MEASUREMENT OF RELATIVISTIC ORBITAL DECAY IN THE PSR B1534+12 BINARY SYSTEM

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ABSTRACT

We have made timing observations of binary pulsar PSR B1534+12 with radio telescopes at Arecibo, Green Bank, and Jodrell Bank. By combining our new observations with data collected up to seven years earlier, we obtain a significantly improved solution for the astrometric, spin, and orbital parameters of the system. For the first time in any binary pulsar system, no fewer than five relativistic or “post-Keplerian” orbital parameters are measurable with useful accuracies in a theory-independent way. We find the orbital period of the system to be decreasing at a rate close to that expected from gravitational radiation damping, according to general relativity, although the precision of this test is limited to about 15% by the otherwise poorly known distance to the pulsar. The remaining post-Keplerian parameters are all consistent with one another and all but one of them have fractional accuracies better than 1%. By assuming that general relativity is the correct theory of gravity, at least to the accuracy demanded by this experiment, we find the masses of the pulsar and companion star each to be $1.339 \pm 0.003 \, M_\odot$ and the system’s distance to be $d = 1.1 \pm 0.2 \, kpc$, marginally larger than the $d \approx 0.7 \, kpc$ estimated from the dispersion measure. The increased distance reduces estimates of the projected rate of coalescence of double neutron star systems in the universe, a quantity of considerable interest for experiments with terrestrial gravitational wave detectors such as the Laser Interferometer Gravitational-Wave Observatory.

Subject headings: binaries: close — gravitation — pulsars: individual (PSR B1534+12) — stars: distances

1. INTRODUCTION

Pulsars in double neutron star binaries provide the best known laboratories for experimental tests of gravity in the radiative and strong field regimes. Timing analysis of pulsar signals allows measurement of five Keplerian orbital elements as well as a number of post-Keplerian (PK) orbital parameters. The PK parameters can be analyzed using a theory-independent procedure in which the masses of the two stars are the only dynamically important a priori unknowns (Damour & Taylor 1992). Each of the PK parameters depends on the masses in a different way; consequently, if any two of them are measured, the relevant parameters of the two-body system are fully determined within any gravitational theory. If three or more PK parameters can be measured, the overdetermined system can be used to test the gravitational theory itself. Measured values of the PK parameters $\omega$ (rate of advance of periastron), $\gamma$ (time dilation and gravitational redshift), and $P_\text{s}$ (orbital period derivative) for binary pulsar PSR B1913+16 have been found to be in excellent agreement with the predictions of general relativity (Taylor & Weisberg 1989; Damour & Taylor 1991; Taylor 1994). In particular, the observed value of $P_\text{s}$ confirms that the system is losing energy in the form of quadrupolar gravitational waves at the rate expected according to general relativity (GR).

An opportunity to repeat and extend this test of relativistic gravitation was provided by discovery of a second suitable binary pulsar, PSR B1534+12, in a 10.1 hr orbit (Wolszczan 1991). PSR B1534+12 is significantly brighter than PSR B1913+16, and its pulse has a narrow peak, allowing more precise timing measurements. Because the orbit is nearly edge-on as viewed from the Earth, the PK parameters $r$ and $s$ (the “range” and “shape” of the Shapiro time delay) are more easily measured. In addition, both $\omega$ and $\gamma$ are measurable, as for PSR B1913+16, because of their contribution to secularly accumulating effects in the data. The resulting overdetermination of the orbit has already led to a nonradiative test of gravitation theory in the strong-field regime, complementing the $\omega-\gamma-P_\text{s}$ test for PSR B1913+16 (Taylor et al. 1992).

