Observations of Post-Newtonian Timing Effects in the Binary Pulsar PSR 1913+16

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We report the latest results of timing measurements of the binary pulsar PSR 1913+16. Recent high-quality data have enabled us to measure the excess propagation delay of the pulsar signal caused by the gravitational field of the companion star; this result provides strong additional support for the simplest and most straightforward model of the system. The observed rate of orbital period decay is equal to 1.00 ± 0.04 times that expected from gravitational radiation damping.

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General relativity predicts that a pair of masses in mutual orbit should gradually spiral closer together as the system loses energy in the form of gravitational radiation. The binary pulsar PSR 1913+16 provides a uniquely suitable system[1] for testing this prediction quantitatively,[2–4] and results already published have shown that the orbital period is decreasing at the rate expected from damping by gravitational radiation.[5–8] In this Letter we report improved measurements of the orbital period decay, based on measurements through August 1983. In addition, we have detected an additional relativistic effect in the PSR 1913+16 system—an excess delay of the pulsar signal, caused by propagation through the gravitational field of the companion star. Measurement of this effect yields another redundant constraint on the already overdetermined parameters of the orbiting pair. The value of the new parameter is in excellent agreement with our earlier prediction.[7] The overall self-consistency of observable parameters now establishes, with a high level of confidence, that the measured decrease in orbital period is the result of gravitational radiation.

Our experimental data, obtained with the 305-m telescope at the Arecibo Observatory in Puerto Rico, consist of 5-min synchronous integrations of the pulsar wave form. Each integration is tagged with the Coordinated Universal Time (UTC) to an accuracy of approximately 1 μs. We determine a "pulse arrival time" for each integrated profile by measuring its phase offset relative to a standard profile (obtained by averaging many hundreds of integrations), and adjusting the nominal UTC accordingly.[7,9] Approximately 3300 such measurements have been accumulated since 1974; the standard errors vary from about 300 μs in the early data to approximately 20 μs in the most recent observations.

The observed pulse arrival times—expressed in units of atomic time as measured by an Earth-based clock—depend on the rotation rate of the neutron star, on the motions of the observatory in the solar system and the pulsar in its orbit, and on relativistic effects involving the accelerations and changes in gravitational potential at both ends of the Earth-pulsar path. The data are used as inputs in a multiparameter least-squares solution for four classes of parameters: (1) the pulsar rotation phase and its time derivatives; (2) the celestial coordinates of the pulsar, measurable because of the large (~ 1000 s) annual variations caused by the Earth's orbital motion; (3) five "classical" orbital elements for the pulsar, essentially determined from the large (~ 4 s) first-order effects of the pulsar's orbital motion; (4) four "relativistic" orbital parameters, measurable in this system because of the extreme conditions $[v/c \sim (GM/c^2R)^{1/2} \sim 10^{-3}]$ that are present.

Classification of the parameters of the orbiting system as "classical" or "relativistic" is done only as a matter of convenience in discussing them. It is well known that a purely Newtonian treatment of data like ours can be used to determine just five orbital parameters; a relativistic analysis, carried out to a precision consistent with present experimental uncertainties, can determine a total of nine. Following essentially the procedure outlined by Blandford and Teukolsky[10] and Epstein,[11] we have adopted a set of nine orbital parameters, the first five of which have the same names, and essentially the same meanings, as their Newtonian counterparts. Measured values of these five parameters are given in the first part of Table I.

The four relativistic parameters listed in Table I are $\langle\dot{\omega}\rangle$, the average rate of rotation of the orbital ellipse within its plane; γ, the amplitude of delays caused by variations in gravitational red shift and time dilation as the pulsar traverses its elliptical or-

TABLE I. Orbital parameters of PSR 1913+16.

(a) "Classical" parameters	
Projected semimajor axis	$a_p \sin i = 2.341\,85 \pm 0.000\,12$ light sec
Eccentricity	$e = 0.617\,127 \pm 0.000\,003$
Orbital period	$P_b = 27\,906.981\,63 \pm 0.000\,02$ s
Longitude of periastron	$\omega_0 = 178.8643 \pm 0.0009$ deg
Julian ephemeris date of periastron and reference time for P_b and ω_0	$T_0 = 2442\,321.433\,208\,4 \pm 0.000\,001\,2$
(b) "Relativistic" parameters	
Mean rate of periastron advance	$\langle \dot{\omega} \rangle = 4.2263 \pm 0.0003$ deg yr^{-1}
Gravitational red shift and time dilation	$\gamma = 0.004\,38 \pm 0.000\,12$ s
Orbital period derivative	$\dot{P}_b = (-2.40 \pm 0.09) \times 10^{-12}$ s s^{-1}
Orbital inclination	$\sin i = 0.76 \pm 0.14$

bit; $\dot{P}_b$, the time derivative of orbital period, which we attribute to the emission of gravitational waves; and $\sin i$, where i is the angle of inclination between the plane of the orbit and the plane of the sky. The last parameter, although cast in terms of geometry, actually specifies the excess delay caused by propagation of the pulsar signal through the gravitational field of the companion. This effect is the phenomenon first postulated by Shapiro[12] and observed in solar system distance measurements.[13] In the PSR 1913+16 system the orbital variation in the gravitational propagation delay as seen from Earth is approximately 25 μs.

