THE ASTROPHYSICAL JOURNAL, 456:L33–L35, 1996 January 1

A NEW METHOD FOR OBTAINING BINARY PULSAR DISTANCES AND ITS IMPLICATIONS FOR TESTS OF GENERAL RELATIVITY

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Received 1995 September 12; accepted 1995 October 12

ABSTRACT

We demonstrate how measuring orbital period derivatives can lead to more accurate distance estimates and transverse velocities for some nearby binary pulsars. In many cases this method will estimate distances more accurately than is possible by annual parallax, as the relative error decreases as $t^{-5/2}$. Unfortunately, distance uncertainties limit the degree to which nearby relativistic binary pulsars can be used for testing the general relativistic prediction of orbital period decay to a few percent. Nevertheless, the measured orbital period derivative of PSR B1534+12 agrees within the observational uncertainties with that predicted by general relativity if the proper-motion contribution is accounted for.

Subject headings: gravitation — pulsars: general — relativity

1. INTRODUCTION

The most common method for determining the distances to radio pulsars is based on their dispersion measure and models of the Galactic distribution of free electrons (Taylor & Cordes 1993). These distance estimates typically have an uncertainty of 30%. Distances may also be determined by measuring annual parallax, based either on timing (Ryba & Taylor 1991) or on interferometric measurements (Gwinn et al. 1986). H I absorption by interstellar hydrogen is also a common distance indicator (Frail & Weisberg 1990). However, no pulsar has a distance estimate more accurate than ~10%, and for all but two, the errors are greater than 20%.

Any acceleration of a pulsar along the line of sight will change the observed pulse period derivative $\dot{P}$. As Shklovskii (1970) pointed out, an apparent acceleration occurs when the proper motion (pm) is significant. The magnitude of this contribution is $\dot{P}_{(\rm pm)}/P = v^2/(cd)$, where P is the pulse period, v is the transverse velocity, d is the pulsar distance, and c is the speed of light. For many millisecond pulsars, this effect is of similar magnitude to the intrinsic pulse period derivative, which makes it hard to determine accurately from timing data either the intrinsic pulse period derivative (Camilo, Thorsett, & Kulkarni 1994) or the distance and transverse velocity.

2. DISTANCES AND VELOCITIES

This apparent acceleration also applies to orbital period derivatives, and the contribution is $\dot{P}_{b(\rm pm)}/P_b = v^2/(cd)$, where P_b is the orbital period (Damour & Taylor 1991). In fact, for many nearby millisecond pulsars, it is expected to dominate completely future observed orbital period derivatives. This means that v^2/d can be obtained, and, when combined with the measured proper motion $\mu = v/d$, the distance and transverse velocity can be easily separated. Hence, the proper-motion contribution to the pulse period derivative can also be determined, which gives accurate estimates of the intrinsic pulse period derivative and hence the magnetic field strengths, ages, and spin-down luminosities of binary millisecond pulsars.

The amplitude and functional form of the residuals from a least-squares fit to the observed pulse arrival times, if one parameter is set to zero, is often called the "timing signal" for that parameter. For proper motion, the timing signal is often relatively large, with its amplitude increasing linearly with time. With continued measurement, therefore, its relative error decreases as $t^{-1.5}$. The peak-to-peak amplitude $\Delta T_{\rm pm}$ of the timing signal owing to the contribution of the proper motion to the observed orbital period derivative is

$$\Delta T_{\rm pm} = \frac{a \sin i}{c}\frac{2\pi}{P_b}\frac{v^2}{cd}t^2, \qquad (1)$$

where a is the semimajor axis of the pulsar's orbit, and i is the orbital inclination. The accuracy of distances obtained in this way is limited by the accuracy of the orbital period derivative measurements. Their accuracy, and therefore the accuracy of distances, improves as $t^{2.5}$. The fact that the relative error in both of these critical parameters decreases in such a spectacular fashion with time demonstrates the power of this method for determining distance and transverse velocity.

Table 1 shows the predicted size of the timing signal $\Delta T_{\rm pm}$ after 10 yr of regular timing observations for a selection of binary millisecond pulsars. Where the proper motion was not available, we used the median transverse velocity for millisecond pulsars of 69 km s^{-1}. Also shown is the timing signal due to parallax (Ryba & Taylor 1991), $\Delta T_\pi = r^2 \cos^2 \theta/(2cd)$, where r is the radius of Earth's orbit, and θ is the angle between the line of sight to the pulsar and Earth's orbital plane. After 10 yr, the new method will provide better distance estimates than parallax measurements. This is possible because $\Delta T_{\rm pm} \propto t^2$, while ΔT_π is constant. If an rms timing residual of 1.0 μs could be obtained, it would be possible to determine distances in this way for several of the currently known binary millisecond pulsars. On average, for the pulsars listed in Table 1, 2–3 yr of

