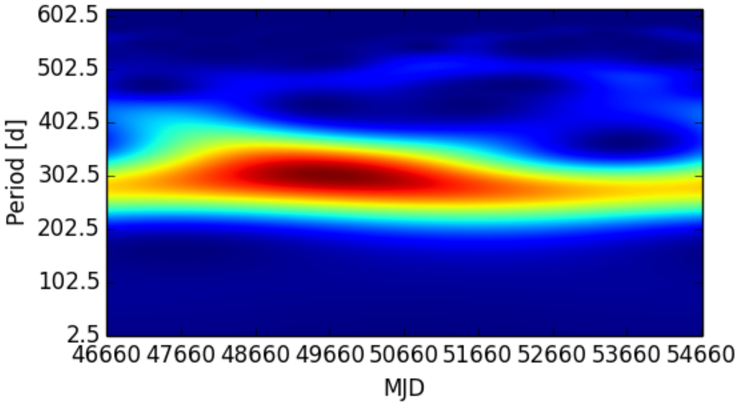

**Figure 2:** Ricker wavelet analysis of the spin-down evolution of PSR J1326-5859. Pure periodic variations in the data cannot be assumed and therefore wavelet analysis can be considered to be a better period finding method than Lomb-Scargle analysis (in this case, see [6] for more detail).

PoS(HEASA2015)030

residuals and high signal-to-noise ratio (SNR) pulses (with polarization profiles) will enable the search for correlations between the magnetospheric activity and any changes in the pulse profiles.

At this point we can introduce some novel models that were suggested recently [3] as a possible explanation for the mode switching seen in a number of millisecond pulsars [6]. These models are based on two fundamental attributes of the pulsar itself: firstly, there exists some deformation of the star (this is beneficial to both models of precession and gravitational wave detection) and secondly, the observed mode switching retains memory of the previous state. Both the latter arguments support some underlying precession driven mechanism acting as a clock that smoothly and repetitively induces a wobble angle that could change the conditions of the magnetosphere, hence the precession and mode switching of the pulsar could be phase-locked.

## 4. Conclusions and future work

It is suggested that the timing noise observed in millisecond pulsars can be modeled as mode switching in the magnetosphere of the pulsar [6]. Furthermore, the observed mode switching could also possibly be linked to the processes of precession and glitching [3].

It will be an intensive observational campaign to link pulsar moding with precession, but it will be beneficial to understand timing noise and to improve the sensitivity of the pulsar timing arrays. It also remains a premature statement that the model for timing noise consists of only mode switching, since we know that there could be several other factors that influence the spin-down or emission mechanisms of the pulsar. Timing noise signatures are normally seen in some pulsars with data spanning several decades. The population of glitchers and pulsars that exhibit timing noise, is interwoven (see Fig.3).

A possible way forward for timing noise analysis could be to construct models that include both the appropriate mode switching and some degree of precession (this was done to some extent in [6]). The precession component of the model does not need to be detectable in amplitude but

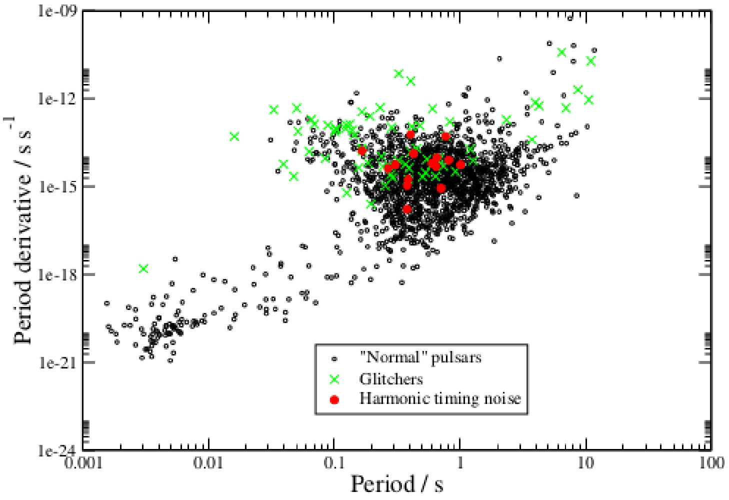

**Figure 3:** $P$-$\dot{P}$ diagram for the pulsar population. The diagram also contains pulsars that show glitch and timing noise activity. Adopted from [3].

could just switch the magnetosphere from one state to the other [3] (assuming that the magnetosphere is delicately balanced between two magnetospheric states). From the observational point of view, if timing noise is seen in pulsar timing residuals then a long baseline data set exists. To compliment this extended data set we suggest high quality Stokes profiles for different temporal regions that can be used to track polarization changes throughout the different observed modes. Tracking the correctly calibrated polarization swing of Stokes profiles across different temporal regions of the spin-down evolution of the pulsar could allow for a better campaign to correlate events in the spin-down and magnetosphere of the pulsars.

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PoS(HEASA2015)030

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PoS(HEASA2015)030