Previously published timing measurements of PSR B1534+12 were all made with the Arecibo 305 m telescope. We have extended this sequence of observations (Arzoumanian 1995) through early 1994, when the telescope went out of normal service for a major upgrading; since then we have used the 43 m telescope at Green Bank, West Virginia, and the 76 m Lovell telescope at Jodrell Bank, England, to acquire additional data. Owing to its slower and less eccentric orbit, the expected rate of orbital period decay for PSR B1534+12 is more than an order of magnitude less than for PSR B1913+16. However, the timing data are considerably more precise, and we find that fitting our full sequence of pulse times of arrival (TOAs) to the standard relativistic pulsar timing model now yields a measurement of $P_\text{s}$ in the solar system barycentric rest frame with uncertainty approximately 7% of the expected GR value. The result is a convincing second test of the dissipative coupling between accelerating masses and a gravitational radiation field that carries energy and angular momentum away from the system. Like the first such test
(Taylor & Weisberg 1989; Taylor 1994) these results are in good accord with general relativity theory. The precision of the new result is limited by uncertainty in the necessary kinematic corrections, which depend on the poorly known pulsar distance. Interestingly, we can invert the test, assuming that GR is the correct theory of gravity, and calculate that the distance of PSR B1534+12 must be about 1.6 times that estimated from the dispersion measure (Taylor & Cordes 1993).

2. OBSERVATIONS

Observations at the 305 m Arecibo telescope were made primarily with the Princeton Mark III system (Stinebring et al. 1992), using dual-polarization 2 × 32 channel filter banks with 0.25 MHz channels at 430 MHz and 1.25 MHz channels at 1400 MHz. The signals in each channel were square-law detected, and the two polarizations were summed in hardware and then folded at the topocentric pulsar period. Integration times were typically 3 minutes at 430 MHz and 5 minutes at 1400 MHz. The resulting total-intensity profiles have 512 (430 MHz) or 1024 (1400 MHz) bins across the 37.9 ms period. The effective time resolution is dominated by the dispersion smearing in a single channel, approximately 304 μs at 430 MHz and 44 μs at 1400 MHz; quadrature addition of the postdetection time constants and the boxcar-averaging bin sizes used for these observations yield the total resolutions quoted in Table 1. The Arecibo observations extend from 1990 August through 1994 March.

We observed PSR B1534+12 with the National Radio Astronomy Observatory 43 m telescope at Green Bank, West Virginia, between 1994 March and 1997 May. Observing sessions were spaced typically at two month intervals, and we used frequencies of 575 and 800 MHz. A digital Fourier transform spectrometer (the "Spectral Processor") analyzed signals in each of two polarizations into 512 spectral channels across a 40 MHz passband. The spectra were folded synchronously at the predicted topocentric pulse period and averaged for 3 minutes. The resulting pulse profiles had 128 phase bins, or a resolution of 296 μs. The data were dedispersed after detection and opposite polarizations summed to produce a single total-intensity pulse profile for each integration.

We observed PSR B1534+12 with the 76 m Lovell Telescope between January and July of 1997, using the Princeton Mark IV data acquisition system at 610 MHz (Stairs, Taylor, & Thorsett 1998). Exploratory observations were made in January and February, followed by a concentrated campaign from June 16 to July 14, during which time the pulsar was observed for up to 3 hr, during scintillation maxima, nearly every day. For each sense of circular polarization, a 5 MHz bandpass was mixed to baseband using local oscillators in phase quadrature. The four resulting signals were low-pass filtered at 2.35 MHz (filters 60 dB down at 2.5 MHz), sampled at 5 MHz, quantized to 4 bits, and written to a large disk array and later to magnetic tapes. Upon playback, the undetected signal voltages were dedispersed using the phase-coherent technique described by Hankins & Rickett (1975). After amplitude calibrations are applied, self- and cross-products of the right- and left-handed complex voltages yield the Stokes parameters of the incoming signal. These products were folded at the topocentric pulsar period using 2048 phase bins, and pulse TOAs were determined from the resulting total-intensity profiles using 190 s integrations. A summary of the more important parameters and statistics of all four observing systems is presented in Table 1.