TABLE 1

PREDICTED ORBITAL PERIOD DERIVATIVES AND TIMING SIGNALS

PULSAR NAME	ΔT_{pm} (μs)	ΔT_{π} (μs)	CONTRIBUTIONS TO $\dot{P}_b/P_{b(obs)}$ ($\times 10^{-19}$ s^{-1}) $\dot{P}_{b(kz)}/P_b$	$\dot{P}_{b(dr)}/P_b$	$\dot{P}_{b(gr)}/P_b$	$\dot{P}_{b(pm)}/P_b$	REFERENCES
J1713+0747	0.3	1.0	−0.89	−0.29	~0	0.88	1
B1855+09	0.5	0.8	−0.029	−0.002	−0.001	0.96	2
J0613−0200	1.5	0.4	−0.33	−0.67	−0.25	2.4	3
J2317+1439	1.8	0.5	−2.2	0.89	−0.043	2.8	4
J2145−0750	2.2	2.4	−1.3	0.033	−0.009	2.1	5
J0751+1807	2.8	0.6	−0.98	−0.77	−21.8	2.6	6
J0034−0534	3.4	1.2	−2.8	0.17	−0.15	5.3	5
B1913+16	3.8	0.1	−0.064	5.4	−845.3	0.74	7
J2019+2425	4.5	0.7	−0.11	0.45	~0	12.6	8
J1012+5307	7.0	1.5	−1.7	0.16	−1.8	10.1	9
J1022+1001	13.5	2.0	−1.8	0.048	−0.010	8.7	10
J1455−3330	22.4	1.5	−0.69	−0.24	~0	73.1	3
J0437−4715	28.5	1.2	−0.57	0.058	−0.004	67.5	11
B0655+64	31.5	1.4	−0.65	−0.16	−2.1	10.9	2
B1534+12	70.5	1.3	−1.8	−0.24	−52.8	11.0	12

REFERENCES.—(1) Camilo, Foster, & Wolszczan 1994; (2) Taylor, Manchester, & Lyne 1993; (3) Lorimer et al. 1995; (4) Camilo, Nice, & Taylor 1993; (5) Bailes et al. 1994; (6) Lundgren, Zepka, & Cordes 1995; (7) Damour & Taylor 1991; (8) Nice & Taylor 1995; (9) Nicastro et al. 1995; (10) Camilo 1995; (11) Bell et al. 1995; (12) Arzoumanian 1995.

precise timing data have been recorded by various observers. So, to reap the rewards of this method, a further 7–8 yr of precise timing will be required.

3. OTHER CONTRIBUTIONS TO PERIOD DERIVATIVES

Many other effects could contribute to an observed orbital period derivative; for example, changes in the gravitational constant (Damour & Taylor 1991), tidal effects (Will 1993; Arzoumanian, Fruchter, & Taylor 1994; Applegate & Shaham 1994), companion mass loss (Iben & Tutukov 1986), and accelerations in globular cluster potentials (Blandford, Romani, & Applegate 1987). These contributions are indistinguishable from the proper-motion contribution, and so it is important to determine which of them are significant. Known pulsars possess one of five types of companion: a neutron star, a main-sequence star, a white dwarf, a very low mass star, or a planetary system (Wolszczan 1994). Fortunately, binary pulsars with either white dwarf or neutron star companions are very “clean,” and their orbital periods are not affected by tidal or mass-loss effects (Iben & Tutukov 1986). Systems with low-mass companions such as PSR B1957+20 possess large orbital period derivatives, possibly caused by tidal effects (Applegate & Shaham 1994). The small $a \sin i$ induced by planetary companions in the pulsar orbit makes it extremely difficult to measure their orbital period derivatives. The only significant contributions to the orbital period derivatives in neutron star and white dwarf systems are those due to acceleration in the Galactic potential $\dot{P}_{b(kz)}$, Galactic differential rotation $\dot{P}_{b(dr)}$, proper motion $\dot{P}_{b(pm)}$, and general relativity $\dot{P}_{b(gr)}$. Table 1 lists those contributions, showing that the proper-motion term will dominate for many of the binary millisecond pulsars.

For the nearby millisecond pulsar J0437−4715, the uncertainty in $\dot{P}_{b(kz)}$ is ~1% of $\dot{P}_{b(pm)}$. Hence, measurement of the orbital period derivative will ultimately provide a distance estimate that is limited in accuracy to ~1%. If the distance could be independently estimated with superior accuracy, it would be possible to determine the acceleration of the binary in the Galactic gravitational potential and thereby constrain the distribution and composition of dark matter (Flynn & Fuchs 1994). However, pulsars such as PSR J2317+1439 with large z-heights are probably better suited to such an exercise because the contribution from the Galactic acceleration in such pulsars is comparable to the contribution from the proper motion. This emphasizes the importance of monitoring known binary millisecond pulsars and searching for new ones.

4. IMPLICATIONS FOR TESTS OF GENERAL RELATIVITY

The double neutron-star system PSR B1534+12 has been predicted to provide an even better relativistic laboratory than the binary pulsar B1913+16 (Arzoumanian 1995). Unfortunately, the distance to this pulsar is known only to an accuracy of some 30% (Taylor & Cordes 1993), and therefore the proper-motion contribution to the orbital period derivative is uncertain by a similar amount. Recent measurements (Arzoumanian 1995) indicate that the predicted orbital period derivative due to gravitational wave emission $\dot{P}_{b(gr)}$ is -1.924×10^{-13}, whereas the observed value $\dot{P}_{b(obs)}$ is only $-1.5 \pm 0.3 \times 10^{-13}$. Using the dispersion measure distance of 0.68 ± 0.2 pc and the measured proper motion, the contribution to the observed value from the proper motion is $\dot{P}_{b(pm)} = 0.40 \pm 0.12 \times 10^{-13}$. Since $\dot{P}_{b(gr)} = \dot{P}_{b(obs)} - \dot{P}_{b(pm)} = -1.9 \pm 0.3 \times 10^{-13}$, the observed value is in excellent agreement with the general relativistic prediction. Unless the distance estimate can be improved, the orbital period decay due to the emission of gravitational waves cannot be verified to better than ~5% in the PSR B1534+12 system. This is a surprising result, which underlines the importance of obtaining independent distance estimates to this system.

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