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Kinematic effects on high order spin frequency derivatives

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Abstract. The radial velocity of a pulsar induces the Doppler effect on its intrinsic spin properties. In particular, it can generate a contribution to the frequency second derivative. We estimated this effect for each of the International Pulsar Timing Array pulsars. We also assessed the possibility of measuring the frequency second derivative in the observational data.

Keywords. Pulsar timing, radial velocity, frequency derivative

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1. Introduction

The pursuit of even higher precision pulsar timing, e.g. the International Pulsar Timing Array (IPTA) (Verbiest *et al.* (2016)), to detect gravitational waves and/or to improve tests of gravity, requires us to consider many effects which can influence the pulse arrival times. The influence of the motion of the pulsar through the Galaxy is an important contribution to the observed arrival time. The proper motion induces a quadratically increasing annual sinusoid in the residuals and for most millisecond pulsars is easily measured. It was recognised by Shklovskii (1970) that the proper motion can affect the observed frequency derivative of the pulsar. To date, apart from optically, and spectroscopically, identifying a companion to a pulsar, it is not possible to measure the radial velocity of a pulsar. Here we will show how the radial velocity can induce a so-called second-order Shklovskii effect on the observed frequency second derivative.

2. The amplitude of the second-order Shklovskii effect

The apparent spin frequency observed for a pulsar with an intrinsic spin frequency of f_0 is $f = f_0(1 - v_\mathrm{r}/c)$, where v_r is the radial velocity of the pulsar and c is the speed of light. Differentiating this expression twice, one can find the contribution to the frequency second derivative from the radial velocity to be $\ddot{f}_\mathrm{shk}/f = 3v_\mathrm{r}\mu^2/c$, where μ is the proper motion of the pulsar, see Phinney (1992) and van Straten (2003).

Currently, in the list of IPTA pulsars, only four pulsars J1012+5307, J1024−0719, J1738+0333, J1909−3744 have measured v_r†. To make an estimation of the amplitude of $\ddot{f}_\mathrm{shk}$ for the pulsars without a measured radial velocity, we followed Hobbs *et al.* (2005) to assume $v_\mathrm{r} = 2\mu d/\pi$, where d is the distance to the pulsar. We computed $\ddot{f}_\mathrm{shk}/f$ for IPTA

† These radial velocities were measured via the optical spectrum of the corresponding pulsar companions.

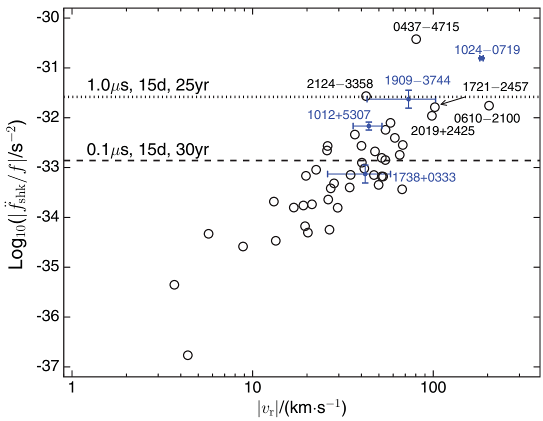

Figure 1. The predicted $\ddot{f}_{\rm shk}/f$ for IPTA pulsars. The pulsars which have measured radial velocities are shown in blue dots with the error bars, while the pulsars whose radial velocity are computed from $v_{\rm r} = 2\mu d/\pi$ are represented by the black circles. The dotted and the dashed lines represent the measurement uncertainties of two proposed observing scenarios.

pulsars by using the pulsar proper motions and the distances‡ reported in Desvignes *et al.* (2016) and Reardon *et al.* (2016). The results are shown in Fig. 1.

3. What are the prospects of measuring $\ddot{f}_{\rm shk}$

The possibility of measuring $\ddot{f}_{\rm shk}$ can be estimated by comparing the value of this term with the corresponding measurement uncertainty. Ignoring the timing noise for now, in an observing scenario where the pulsars are observed every Δt days with the same timing precision of $\sigma_{\rm rms}$ μs over T years, the measurement uncertainty $\sigma(\ddot{f})$ is found to be $\sigma(\ddot{f})/f \propto \Delta t^{1/2}\sigma_{\rm rms}/T^{7/2}$. We assumed two observing scenarios: $\sigma_{\rm rms} = 1.0$ μs, $\Delta t = 15$ days, $T = 25$ years and $\sigma_{\rm rms} = 0.1$ μs, $\Delta t = 15$ days, $T = 30$ years. The corresponding measurement uncertainties are indicated by the dotted and dashed lines respectively in Fig. 1.

As shown in Fig. 1, some pulsars like PSR J0437-4715 and PSR J1024-0719 have significant $\ddot{f}_{\rm shk}$ that may be measurable. With the continued improvement of timing performance (dashed line), more and more pulsars will have measurable $\ddot{f}_{\rm shk}$. However, the presence of timing noise and the $\ddot{f}$ contribution from other kinematic effects may affect the prospects for detecting $\ddot{f}_{\rm shk}$ and these aspects will be investigated in future work.

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‡ We used parallax based distances or the distances obtained according to the dispersion measurements and the NE2001 electron distribution model.

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