We used the same TOA-fitting procedure for all data sets. Each observed profile was fitted to a standard template, using a least-squares method in the Fourier transform domain to measure its time offset (Taylor 1992). The offset was added to the time of the first sample of a period near the middle of the integration, thereby yielding an effective pulse arrival time. A different standard template was used for each observing system and frequency; they were made by averaging the available profiles over several hours or more. Uncertainties in the TOAs were estimated from the least-squares procedure and also from the observed scatter of the TOAs within 30 minutes of each one. Each observatory’s local time standard was corrected retroactively to the UTC timescale, using data from the Global Positioning System (GPS) satellites.

3. DATA ANALYSIS

3.1. The Timing Model

A pulse received on Earth at topocentric time \( t \) is emitted at a time in the comoving pulsar frame given by

\[
T = t - t_0 + \Delta_c - Df^2 + \Delta_{R_\odot} + \Delta_{E_\odot} - \Delta_{S_\odot} - \Delta_R - \Delta_E - \Delta_S\,.
\]

Here \( t_0 \) is a reference epoch and \( \Delta_c \) is the offset between the observatory master clock and the reference standard of terrestrial time. The dispersive delay is \( Df^2 \), where \( D = \text{DM/2.41} \times 10^{-4} \), with dispersion measure \( \text{DM in cm}^{-3}\text{pc} \), radio frequency \( f \) in MHz, and the delay in seconds. Finally, \( \Delta_{R_\odot} \), \( \Delta_{E_\odot} \), and \( \Delta_{S_\odot} \) are propagation delays and relativistic time adjustments for effects within the solar system, and \( \Delta_R \), \( \Delta_E \), and \( \Delta_S \) are similar terms accounting for phenomena within the pulsar’s orbit (Damour & Deruelle 1986; Taylor &

| TABLE 1 | PARAMETERS OF THE FOUR OBSERVING SYSTEMS |
|----------|-----------------------------------|
| Parameter | Arecibo Mark III | Arecibo Mark III | Green Bank Spectral Processor | Jodrell Bank Mark IV |
| Frequency (MHz) .......... | 430 | 1400 | 575, 800 | 610 |
| Bandwidth (MHz) ........... | 8 | 40 | 40 | 5 |
| Spectral channels ...... | 32 | 32 | 512 | 1 |
| Dedispersing system...... | Incoherent | Incoherent | Incoherent | Coherent |
| Time resolution (μs) ...... | 329 | 97 | 296 | 19 |
| Integration time (s) ....... | 180 | 300 | 180 | 190 |
| Dates .................. | 1990.7–94.2 | 1990.8–94.1 | 1994.2–97.4 | 1997.0–97.6 |
| Number of TOAs .......... | 2311 | 1170 | 685 | 780 |
| Median σ_{TOA} (μs) ...... | 4.9 | 5.4 | 40 | 21 |
We used the standard TEMPO analysis software (Taylor & Weisberg 1989; Damour & Taylor 1992). (We ignore the uninteresting constant and uniform rate of change of the overall propagation delay.) The orbital Δ terms are defined by

\[ \Delta_R = x \sin \omega (\cos u - e) + x(1 - e^2)^{1/2} \cos \omega \sin u, \]
\[ \Delta_k = x \sin \omega (\cos u - e) + x(1 - e^2)^{1/2} \cos \omega \sin u, \]
\[ \Delta_s = -2r \ln (1 - e \cos u - s) \times [\sin \omega (\cos u - e) + (1 - e^2)^{1/2} \cos \omega \sin u]. \]

These are written in terms of the eccentric anomaly \( u \) and true anomaly \( A_r(u) \), and the time dependence of \( \omega \), which are related by

\[ u - e \sin u = 2\pi \left[ \frac{T - T_0}{P_b} - \frac{p_b}{2} \left( \frac{T - T_0}{P_b} \right)^2 \right], \]
\[ A_r(u) = 2 \arctan \left[ \frac{1 + e}{1 - e} \frac{\tan u}{2} \right], \]
\[ \omega = \omega_0 + \frac{p_b \omega_b}{2\pi} A_r(u). \]

At a given time \( t \), then, the propagation delay across the pulsar orbit is calculated by a model that incorporates 10 parameters implicitly defined in the above equations: five Keplerian parameters \((x, \omega, T_0, P_b, \text{ and } e)\) and five PK parameters \((\omega, P_b, \gamma, r, \text{ and } s)\). These quantities, in conjunction with a simple time polynomial to model the spin of the pulsar and with astrometric parameters to model the propagation of the signal across the solar system, constitute the free parameters to be fitted in the theory-independent timing model.

