Astronomy in Focus, XXIXB, Focus Meeting 14
XXIXth IAU General Assembly, August 2015
Piero Benvenuti, ed.

doi:10.1017/S1743921316005500

Search for Ultralight Scalar Dark Matter from Pulsar Timing

Konstantin Postnov[1] **and Nataliya Porayko**[2]

[1]M.V. Lomonosov Moscow State University, Faculty of Physics, and Sternberg Astronomical Institute
email: pk@sai.msu.ru

[2]M.V. Lomonosov Moscow State University, Faculty of Physics, and Max Planck Institute for Radio Astronomy, Bonn
email: porayko.nataliya@gmail.com

Abstract. We perform a Bayesian analysis of pulsar-timing residuals from the NANOGrav pulsar-timing array to search for a specific form of stochastic narrow-band signal produced by oscillating gravitational potential (Gravitational Potential Background) in the Galactic halo. Such oscillations arise in models of warm dark matter composed of an ultralight massive scalar field ($m \simeq 10^{-23}$ eV). The propagation of an electromagnetic signal from a pulsar through the time-dependent spacetime will leave an imprint in the pulsar timing, much like a gravitational wave. From the physical point of view, this is the classical Sachs-Wolfe effect. A distinctive feature of the pulsar-timing residuals due to GBP produced by a variable scalar field is that the amplitude of the TOA residuals should be independent of the pulsar location in the sky. In the monochromatic approximation, the stringent upper limit (95% C.L.) on the variable gravitational potential amplitude is found to be $\Psi_c < 1.14 \times 10^{-15}$, corresponding to the characteristic strain $h_c = 2\sqrt{3}\Psi_c < 4 \times 10^{-15}$ at $f = 1.75 \times 10^{-8}$ Hz. In the narrow-band approximation, the upper limit of this background energy density is $\Omega_{GPB} < 1.27 \times 10^{-9}$ at $f = 1.75 \times 10^{-8}$ Hz. These limits are an order of magnitude higher than the expected signal amplitude assuming all Galactic dark matter is made of such scalar particles. The applied analysis of the pulsar-timing residuals can be used to search for any narrow-band stochastic signals with different correlation properties. As a by-product, parameters of the red noise present in four NANOGrav pulsars were found.

Keywords. pulsar timing, ultralight scalar field, Bayesian approach

1. Introduction

Pulsar timing arrays (PTAs) are used to detect GWs in the low-frequency (nHz) range (Sazhin 1978; Detweiler 1979; Foster & Backer 1990). Here we use PTA data to search for a Gravitational Potential Background (GPB) formed by hypothetical ultralight scalar field in the halo of our Galaxy, which can be a viable warm dark matter candidate (Khmelnitsky & Rubakov 2014). The oscillating pressure of this field induces variations of gravitational potentials with nHz frequencies which could be probed with PTA technique in a similar way as traditional GWs.

2. Pulsar-timing response and method of data analysis

The pulses from pulsars moving in time-dependent gravitational potentials Φ and Ψ are shifted due to the Sachs-Wolfe effect. Due to small virial velocity v in our Galaxy, the frequency broadening of the signal $\Delta f/f = (v/c)^2 \simeq 10^{-6}$ is much lower than frequency resolution of PTAs. Thus, the signal can be treated as a monochromatic line

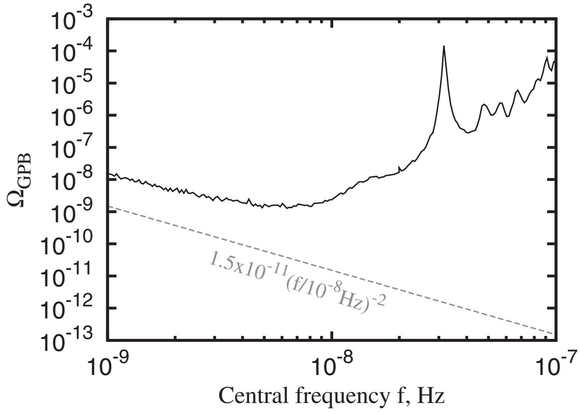

Figure 1. Upper limit on the amplitude of variable GPB Ψ_c as a function of the central frequency f. Shown is the case of the narrow-band approximation (black line) for the 95% confidence level.

or a stochastic narrow-band noise. In the first case the form of the residuals is

$$R(t) = \frac{\Psi_c}{2\pi f}\left\{(\sin(2\pi f t + 2\alpha(\mathbf{x}_e) - \sin(2\pi f(t - D/c) + 2\alpha(\mathbf{x}_p))\right\},$$

where D is the distance to the pulsar, $\alpha(\mathbf{x}_e), \alpha(\mathbf{x}_p)$ are the field phase on Earth and at the pulsar, respectively, Ψ_c is the variable potential amplitude to be constrained from PTA timing analysis. In the narrow-band approximation, the expected signal is stochastic with power contained within the frequency band δf around the central frequency f. The corresponding covariance matrix is:

$$C_{\rm GPB}(\tau_{ij}) = \zeta_{\alpha\beta}\frac{\Psi_c^2 \delta f}{\pi^2 f^3}\cos(f\tau_{ij}).$$

In both cases we have taken into account the red intrinsic pulsar noise. The resultant covariance matrix has the form: $C = C_{\rm WN} + C_{\rm RN} + C_{\rm GPB}$.

In contrast to GWB, the angular correlation coefficient $\zeta_{\alpha\beta} = 1/2(1 + \delta_{\alpha\beta})$ for GPB is monopole and does not depend on angular separations between pulsars which makes GPB similar to clock errors. However, broad-band red-colored nature (Tiburzi *et al.* 2015) makes it possible to distinguish clock errors from the considered GPB.

The Bayesian approach (van Haasteren & Levin 2013) was applied to real NANOGrav dataset (Demorest *et al.* 2013) from 12 pulsars. The results are shown in Figure 1.

The best upper limit is $\Omega_{\rm GPB} < 1.27 \times 10^{-9}$ at $f = 6.2 \times 10^{-9}$ Hz, which corresponds to $\Psi_c < 1.5 \times 10^{-15}$, an order of magnitude higher than the predicted value (Porayko & Postnov 2014). To obtain more stringent limits, pulsars with low red noise component and longer observational timespan should be used.

Acknowledgement

The work is supported by RSF grant 14-12-00203.

References

Demorest, P. B., Ferdman, R. D., Gonzalez, M. E., *et al.* 2013, *ApJ*, 762, 94
Detweiler, S. 1979, *ApJ*, 234, 1100
Foster, R. S. & Backer, D. C. 1990, *ApJ*, 361, 300
Khmelnitsky, A. & Rubakov, V. 2014, *J. Cosmol. Astropart. Phys.*, 2, 019

https://doi.org/10.1017/S1743921316005500 Published online by Cambridge University Press

Porayko, N. & Postnov, K., 2014, *Phys. Rev. D.*, 90, 062008
Sazhin, M. V. 1978, *SvA*, 22, 36
Tiburzi, C., Hobbs, G., Kerr, M., *et al.* 2015, *MNRAS*, in press; arXiv:1510.02363
van Haasteren, R. & Levin, Y. 2013, *MNRAS*, 428, 1147

https://doi.org/10.1017/S1743921316005500 Published online by Cambridge University Press