Binary Radio Pulsars
ASP Conference Series, Vol. TBD, 2004
eds. F.A. Rasio & I.H. Stairs

Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis

Joel M. Weisberg

Dept. of Physics & Astronomy, Carleton College, Northfield, MN

Joseph H. Taylor

Dept. of Physics, Princeton University, Princeton, NJ

Abstract.

We describe results derived from thirty years of observations of PSR B1913+16. Together with the Keplerian orbital parameters, measurements of the relativistic periastron advance and a combination of gravitational redshift and time dilation yield the stellar masses with high accuracy. The measured rate of change of orbital period agrees with that expected from the emission of gravitational radiation, according to general relativity, to within about 0.2 percent. Systematic effects depending on the pulsar distance and on poorly known galactic constants now dominate the error budget, so tighter bounds will be difficult to obtain. Geodetic precession of the pulsar spin axis leads to secular changes in pulse shape as the pulsar-observer geometry changes. This effect makes it possible to model the two-dimensional structure of the beam. We find that the beam is elongated in the latitude direction and appears to be pinched in longitude near its center.

1. Introduction

Pulsar B1913+16 was the first binary pulsar to be discovered (Hulse & Taylor 1975). Thirty years of subsequent observations have enabled us to measure numerous relativistic phenomena. We have used these measurements for fundamental tests of gravitational physics and to place tight constraints on physical parameters of the system. In this paper, we provide the latest results of our observations and analysis.

2. Observations

The observable pulsar is a weak radio source with a flux density of about 1 mJy at 1400 MHz. Its observations are nearly always sensitivity limited. Over the years we and our colleagues have built a number of sensitive receiver "back ends" for use at Arecibo, including a swept local-oscillator system programmed to follow the dispersed pulse, as well as filter banks and signal averagers (see Weisberg & Taylor 2003 for a summary). Our most recent data have been gathered with the Wideband Arecibo Pulsar Processors ("WAPPs"), which for PSR B1913+16 achieve 13 μs time-of-arrival measurements in each of four 100 MHz bands, using 5-minute integrations. In addition to the timing observations, we have used the Princeton Mark IV coherent de-dispersing system (Stairs et al. 2000) to measure average pulse shapes and polarization over the last five years. A major improvement in data acquisition for this experiment was made in 1981, and data taken since then have much higher quality than the earlier observations. The results reported here are based largely on data gathered from 1981 through 2003.

3. Relativistic Timing Analysis

Non-relativistic analysis of arrival time data from this system can yield five orbital parameters: the projected semimajor axis of the pulsar orbit $a_p \sin i$, orbital eccentricity e, epoch of periastron T_0, orbital period P_b, and argument of periastron ω_0. Relativistic effects lead to three additional measurables: the mean rate of advance of periastron $\langle\dot{\omega}\rangle$, gravitational redshift and time-dilation parameter γ, and orbital period derivative $\dot{P}_b$. Measured pulse times of arrival calculated for each five minutes of observation serve as the input data for program TEMPO (http://pulsar.princeton.edu/tempo). This program fits a model with eighteen parameters (eight orbital quantities plus ten astrometric and spin parameters) to the data, using the timing model of Damour & Deruelle (1985, 1986). Fitted values for the orbital parameters are listed in Table 1, with uncertainties in the last shown in parentheses.

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)

The pulsar orbit is fully specified (up to an unknown rotation about the line of sight) by the first seven parameters listed in Table 1. Other orbital quantities such as inclination, masses of the stellar components, and the semimajor axes, may be derived from these seven; Taylor & Weisberg (1982) provide the relevant formulas. For example, the masses of the pulsar and companion are $m_p = 1.4414 \pm 0.0002$ and $m_c = 1.3867 \pm 0.0002$ solar masses, respectively. (Note that in order to express the masses in grams, a value would need to be introduced for the Newtonian gravitational constant G. The uncertainty in G is comparable to our quoted uncertainties in m_p and m_c.) As described below, the eighth measured orbital parameter, $\dot{P}_b$, overdetermines the system dynamically and thus provides a test of gravitation theory.