In a particular theory of gravity, the five PK parameters can be written as functions of the pulsar and companion star masses, \( m_1 \) and \( m_2 \), and the well-determined Keplerian parameters. Of particular interest is general relativity, where the equations are as follows:

\[ \dot{\omega} = 3 \frac{P_b^2}{2 \pi} \left( \frac{T - T_0}{P_b} \right)^{-5/3} \frac{M^2/3(1 - e^2)^{-1}}{1 + \frac{1}{12} e^2 + \frac{1}{720} e^4}, \]
\[ \dot{\gamma} = 3 \frac{P_b^2}{2 \pi} \frac{T^{2/3}}{m_1 + m_2}, \]
\[ \dot{P_b} = -192 \pi \frac{p_b}{2\pi} \frac{1}{5} \frac{m_1 + m_2}{m_1 + m_2} \left( \frac{1}{24} e^2 + \frac{37}{96} e^4 \right), \]
\[ r = T_{\odot} m_2, \]
\[ s = x \frac{P_b}{2 \pi} \left( \frac{T - T_0}{P_b} \right)^{-2/3} \frac{m_1 + m_2}{M^2/3m_2^{-1}}, \]

(see Damour & Deruelle 1986; Taylor & Weisberg 1989; Damour & Taylor 1992). Here the masses \( m_1, m_2, \text{ and } M \equiv m_1 + m_2 \) are expressed in solar units, and we use the additional shorthand notations \( s = \sin i \) and \( T_{\odot} = GM_\odot/c^2 = 4.925490047 \mu s \), where \( i \) is the angle between the orbital angular momentum and the line of sight, \( G \) the Newtonian constant of gravity, and \( c \) the speed of light.

3.2. Arrival Time Analysis

We used the standard TEMPO analysis software (Taylor & Weisberg 1989) together with the JPL DE200 solar system ephemeris (Standish 1990) to fit the measured pulse arrival times to the timing model with a least-squares technique. Results for the astrometric, spin, and dispersion parameters of PSR B1534 + 12 are presented in Table 2. Initial tests indicated the likely presence of systematic errors in the Arecibo data taken at 430 MHz (see below), so these data were used only for the calculation of the dispersion correction. The uncertainty quoted for DM is dominated by the unavoidable difficulty in aligning the frequency-dependent pulse shapes obtained in the different observing bands. We list for the first time a significant measurement of the rate of change of dispersion measure for this pulsar, determined from the dual-frequency data collected at Arecibo from 1990 to 1994. We note that there is no guarantee that this parameter will have remained constant since 1994.

We fitted the data to two models of the pulsar orbit. The theory-independent “DD” model (Damour & Deruelle 1986) treats all five PK parameters defined in § 3.1 as free parameters in the fit. Alternatively, the “DDGR” model (Taylor 1987; Taylor & Weisberg 1989) assumes general relativity to be correct and uses equations (8)–(12) to link the PK parameters to \( M = m_1 + m_2 \) and \( m_2 \); consequently, it requires only two post-Keplerian free parameters.

Table 3 presents our adopted orbital parameters. Uncertainties given in the table are approximately twice the formal “1 σ” errors from the fit; we believe them to be conservative estimates of the true 68% confidence uncertainties, including both random and systematic effects. The Keplerian orbital parameters include the period \( P_b \), projected semimajor axis \( x = a \sin i/c \), eccentricity \( e \), longitude of periastron \( \omega \), and time of periastron \( T_0 \). These quantities are followed by the measured post-Keplerian parameters relevant to each of the two models. For the first time, the precision of this experiment requires the DDGR solution to include a parameter we call “excess \( \dot{P}_b \),” which accounts for an otherwise unmodeled acceleration resulting from galactic kinematics.

