Timing millisecond pulsars. II. The PSR J2016+1947 binary system.

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Abstract

We request 96 hours of telescope time to determine the timing ephemeris of the the 65-millisecond pulsar - white dwarf system PSR J2016+1947. It has the particularity of having the second longest orbital period known for such a system, 635 days, the first being a similar system now being timed at Arecibo, PSR J0407+16. The objectives are to determine the positional, rotational and orbital parameters to good accuracy, study the radio emission characteristics and timing precision achievable at several frequencies and study the implications of such binaries for theories of the formation of millisecond pulsars and their binary systems. This is probably the best binary system known to date (by a factor of five) for testing the Strong Equivalence Principle, a basic feature of all metric theories of gravitation (including General Relativity), in the strong field regime. The analogous test in the weak field limit is performed by the Lunar Laser Ranging experiments.

1 The Binary

PSR J2016+1947 was discovered by one of us (Navarro) at the Arecibo Observatory in an observation made in December 1997 as part of the Caltech drift-scan search made with the Carriage House 430-MHz line feed. The PSPM was used as a backend. It has been observed for about 700 days after that. Due to the very long orbital period, and to the lack of coverage for about half of the orbit, it it has been very difficult to determine the timing parameters so far. The best solution, still marred by possible rotation count ambiguities, yields the following parameters:

Name	PSR J2016+1947
α	$20^h\ 16^m\ 57.43(2)^s$
δ	+19° 47' 51.5(8)"
P	64.9403881791(7) ms
$\dot{P}$	–
DM	34 cm^{-3} pc
P_B	635.0255(18) days
x	150.77419(18) s
T_0	50913.8(3)
e	0.001478(9)
ω	95.79(14)°
m_c	0.29 M$_\odot$

The companion mass was calculated assuming a pulsar mass of 1.35 M$_\odot$ and an inclination of 90°.

It is not clear whether we have genuine phase connection, as there is a large gap in the data in 1998 (see Fig. 1). A second full orbit must be observed to make this clear. Therefore, the timing parameters could be well outside the error margins given in the table above. We note that even if we were sure of having achieved phase connection, the pulsar's period derivative ($\dot{P}$) cannot still be measured, because of correlations with the orbital parameters (orbital period P_B, projected semi-major axis of the orbit of the pulsar in light seconds $x \equiv a_l \sin i / c$, time of periastron T_0, eccentricity e and longitude of periastron ω). These correlations are sure to disappear by timing a full second orbit.

The timing correlations also affect the determination of the position, and make the determination of the proper motion a long-term project. This is one extra reason behind our time request. If the timing is extended to the 2002-2004 period, this will give us a baseline of seven years, which will probably be enough to make a good determination of the astrometry of the system.

2 Prospects for the timing

2.1 Orbital parameters and age of the system

As can be seen in Figure 2, the pulse profile is quite narrow, and the pulsar appears with excellent signal-to-noise ratio in a 40-second integration. Because of its scintillation, it has not been possible to determine the average flux density. Given the object's low Dispersion Measure (DM), the prospects for high-precision timing are good, mainly in view of the new capabilities available at the Arecibo Observatory, like the new L-wide receiver and the possibility of observing pulsars with a total bandwidth of 400 MHz using 4 WAPPs.

The determination of $\dot{P}$ will allow the determination of the characteristic age (τ_c) of the system. This will be very important for determining the system's age and constraining formation scenarios. The confirmation of the present value for the eccentricity is also very important, as the theories that describe the formation of millisecond pulsar (MSP) - white dwarf systems predict an eccentricity of the order of 1×10^{-3} [3]. The value derived so far seems to be in perfect agreement with the prediction.

The precise monitoring of the pulsar's rotation, after correction for the binary, motion might allow the detection of any low-mass companions, which include planets, as in the case of the triple system PSR B1620−26 in the globular cluster M4, which includes a white dwarf companion in a relatively wide of 191 days and a Jovian-sized plane in an orbit several decades long [4].

The Shapiro delay, an effect on arrival times of pulses at the Earth caused by the gravitational field of the companion object, depends on two quantities: the mass of the companion (m_c, the larger it is, the larger the effect) and the inclination of the binary i. Such measurements have been made before at Arecibo for the MSP/white dwarf binary PSR B1855+09 [2], and could in principle be made for PSR J2016+1947. In order to measure such an effect, the dispersion of the residuals would have to be at least ten times smaller than the present value of 45 μs. We intend to make the timing as precise as possible, in an attempt to detect such effects, but these are only likely to be detected if the inclination is near 90°.

2.2 Testing the Strong Equivalence Principle in the strong field regime

The PSR J2016+1947 system promises to excel as tool to test the Strong Equivalence Principle (SEP). This principle requires the universality of free fall, even for objects that have very significant gravitational self-energies. Therefore, both the pulsar itself, PSR J2016+1947, with its very large (negative) self-gravitation energy of about 15% of the total mass (depending on the equation of state for cold matter at high densities) and the white dwarf companion, with its negligible self-gravitational energy, should fall in the gravitational field of the Galaxy with the same acceleration. However, if the assumption of SEP is wrong, as postulated in many alternative theories of gravitation (i.e., if $|\Delta| = |1 - m_I/m_G| \neq 0$) the accelerations for the pulsar and the white dwarf will be different. The effect will be similar to that of a neutral atom under a strong electric field, which causes different accelerations on the nucleus and electrons, with the net effect of a polarization of the atom. In atomic physics, this is known as the "Stark" effect, the resulting polarization is more intense as the electrons are further from the nucleus. The equivalent "Nordtvedt" effect on an MSP / white dwarf binary is an increase in the eccentricity of the system, and it too becomes more pronounced for wider orbits.