Unambiguous detection of the propagation delay term, and consequently measurement of $\sin i$, is made difficult by the large covariances between it and several of the other orbital parameters. Our success was made possible by the high quality of the most recent data and by the recognition of Haugan[14] that the rate of precession of the orbital ellipse in its plane, $\dot{\omega}$, is not constant but varies with the separation of the two stars. The effect on pulse arrival times is of the same order as the gravitational propagation delay and the small post-Newtonian [order $(v/c)^3$] corrections already explicitly included in the analysis.[11] We now include all of these effects in the model, and we believe that our analysis is complete and self-consistent at the microsecond level. Our measurement of $\sin i$ marks the first successful observation of gravitational propagation delay outside the solar system. More importantly, it furnishes a new and independent test of the clean and uncomplicated nature of this binary pulsar system.

The uncertainties listed for the parameter estimates in Table I are between two and four times the formed standard deviations. They are based on a

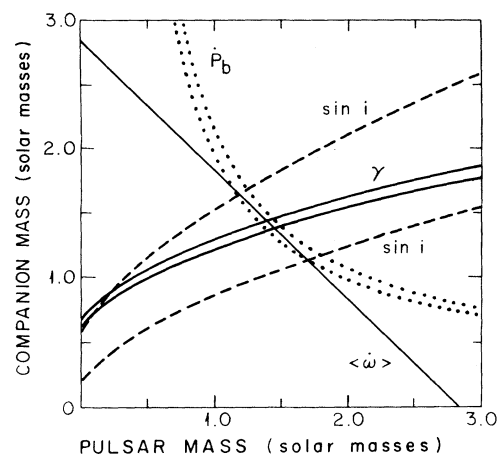

FIG. 1. Families of curves showing how the stellar masses in the PSR 1913+16 system are constrained by the measured values (and estimated errors) of parameters $\langle \dot{\omega} \rangle$, γ, and $\sin i$. (The uncertainty in $\langle \dot{\omega} \rangle$ is less than the width of the sloping straight line.) The fourth pair of curves bracket those mass values that would, according to general relativity, cause the system to emit enough gravitational radiation to explain the observed orbital period derivative $\dot{P}_b$. The simplest model of the system is in good accord with the data if both the pulsar and the compansion star have approximately the Chandrasekhar limiting mass, 1.4 solar masses.

cautious assessment of the range of variation observed for each parameter in a number of different test solutions, and on our semiquantitative judgments about the possible presence of low-level systematic errors in the data. Further details of the error estimation process are contained in Ref. 9.

The simplest model of the PSR 1913+16 system consistent with the observations treats it as a pair of compact masses with negligible quadrupole moments and no significant nonrelativistic dissipative mechanisms. The pulsar itself clearly satisfies these conditions, and the most plausible evolutionary scenarios[4,7] imply that the companion should also be a compact object. If this model is valid, then seven orbital parameters are enough to describe it. Our nine-parameter solution then overdetermines the astrophysical quantities and provides a true test of gravitation theory.

A reasonable choice for a minimal set of parameters would be to replace the last four in Table I with the masses, m_p and m_c, of the pulsar and companion star. The four observable quantities depend on the masses according to the equations (see Ref. 7 and references therein)

$$\dot{\omega} = 3G^{2/3}c^{-2}(P_b/2\pi)^{-5/3}(1-e^2)^{-1}(m_p+m_c)^{2/3} , \tag{1}$$

$$\gamma = G^{2/3}c^{-2}e(P_b/2\pi)^{1/3}m_c(m_p+2m_c)(m_p+m_c)^{-4/3} , \tag{2}$$

$$\sin i = G^{-1/3}c(a_p \sin i/m_c)(P_b/2\pi)^{-2/3}(m_p+m_c)^{2/3} , \tag{3}$$

$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2}(1+\tfrac{73}{24}e^2+\tfrac{37}{96}e^4)m_p m_c(m_p+m_c)^{-1/3} \tag{4}$$

Figure 1 shows graphically the values of m_p and m_c that are consistent with the observations and with Eqs. (1)–(4) taken one at a time. It is evident that all four measured parameters are satisfied simultaneously if both masses are close to 1.4 solar masses. At present levels of accuracy the $\sin i$ parameter does not tighten constraints on the masses very much, but it is significant that its measured value is fully consistent with expectations based on the other parameters, using the simplest model of the system.

The most profound result of our observations remains the measurement of orbital period decay at just the rate expected from gravitational radiation damping. In order to state this result succinctly and quantitatively, Eqs. (1)–(3) can be used to solve (by least squares) for the best-fitting values of the masses m_p and m_c. Using the parameter values quoted in Table I, and correctly propagating errors and taking note of the parameter covariances, we obtain the results $m_p = 1.42 \pm 0.03$ and $m_c = 1.40 \pm 0.03$ solar masses. When these values are inserted in Eq. (3), we obtain the predicted rate of orbital period change $\dot{P}_b = (-2.403 \pm 0.002)\times 10^{-12}$ s s^{-1}, in excellent agreement with the observed value $(-2.40 \pm 0.09)\times 10^{-12}$. As we have pointed out before[6,7] most relativistic theories of gravity other than general relativity conflict strongly with our data, and would appear to be in serious trouble in this regard. It now seems an inescapable conclusion that gravitational radiation exists as predicted by the general relativistic quadrupole formula.

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