Pulsar Astrophysics the Next Fifty Years
Proceedings IAU Symposium No. 337, 2017
P. Weltevrede, B.B.P. Perera, L.L. Preston & S. Sanidas, eds.

doi:10.1017/S1743921317010018

Conquering systematics in the timing of the pulsar triple system J0337+1715: Towards a unique and robust test of the strong equivalence principle

N. V. Gusinskaia[1], **A. M. Archibald**[1], **J. W. T. Hessels**[1,2], **D. R. Lorimer**[3,4,5], **S. M. Ransom**[6], **I. H. Stairs**[7] and **R. S. Lynch**[5,4]

[1]Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands.
email: N.Gusinskaia@uva.nl

[2]ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands

[3]Dept. of Physics and Astronomy, West Virginia University, PO Box 6315, Morgantown, WV 26506, USA

[4]Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV 26505, USA

[5]Green Bank Observatory, Green Bank, WV 24944, USA

[6]National Radio Astronomy Observatory, Charlottesville, VA 22903, USA

[7]Dept. of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada

Abstract. PSR J0337+1715 is a millisecond radio pulsar in a hierarchical stellar triple system with two white dwarfs. This system is a unique and excellent laboratory in which to test the strong equivalence principle (SEP) of general relativity. An initial SEP-violation test was performed using direct 3-body numerical integration of the orbit in order to model the more than 25000 pulse times of arrival (TOAs) from three radio telescopes: Arecibo, Green Bank and Westerbork. In this work I present our efforts to quantify the effects of systematics in the TOAs and timing residuals, which limit the precision of an SEP test. In particular, we apply Fourier-based techniques to the timing residuals in order to isolate the effects of systematics that can masquerade as an SEP violation.

Keywords. gravitation, relativity, methods: data analysis, methods: statistical, methods: numerical, (stars:) pulsars: individual (PSR J0337+1715)

Einstein's strong equivalence principle (SEP) is a fundamental tenet of general relativity (GR): it postulates that gravitational interactions do not depend on the gravitational binding energy of self-gravitating bodies, and hence that gravitational mass (M_G) equals inertial mass (M_i), even for objects with strong gravity. Given the relation $M_G = (1+\Delta)M_i$, where Δ is a dimensionless parameter, the SEP states $\Delta = 0$. It holds only in GR and all plausible alternatives to GR violate the SEP at some level ($\Delta \neq 0$). A straightforward method of testing the SEP is to compare how two bodies that have different gravitational binding energies fall in the presence of an external gravitational potential. Thus, hierarchical triple systems are ideal test-beds for the SEP. If the SEP is violated ($\Delta \neq 0$), then the fractional difference in acceleration of the two bodies gives rise to excess eccentricity of their orbits in the direction of the external acceleration.

The only known millisecond radio pulsar in a hierarchical stellar triple system is PSR J0337+1715, which has two white-dwarf companions. The pulsar orbits an inner white dwarf (hereafter WD_i) every 1.6 days. In turn, this inner binary system orbits an

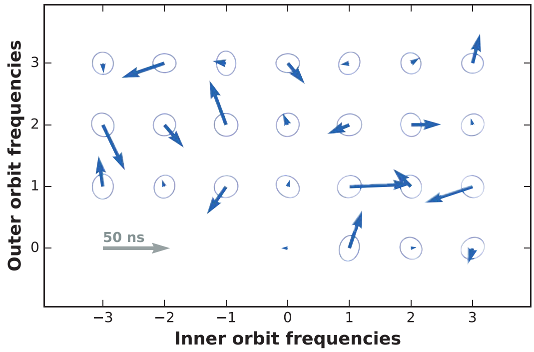

Figure 1. "Arrow plot" of the residuals of the full fit (blue arrows). The length of each arrow represents the amplitude A of the harmonic systematic in the data, whose phase is the combination of integer inner and outer orbital frequencies represented by values on the x and y axes, respectively (see Eq. 0.1). The direction of each arrow is the phase offset. Ellipses represent uncertainties on the linear least--squares fit

outer white dwarf (hereafter WD_o) every 327 days. If the SEP is violated, the pulsar-WD_i binary would acquire an excess eccentricity in the direction of WD_o, keeping this orientation as it moves in its outer orbit. This effect would lead to periodic changes in the TOAs with an exact frequency of $(-2\,\varphi_i + 1\,\varphi_o)$, where (φ_i) and (φ_o) are the inner and outer orbital frequencies ($\varphi = 2\pi/P_{\rm orb}$). This signal can be detected in the residuals of a pulsar timing fit, and hence the value of Δ can be constrained (see A. M. Archibald *et al.*, this volume).

Ideally, the fitted value of Δ and its uncertainty would determine how well we constrain an SEP violation and whether GR is violated. However, fit uncertainties are only correct once we account for systematics in the residuals. Most importantly, such systematics could potentially masquerade as an SEP violation, especially if they have a similar frequency structure. To quantify this, we used a Fourier-based technique to search for systematics whose frequency is harmonically related to the inner and outer orbital frequencies, assuming that these systematics have the same origin and, thus, roughly the same amplitude as the one related to Δ with $(-2\,\varphi_i + 1\,\varphi_o)$ frequency.

Quasi-Fourier search: We perform a linear least-squares fit of the periodic signal to the residuals of the pulsar timing fit, in the form:

$$f(t) = A\,[\cos(k\varphi_i(t - T_{asc\,i}) + l\varphi_o(t - T_{asc\,o}));\, \sin(k\varphi_i(t - T_{asc\,i}) + l\varphi_o(t - T_{asc\,o})] \quad (0.1)$$

Here t represents the TOAs (in MJD), $T_{asc\,i}$ and $T_{asc\,o}$ are times of the ascending nodes of the inner and outer orbits, respectively, k and j are integer number of inner and outer orbital frequencies, and A is the amplitude of the harmonic systematic. As parameters of the fit, we use the amplitudes of a sinusoid and cosinusoid with the same frequency $[A_{cos}; A_{sin}]$. We fit these amplitudes to the residuals (and their uncertainties) provided by the pulsar timing fit. As a result, we measure the amplitude and phase of the signal at each frequency where $k \in [-3; 3]$ and $l \in [0; 3]$. This fitting process is analogous to the discrete two-dimensional Fourier-transform.

We performed our quasi-Fourier fit to all PSR J0337+1715 timing fit residuals (see blue arrows in Figure 1). Our results show that some periodic structures remain in our pulsar timing fit residuals that are not yet accounted for. The largest systematic that we found in our data has amplitude ≈ 50 ns, which is a factor of a few larger than our formal uncertainties.

The arrow that corresponds to the $(-2\,\varphi_i + 1\,\varphi_o)$ frequency is smaller than the fit uncertainty, which means that fitting absorbed any periodic structure in this frequency. However, other arrows have *not* been absorbed, and their lengths can be used to estimate the remaining systematics. Thus, the upper limit on Δ is set not by pulsar timing fit uncertainty but by the systematic contribution, which we estimate with our quasi-Fourier technique.

https://doi.org/10.1017/S1743921317010018 Published online by Cambridge University Press