Binary Pulsars and Evidence for Gravitational Radiation

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ABSTRACT

A discussion of binary pulsars and their utility in providing evidence for gravitational radiation is presented. The results focus on the binary pulsar PSR 1913+16, as it was the first discovered and most studied. Assuming general relativity is correct, the masses of the pulsar and its companion are determined to be $m_1 = 1.4414 \pm 0.0002$ and $m_2 = 1.3867 \pm 0.0002$ times the mass of the Sun. The decay rate of the orbital period due to gravitational radiation emission is measured to be 1.0013 ± 0.0021 times the general relativistic prediction, providing strong evidence for the existence and nature of gravitational radiation.

1. INTRODUCTION

Prior to the discovery of binary pulsars all tests of general relativity and other theories of gravity were restricted to the weak-field, slow-motion interactions present within the solar system. In this limit nonlinearities and the predicted effects of gravitational radiation are negligible. Therefore it was greatly desired to find or create a system sufficiently relativistic to extend the experimental tests of general relativity and other competing theories of gravity. These tests were made possible in 1975 with the discovery of a binary pulsar system by Hulse and Taylor[1].

Binary pulsars are composed of at least one pulsar and a companion massive object. Pulsars regularly emit detectable pulses of radiation and thereby serve as extremely stable clocks. The masses of the two bodies are often on the order of the solar mass and they rapidly orbit each other. By virtue of their large mass and rapid orbits, binary pulsars provide the experimentalist the opportunity to test the predictions of general relativity in the strong-field, rapid motion limit. Consequently, great effort has been put forth to discover and characterize many pulsar systems. Figure 1 shows a celestial map[2] of all known pulsars as of July 1994.

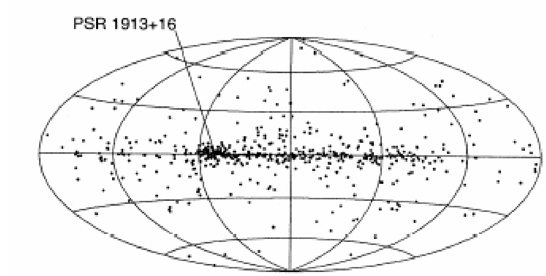

Fig. 1. Distribution of 558 pulsars in Galactic coordinates. The center of the galaxy is in the middle, and longitude increases to the left.

One of the fundamental predictions of general relativity is the emission of quadrupolar gravitational radiation. However, being a relativistic effect, gravitational radiation emission is only significant in the relativistic limits of strong gravitational fields and rapid accelerations. These limits do not exist in the solar system and therefore gravitational radiation was undetectable within the confines of the solar system.

Binary pulsars, on the other hand, are sufficiently relativistic that gravitational radiation emission is expected to be significant. Gravitational radiation has yet to be detected directly. However, gravitational radiation carries both energy and angular momentum away from the orbiting bodies. These losses produce a decrease in the orbital period and eccentricity of the binary system. By observing time variations in the pulsar period it is possible to determine both the slow-down rate of the orbit and the change in eccentricity[3,4,5,6].

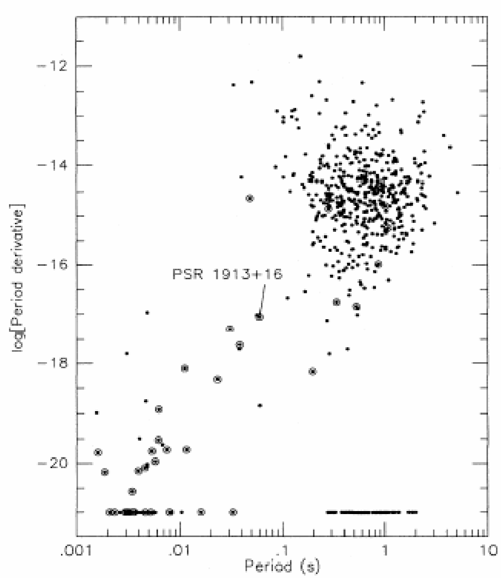

Fig. 2. Spin-down rates and periods of pulsars observed before July 1994. Pulsars known to be in binary systems are denoted by larger circles around the dots. Symbols aligned near the bottom represent pulsars for which the orbital period decay has yet to be measured.

The decay of the orbital period of a binary pulsar system may serve as an indirect test of theoretical predictions for gravitational radiation emission. Figure 2 illustrates the observed spin-down rate and period of a collection of pulsars[2]. Binary systems are marked by larger circles around dots. The spin-down rate of binaries spans nine orders of magnitude, providing unique opportunities to test gravity theories.