3.1. Emission of Gravitational Radiation

According to general relativity, a binary star system should emit energy in the form of gravitational waves. The loss of orbital energy results in shrinkage of the orbit, which is most easily observed as a decrease in orbital period. Peters & Matthews (1963) showed that in general relativity the rate of period decrease is given by

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

Note that except for Newton's constant G and the speed of light c, all quantities on the right hand side of Eq. (1) have measured values listed in Table 1, or, in the case of the component masses, are derivable from those quantities. The predicted orbital period derivative due to gravitational radiation computed from Eq. (1) is $\dot{P}_{b,GR} = -(2.40242 \pm 0.00002) \times 10^{-12}$ s/s.

Comparison of the measured $\dot{P}_b$ with the theoretical value requires a small correction, $\dot{P}_{b,Gal}$, for relative acceleration between the solar system and binary pulsar system, projected onto the line of sight (Damour & Taylor 1991). This correction is applied to the measured $\dot{P}_b$ to form a "corrected" value $\dot{P}_{b,corrected} = \dot{P}_b - \dot{P}_{b,Gal}$. The correction term depends on several rather poorly known quantities, including the distance and proper motion of the pulsar and the radius of the Sun's galactic orbit. The best currently available values yield $\dot{P}_{b,Gal} = -(0.0128 \pm 0.0050) \times 10^{-12}$ s/s, so that $\dot{P}_{b,corrected} = (2.4056 \pm 0.0051) \times 10^{-12}$ s/s. Hence

$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021, \tag{2}$$

and we conclude that the measured orbital decay is consistent at the $(0.13 \pm 0.21)\%$ level with the general relativistic prediction for the emission of gravitational radiation. The observed and theoretical orbital decays are compared graphically in Figure 1.

Accuracy of the test for gravitational radiation damping is now dominated by the uncertainty in the galactic acceleration term. Work now underway should lead to improved accuracy of the pulsar proper motion, and the Sun's galactocentric distance may be better known in the future. However, we see little prospect for a significant improvement in knowledge of the pulsar distance. Consequently, it seems unlikely that this test of relativistic gravity will be improved significantly in the foreseeable future.

4. Geodetic Precession: Mapping the Emission Beam

Relativistic spin-orbit coupling causes the pulsar's spin axis to precess (Damour & Ruffini 1974; Barker &O'Connell 1975a,b). In the PSR B1913+16 system