See also http://pulsar.princeton.edu/tempo.
TABLE 3

| Parameter                                      | DD model                  | DDGR model               |
|------------------------------------------------|---------------------------|--------------------------|
| Orbital period, $P_o$ (d)                     | 0.42073729929(4)          | 0.42073729930(4)         |
| Projected semimajor axis, $x$ (s)             | 3.729463(3)               | 3.7294628(7)             |
| Eccentricity, $e$                             | 0.2736777(5)              | 0.2736776(2)             |
| Longitude of periastron, $\omega$ (deg)       | 267.44746(16)             | 267.44760(12)            |
| Epoch of periastron, $T_0$ (MJD)              | 48,777.82595097(6)        | 48,777.82595096(6)      |
| Advance of periastron, $\dot{\omega}$ (deg yr$^{-1}$) | 1.75576(4)               | 1.75577                  |
| Gravitational redshift, $\gamma$ (ms)         | 2.066(10)                 | 2.057                    |
| Orbital period derivative, $(P_o)^{\text{d}}$ (10$^{-12}$) | $-0.129(14)$             | $-0.1924$               |
| Shape of Shapiro delay, $s$                    | 0.982(7)                  | 0.9797                   |
| Range of Shapiro delay, $r$ ($\mu$s)          | 6.7(1.3)                  | 6.60                     |
| Derivative of $x$, $|\dot{x}|$ (10$^{-12}$)   | $<2.5$                    | $<0.022$                 |
| Derivative of $e$, $|\dot{e}|$ (10$^{-15}$ s$^{-1}$) | $<6$                      | $<6$                     |
| Total mass, $M = m_1 + m_2$ ($M_\odot$)      |                           | 2.67838(8)               |
| Companion mass, $m_2$ ($M_\odot$)             |                           | 1.339(3)                 |
| Excess $P_o$ (10$^{-12}$)                      |                           | 0.062(14)                |

$a$ Figures in parentheses are uncertainties in the last digits quoted. Italic numbers represent derived parameters, assuming general relativity.

The best estimates of the masses of the pulsar and its companion come from the DDGR solution. We find the masses to be equal: $m_1 = m_2 = 1.339 \pm 0.003$ $M_\odot$. For the sake of comparison, Table 3 lists, in italic numbers, computed PK parameter values corresponding to the measured masses in the DDGR fit. We call attention to the fact that the fitted and derived parameter values are in excellent accord, indicating good agreement of the theory-independent solution with general relativity.

Figure 1 shows the postfit residuals for the Arecibo 1400 MHz data, the Green Bank data, and the Jodrell Bank data, plotted as functions of date. Even within a single data set, the TOA uncertainties can vary by factors of 3 or more, above and below the median values $\sigma_{\text{TOA}}$ listed in Table 1, because of scintillation-induced intensity variations. We have not attempted to show these differences in data quality by means of error bars in the residual plots. Figure 2 illustrates the average postfit residuals for the Arecibo measurements at 1400 MHz and the Jodrell Bank data at 610 MHz, plotted as functions of orbital phase.

### 3.3. Data Confidence Tests

For some time we have suspected that solutions for the fitted parameters of PSR B1534+12, as determined from the Arecibo 430 MHz data, are biased by small systematic errors in the TOAs. These errors likely arise from imperfect postdetection dispersion removal that follows as a consequence of the relatively coarse frequency resolution of the filter-bank spectrometer. It is extremely difficult to achieve TOAs with systematic errors less than a few percent of the dominant instrumental smoothing effects in the data—in this instance, the dispersion time across a single channel. Variable spectral features caused by interstellar scintillation, together with slightly irregular filter passbands and center frequencies, make the Arecibo 430 MHz measure-
ments unreliable at the several microsecond level.