2. DISCOVERY OF A BINARY PULSAR

The first pulsar was discovered by Burnell and Hewish[7] in 1967. The research team was investigating the scintillation of quasars using a radio array when they found a regular signal of pulsed radiation with a period of roughly a few seconds. The team first sought to prove the origin of the signal was not terrestrial. This was achieved by showing that the radiation source reappeared every sidereal day rather than every solar day. Due to the abnormally regular signal the team dubbed the source LGM-1 for "little green men," as a comical reference to extraterrestrial life. After it was determined that the pulsar was a rapidly rotating neutron star it was named PSR 1919+21.

A systematic survey of pulsars ensued at the Arecibo Observatory in Puerto Rico leading to forty well-characterized pulsars prior to the discovery of PSR 1913+16 by Hulse and Taylor[1]. The 59-ms pulsar was first detected in July 1974. The group sought to determine the period of the pulsar to high precision as they had for others. Their attempts to measure the period with a precision of $\pm 1\ \mu s$ were impeded by apparent changes in the period of up to $80\ \mu s$ from day to day. At times the period would change by as much as $8\ \mu s$ over a 5 minute observation. This apparent change in period was atypical of these seemingly "perfect clocks." The largest observed changes in period of other pulsars were on the order of 10 μs per year, and typical changes were many orders of magnitude lower[8].

Upon further investigation it was determined that Doppler shifts produced by orbital motion of the pulsar correctly explicate the observed period changes. The Doppler shifts allowed the researchers to determine the radial velocity as a function of orbital phase as shown in figure 3[1]. The period of the orbit was determined to be $P_b = 27908 \pm 7$ s and the eccentricity $e = 0.615 \pm 0.010$.

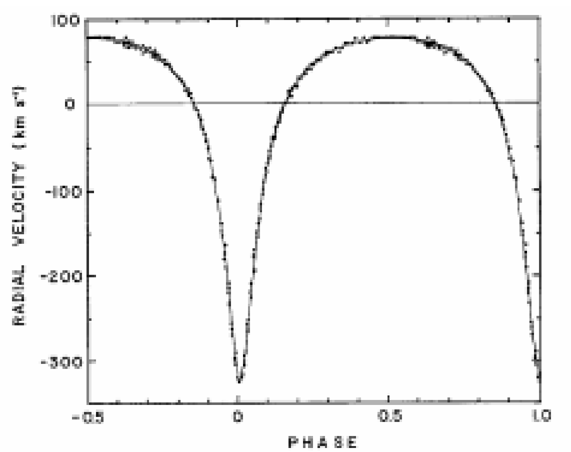

Fig. 3. Velocity curve as determined from Doppler shifts for the binary pulsar PSR 1913+16. Points represent measurements of the pulsar period distributed over parts of 10 different orbital periods. The curve represents a fit to the data as discussed in the reference.

Applying the above and all other measured orbital parameters it was concluded that the change of the pulsar period in the center of mass frame is $< 10^{-12}$, similar to that of other pulsars. These measurements solidified evidence for the first observed binary pulsar.

Table 1. Measured Orbital Parameters for B1913+16 System

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

3. DETERMINATION OF PULSAR AND COMPANION MASSES

Through non-relativistic analysis of the time of arrival data it is possible to obtain five orbital parameters[9,10,11]: the projected semimajor axis of the pulsar orbit $ap \sin i$, orbital eccentricity e, epoch of periastron T_0, orbital period P_b, and argument of periastron ω_0. Effects of relativity lead to three other measurable parameters: the mean rate of advance of periastron $\langle\dot{\omega}\rangle$, gravitational redshift and time-dilation parameter γ, and orbital period derivative $\dot{P}_b$. The orbit of the pulsar may be fully determined by the first seven parameters listed in Table 1[11].

Previous research has shown that the masses of the pulsar and its companion may also be determined from the first seven parameters in Table 1[12]. Assuming general relativity is correct, restrictions may be placed on the masses of the pair. These restrictions appear as curves in the companion mass versus pulsar mass parameter space. These restricting curves are shown in Figure 4[2]. The intersection of the curves at a single point precisely determines the masses of the stellar bodies as $m_1 = 1.4414 \pm 0.0002$ and $m_2 = 1.3867 \pm 0.0002$ times the mass of the Sun.