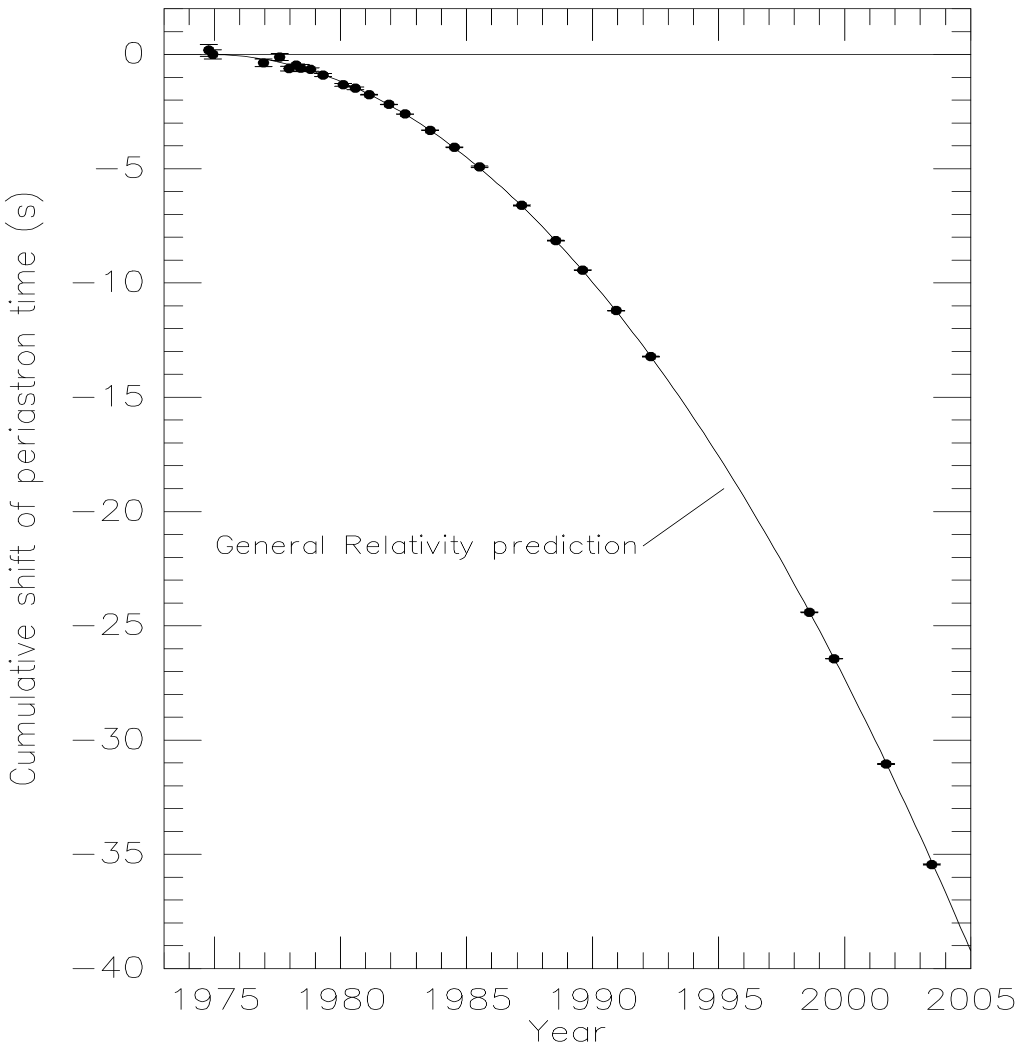

Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

this so-called "geodetic" precession has a period of about 300 y. The resulting change of aspect with respect to the line of sight should cause a secular change in pulse shape. Weisberg, Romani, & Taylor (1989) reported shape changes at 1400 MHz and attributed them to the line of sight moving across the middle of a hollow-cone beam. Kramer (1998) found that the separation between the two principal pulse components began to shrink in the mid-1990s, suggesting that the line of sight had continued to drift across the conal beam, moving farther from its center. Kramer fitted a model to these data, which indicated that the pulsar spin and orbital angular momenta are misaligned by $\sim 20^\circ$ and that the beam will no longer intersect our line of sight after the year 2025. Weisberg & Taylor (2002) confirmed these results and found that the conal beam appears to be elongated in the direction parallel to the spin axis; they also noted that the beam appears to be "hourglass-shaped," or pinched in longitude near its center (see Fig. 2). Kramer (2002) argued that these observations could also result from the line of sight precessing away from the center of a circular emission cone and onto a core pencil beam that is offset below the center and toward the the trailing part of the cone.

We divided all of our 1400 MHz profiles into components that are respectively even and odd about the profile center. We then fitted the even components to a model that allows for a noncircular conal beam (Weisberg & Taylor 2002). With more data now available, we find that the model parameters have changed little from earlier solutions. The current model is illustrated in Figure 2 in the form of equal-intensity contours of the beam.

Rankin (1983) showed that in most pulsars core emission becomes more prominent at low frequencies. We have observed PSR B1913+16 at the lower frequency of 430 MHz at several epochs, and three of the resulting pulse profiles are shown in Figure 3. A core component is quite prominent in the data taken in 1980-81, but it faded very significantly between 1980 and 1998 and was nearly gone by 2003. This behavior further supports our model in which the line of sight is precessing away from the axis of a centered pencil beam plus a longitude-pinched cone elongated in the latitude direction.

Even with 30 years of observations, only a small portion of the north-south extent of the emission beam has been observed. As a consequence, our model is neither unique nor particularly robust. The north-south symmetry of the model is assumed, not observed, since the line of sight has fallen on the same side of the beam axis throughout these observations. Nevertheless, accumulating data continue to support the principal features noted above.

References

Barker, B. M. & O'Connell, R. F. 1975a, Phys.Rev.D, 12, 329

Barker, B. M. & O'Connell, R. F. 1975b, ApJ, 199, L25

Damour, T. & Ruffini, R. 1974, Academie des Sciences Paris Comptes Rendus Serie Sciences Mathematiques, 279, 971

Damour, T. & Deruelle, N. 1985, Ann. Inst. H. Poincare (Phys. Theorique), 43, 107