Some further information on the data quality is presented in Figure 3. Here we follow Taylor & Weisberg (1989) and explore the statistical properties of the postfit residuals to see if they “integrate down” as $n^{-1/2}$ when $n$ consecutive values are averaged. As expected, this test confirms that the Arecibo 430 MHz data (and, to a lesser extent, the Green Bank data, which anyway receive low weight) deviate from the ideal $n^{-1/2}$ behavior. This indicates the likely presence of systematic errors in the TOAs, although we cannot completely rule out the possibility of a frequency-dependent deviation from the timing model (e.g., aberration-induced pulse profile variations). In any case, it is clear that for the highest accuracy within our preferred models we must omit the existing Arecibo 430 MHz measurements from our solution, as described above.

The parameters of PSR B1534+12 are therefore best determined from the Arecibo 1400 MHz data along with the Green Bank and Jodrell Bank data sets. The higher observing frequency of 1400 MHz assures that for these measurements the total instrumental smoothing, even with 1.25 MHz channel bandwidths, is only 97$\mu$s (see Table 1). Better still, the Princeton Mark IV system used at Jodrell Bank was explicitly designed to minimize or eliminate dispersion-related systematic errors in TOAs. We used these two data sets, both with and without the much lower weighted Green Bank data, to measure and check the systematic errors of unknown origin. To partially compensate for this effect, uncertainties in TOAs were increased (in quadrature) by 2.9, 17.1, and 20.5$\mu$s, respectively, when calculating weights for the Arecibo, Jodrell Bank, and Green Bank data sets.

4. DISCUSSION

4.1. Observed Change in Orbital Period: Distance to PSR B1534+12

Before proceeding to tests of GR, we must correct the observed $P_{\text{b}}$, which is expressed in the reference frame of the solar system barycenter, to the center-of-mass frame of the binary pulsar. Damour & Taylor (1991) derived an expression for the most significant bias, which arises from galactic kinematic effects. It can be written as the sum of terms arising from acceleration toward the plane of the Galaxy, acceleration within the plane of the Galaxy, and an apparent acceleration due to the proper motion of the binary system:

$$
\frac{dP_{\text{b}}}{P_{\text{b}}} = -\frac{a_z}{c} \sin b - \frac{v_0^2}{cR_0} \left( \cos l + \frac{\beta}{\sin^2 l + \beta^2} \right) + \frac{\mu^2 d}{c^3}. 
$$

(13)

Here $a_z$ is the vertical component of galactic acceleration, $l$ and $b$ are the Galactic coordinates of the pulsar, $R_0$ and $v_0$ are the Sun’s Galactocentric distance and Galactic circular velocity, and $\mu$ and $d$ are the proper motion and distance of the pulsar; we use the shorthand notation $\beta = d/R_0 - \cos l$. The pulsar distance can be estimated from the dispersion measure, together with a smoothed-out model of the free electron distribution in the Galaxy. The Taylor & Cordes (1993) model yields $d \approx 0.7$ kpc for PSR B1534+12, with an uncertainty of perhaps 0.2 kpc. At this distance we estimate $a_z/c = (1.60 \pm 0.13) \times 10^{-19}$ s$^{-1}$ from the model of Kuijken & Gilmore (1989). Following Damour & Taylor (1991), we take $v_0 = 222 \pm 20$ km s$^{-1}$ and $R_0 = 7.7 \pm 0.7$ kpc. Then, summing the terms in equation (13) and multiplying by $P_{\text{b}}$, we find the total kinematic correction to be

$$
(\tilde{P}_{\text{b}})_{\text{kin}} = (0.038 \pm 0.012) \times 10^{-12}. 
$$

(14)

The uncertainty in this correction is dominated by the uncertainty in distance, which is only roughly estimated by the Taylor and Cordes model.