The figure-of-merit for such a test is P_B^2/e [1], and it is higher for PSR J2016+1947 than for any other system with a known eccentricity, with the exception of the PSR B1800−27 binary system. However, the latter system is inadequate for such tests, as the pulsar's τ_c is of the order of a single Galactic orbit [5]. For an unambiguous interpretation of the low eccentricity (which, as mentioned previously, we aim to confirm), the system's age (which we also intend to determine from the pulsar's $\dot{P}$) has to be significantly larger than one Galactic orbit. Using all the binary systems that pass this criterion, a value of $|\Delta| < 0.004$ was obtained [5]. If a large τ_c is measured for PSR J2016+1947, then this pulsar is 5 times better for this test than the next best system (PSR J1713+0747, which has $\tau_c = 8.5\,\mathrm{Gyr}$). This would enable a limit for Δ of the order of 0.001. If the PSR J0407+16 binary system now being timed at Arecibo proves to have a low eccentricity, then the derived limit could again improve by a large factor.

The test here proposed is an analog of the Lunar Laser Ranging (LLR) experiment, with the exception that LLR tests SEP violation in the weak field limit.

3 Observations

We request a total of 96 hours over the next 3 years to time PSR J2016+1947. This is to be divided in 1-hour slots, which include about 15 minutes for setting the experiment and 45 minutes for observation. Because of its declination, the pulsar approaches zero zenith angle, where it cannot be tracked by the telescope. We prefer to observe the pulsar after this event (i.e., slightly after 20h 16m LST), as previous time is Galactic and therefore bound to be over-subscribed. We intend to devote most of time requested to observe PSR J2016+1947 at 430 MHz using the PSPM as a backend, exactly as used to time the pulsar so far; which is necessary for time continuity. However, we also plan to make observations at other frequencies to establish if 430 MHz is indeed the best timing band, and if the timing precision can be improved significantly at any other band.

References

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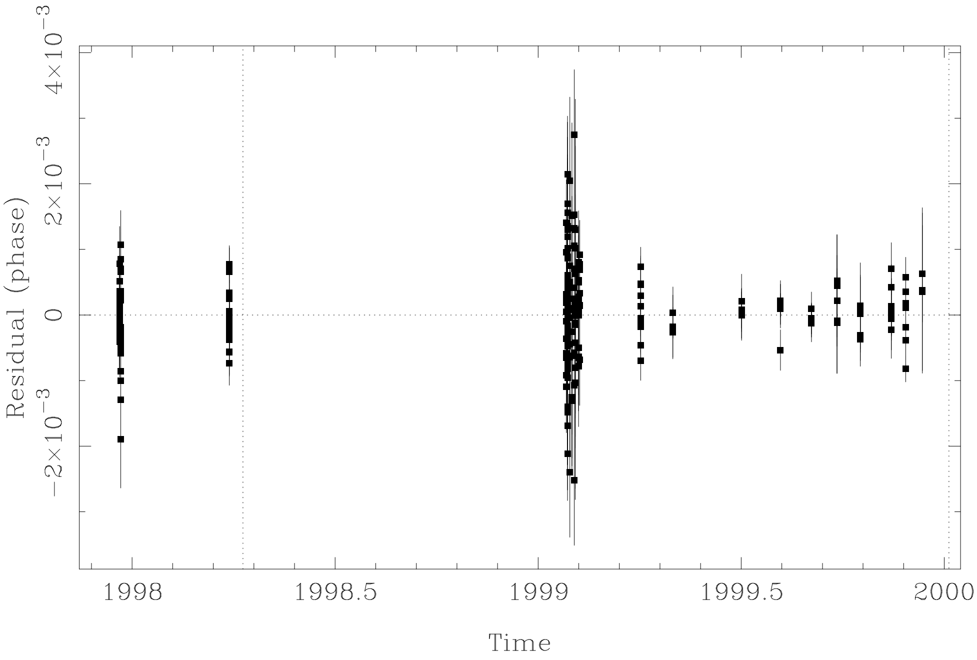

Figure 1: Timing residuals for PSR J2016+1947 as a function or date. The very small r.m.s. makes us believe that phase connection might have been achieved, but there is still a large gap in the data between early 1998 and 1999, so up to three phase rotations are allowed by the fitting in that interval. Times of periastron are marked with vertical dotted lines, there is no data for practically 180 degrees after periastron.

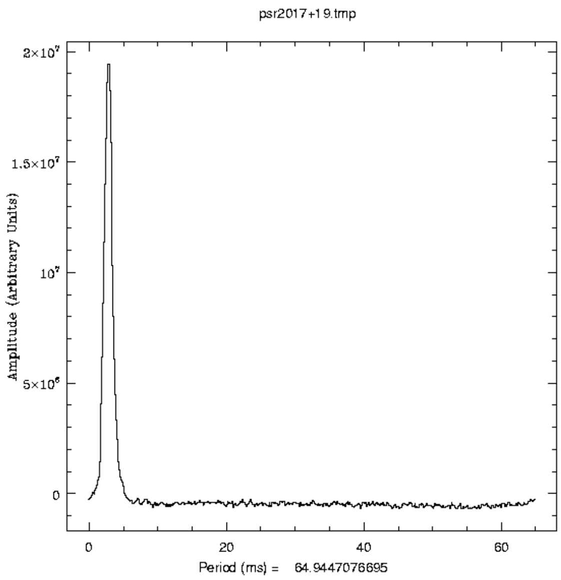

Figure 2: Pulse profile of PSR J2016+1947 for a 40-second integration at 430-MHz, obtained with the PSPM as a backend.