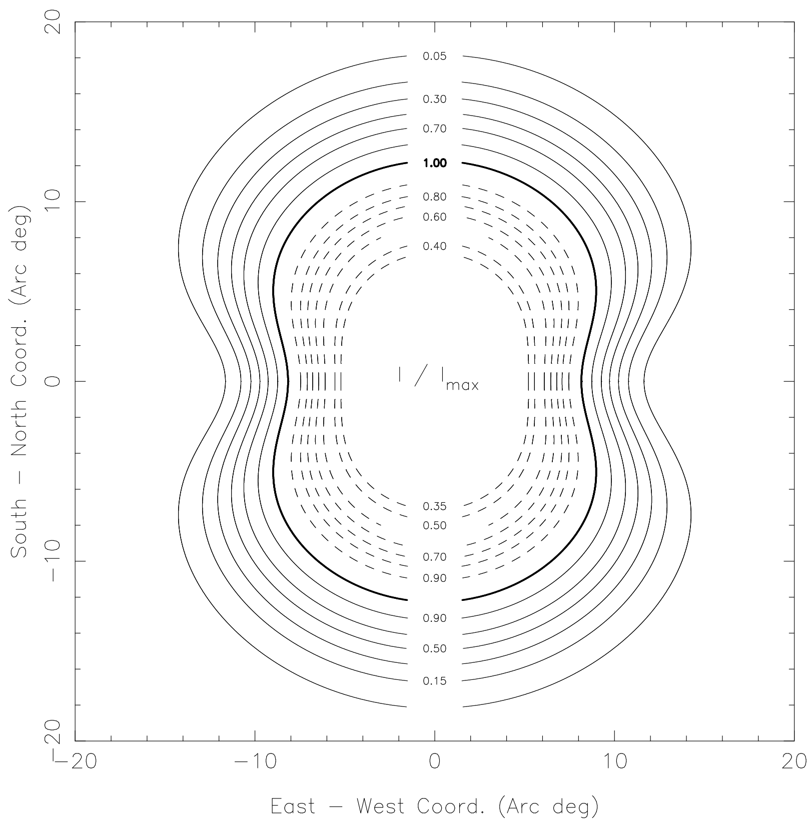

Figure 2. Hourglass-shaped conal beam model. The model was fitted to the even components of 1400 MHz profiles from 1981 to 2003.

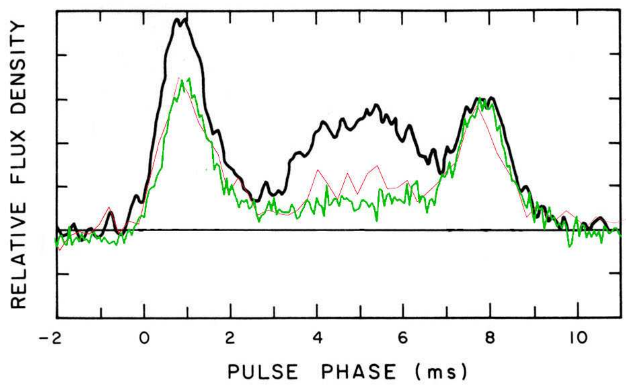

Figure 3. Profiles of PSR B1913+16 at 430 MHz at three epochs. The core component declines from 1980 to 1998 through 2003, indicating that the line of sight is precessing away from the axis of a *centered* core pencil beam.

Damour, T. & Deruelle, N. 1986, Ann. Inst. H. Poincare (Phys. Theorique), 44, 263

Damour, T. & Taylor, J. H. 1991, ApJ, 366, 501

Hulse, R. A. & Taylor, J. H. 1975, ApJ, 195, L51

Kramer, M. 1998, ApJ, 509, 856

Kramer, M. 2002, Proc. Ninth Marcel Grossmann Meeting, Eds.: Vahe G. Gurzadyan, Robert T. Jantzen, Remo Ruffini (Singapore: World Scientific), 219; astro-ph/0105089

Peters, P. C. & Mathews, J. 1963, Phys. Rev., 131, 435

Rankin, J. M. 1983, ApJ, 274, 333

Stairs, I. H., Splaver, E. M., Thorsett, S. E., Nice, D. J., & Taylor, J. H. 2000, MNRAS, 314, 459

Taylor, J. H. & Weisberg, J. M. 1982, ApJ, 253, 908

Weisberg, J. M., Romani, R. W., & Taylor, J. H. 1989, ApJ, 347, 1030

Weisberg, J. M. & Taylor, J. H. 2002, ApJ, 576, 942

Weisberg, J. M. & Taylor, J. H. 2003, ASP Conf. Ser. 302: Radio Pulsars, Ed. M. Bailes, D. J. Nice, & S. E. Thorsett (San Francisco: ASP), 93