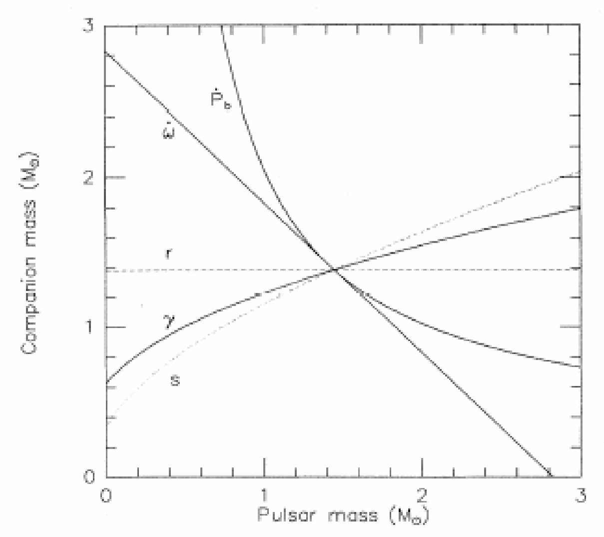

Fig. 4. Restrictions on the pulsar mass and companion mass are imposed by general relativity and the observed orbital parameters. The intersection of the curves at a single point provides strong agreement with general relativity and the existence of gravitational radiation (which is discussed below). The dashed curves are predicted values, which also clearly agree with all other measured quantities.

4. EVIDENCE FOR GRAVITATIONAL RADIATION

General relativity predicts that binary pulsars should emit energy in the form of gravitational radiation. The loss of energy results in a decaying orbit, which may be directly observed as a decrease in the orbital period. The spin-down rate is given by Peters and Matthews[13] as

All required parameters required to

$$\dot{P}_{b,GR} = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)\times \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)m_p m_c\left(m_p+m_c\right)^{-1/3}$$

predict the slow-down rate for the binary pulsar PSR 1913+16 are shown in Table 1, with the exception of the masses, m_p and m_c the pulsar and companion, respectively. The stellar masses were determined by assuming that general relativity is correct and were discussed in the previous section. The general relativistic prediction for the period derivative resulting from the emission of gravitational radiation is $\dot{P}_{b,GR} = -\left(2.40242 \pm 0.00002\right)\times 10^{-12}\ s/s$

To directly compare the observed period derivative with the theoretically predicted value a small correction, $P_{b,gal}$, must be made to account for the relative acceleration between the solar system and the binary pulsar[14]. The correction depends upon the distance and proper motion of the pulsar and the radius of the Sun's galactic orbit, quantities which are not precisely know. The best value[11] yields $\dot{P}_{b,gal} = -\left(0.0128 \pm 0.0050\right)\times 10^{-12}\ s/s$

Therefore we have,

$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021.$$

The measured value is consistent with the prediction of general relativity at the (0.13 ± 0.21)% level. The comparison of the predicted and observed values for the past thirty years is shown in figure 5, again reinforcing the excellent agreement between the observed values and the theoretical predictions of general relativity[11]. The strong agreement, therefore, provides experimental evidence for the existence and nature of gravitational radiation as predicted by general relativity.

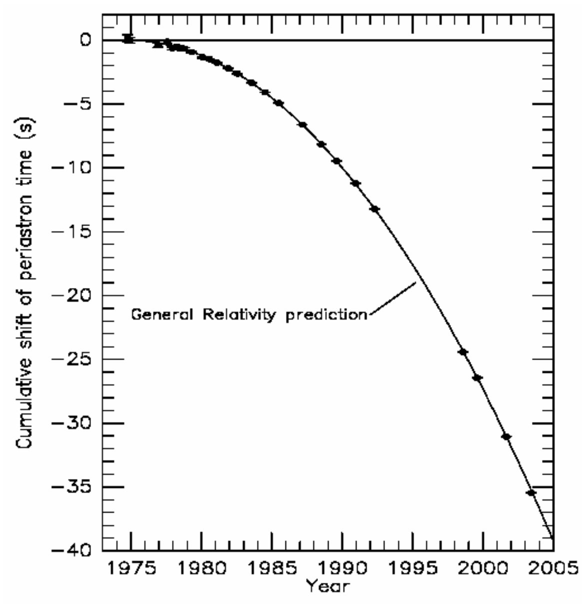

Fig. 5. Comparison of the predicted and observed orbital decay of PSR 1913+16. The data points indicate the observed change in the epoch of periastron and the solid curve represents the prediction of general relativity using the parameters in Table 1.

5. CONCLUSIONS

The binary pulsar PSR 1913+16 provides an excellent source of tests of general relativity and competing theories of gravity in the strong-field, rapid motion limits which are not present within the solar system. By observing and comparing the orbital period decay due to gravitational radiation emission to the general relativity prediction, it is clear that changes in gravity propagate at the speed of light and thereby create a dissipative mechanism in orbiting systems. It is important to note that the observed orbital decay is *only* in good agreement with *general relativity*. Predictions of alternate, competing theories of gravity conflict strongly with the observations discussed here.

Despite the repeated experimental tests that so strongly agree with general relativity, the theory is not a quantum theory. The universe appears to be quantum mechanical, which leaves the door open for future theories of gravity. But, the strong agreement between general relativity and experiment requires that any new theory of gravity properly asymptote to general relativity in a wide range of classical limits.

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