Our measurement of the intrinsic rate of orbital period decay is therefore

$$
(\tilde{P}_{\text{b}})^{\text{obs}} - (\tilde{P}_{\text{b}})_{\text{kin}} = (-0.167 \pm 0.018) \times 10^{-12}. 
$$

(15)

Under general relativity, the orbital period decay due to gravitational radiation damping, $(\tilde{P}_{\text{b}})^{\text{GR}}$, can be predicted from the masses $m_1$ and $m_2$ (eq. 10), which in turn can be deduced from the high-precision measurements of $\dot{\gamma}$ and $\gamma$. The expected value is

$$
(\tilde{P}_{\text{b}})^{\text{GR}} = -0.192 \times 10^{-12}. 
$$

(16)

Although the measured value in the pulsar center-of-mass frame differs from this prediction by 1.4 standard deviations, it can be brought into good agreement by increasing the pulsar distance to slightly over 1 kpc. Stated another way, we can assume that GR is the correct theory of gravity, measure the “excess $\dot{P}_{\text{b}}$” for the system as described above and presented in Table 3, and then invert equation (13) to determine the pulsar distance (Bell & Bailes 1996). By this
method we obtain $d = 1.1 \pm 0.2$ kpc (68% confidence limit). The uncertainty is dominated by the measurement uncertainty of $(P_b)_{\text{obs}}$, rather than uncertainties in the galactic rotation parameters or the acceleration $a_z$. It follows that continued timing of this system should lead to a much more precise distance measurement, in due time.

We note that the timing solution provides a second, independent constraint on the distance. The upper limit on parallax, $\pi < 1.7$ mas (Table 2) constrains the distance to $d > 0.6$ kpc. While the parallax distance has less precision than the kinematic distance, it is reassuring that these measurements are in agreement.

An accurate distance for PSR B1534+12 is of considerable interest because of the importance of this system to estimates of the rate of coalescence of binary neutron star pairs in a typical galaxy. Previous estimates of this rate have used much smaller distances for PSR B1534+12, including 0.4 kpc (Narayan, Piran, & Shemi 1991), 0.5 kpc (Phinney 1991), and 0.7 kpc (Curran & Lorimer 1995; van den Heuvel & Lorimer 1996), leading to a low estimate of its intrinsic luminosity. If our newly determined distance is correct, as we believe it must be, the earlier studies have overestimated the number density of systems like PSR B1534+12 in the universe by factors of 2.5–20. We find that the most recent observational estimate of the double neutron star inspiral rate, $2.7 \times 10^{-7}$ yr$^{-1}$ (van den Heuvel & Lorimer 1996), must be reduced to between $1.1 \times 10^{-7}$ yr$^{-1}$ and $1.4 \times 10^{-7}$ yr$^{-1}$, depending on the unknown scale height of such systems in the Galaxy. This is, of course, a lower bound on the number of coalescence events; the actual rate will be higher by unknown factors that account for the fraction of pulsars with beams that do not cross the Earth and the number of double neutron star binaries that do not contain an active pulsar.

4.2. Test of Relativity

Our analysis of this experiment represents the second test of GR based on the $\dot{\omega}$, $\gamma$, and $P_b$ parameters of a binary pulsar system and the first test to add significant measurements of the Shapiro-delay parameters $r$ and $s$. The left-hand sides of equations (8)-(12) represent measured quantities, as specified for this experiment in the “DD” column of Table 3. If GR is consistent with the measurements and there are no significant unmodeled effects, we should expect the five curves corresponding to equations (8)-(12) to intersect at a single point in the $m_1$-$m_2$ plane. A graphical summary of the situation for PSR B1534+12 is presented in Figure 4, in which a pair of lines delimit the 68% confidence limit for each PK parameter (a single line for $\dot{\omega}$, whose uncertainty is too small to show). A filled circle at $m_1 = m_2 = 1.339$ $M_\odot$ marks the DDGR solution of Table 3, and its location on the $\dot{\omega}$ line agrees well (better than 1%) with the measured DD values of $\gamma$ and $s$. We have already noted that the DD value of $P_b$ is slightly too small when corrected to the dispersion-estimated distance. However, as discussed above, this discrepancy can be removed by invoking a larger distance to the pulsar. Finally, the value of $r$, though presently little better than a 20% measurement, is also well centered on its expected value. Altogether we find the measured parameters of the PSR B1534+12 system to be in excellent accord with general relativity, and, consequently, this theory has passed another very significant astrophysical test.

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