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FURTHER OBSERVATIONS OF THE BINARY PULSAR PSR 1913+16

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ABSTRACT

We report the results of more than a year's timing observations of the binary pulsar PSR 1913+16. Within the accuracy of our measurements, about ± 300 μs, the pulse arrival times are exactly those expected from a clock of well-defined period, moving in a Keplerian orbit with a constant rate of apsidal advance. The observations have yielded much-improved values for the parameters of the pulsar and its orbit, and are approaching the length of baseline needed to perform certain tests of gravitation theories. We place an upper limit of 60 μJy on periodically pulsed radio emission from the companion object.

Subject headings: pulsars — stars: binaries

I. INTRODUCTION

More than a year has elapsed since the discovery of the binary pulsar PSR 1913+16 (Hulse and Taylor 1975, hereafter referred to as HT). Early hopes that the pulsar would behave as a stable clock, so that a number of interesting astrophysical and relativistic "experiments" could be performed, have so far been fulfilled. At the present writing, pulse arrival times have been accumulated over a span of 390 days, and the behavior of the pulsar is perfectly described (within the accuracy of our measurements) as that of a clock with a well defined period, moving in a slowly precessing Keplerian orbit. Relativistic effects such as the $O(v/c)^2$ Doppler shift and the gravitational redshift are undoubtedly present in the data at a significant level, but will not be separable from the much larger first-order effects until several more years have elapsed and the orbit has rotated through an appreciable angle (see Blandford and Teukolsky 1975; Brumberg *et al.* 1975). The existing data have yielded greatly improved values for the orbital elements, including the rate of advance of periastron $\dot{\omega}$ and upper limits to the rates of change of the other orbital elements, as well as accurate celestial coordinates and a small but nonzero spin-down rate $\dot{P}$. We have searched without success for evidence of pulsed radio emission from the still-invisible companion object.

II. OBSERVATIONS

All of the data under discussion were taken with the 305 m telescope at Arecibo, Puerto Rico, at a frequency of 430 MHz. At this frequency the telescope provides a sensitivity of 19 K Jy^{-1} at small zenith angles, decreasing to 8 K Jy^{-1} at 20° from the zenith. The usable bandwidth is 8 MHz, and the effective noise temperature, when pointed at PSR 1913+16, is about 180 K.

Three different data acquisition systems were used. The first system (system 1), in use from 1974 September through 1975 January, consisted of a dual 32-channel filter-bank receiver and an analog dedispersing device (Taylor and Huguenin 1971). The receiver detected both circularly polarized components of the pulsar signal in 32 different frequency bands, each 250 kHz in width. The two detected signals at each frequency were summed, smoothed with a time constant of 5 ms, and introduced, in order of increasing frequency, to summing junctions on the dedispersing shift register. The clock rate of the shift register was adjusted to match the interchannel signal delays caused by interstellar dispersion, assuming a dispersion measure of 167 cm^{-3} pc (HT). The "dedispersed" output from the shift register was sampled at 2 ms intervals and written onto magnetic tape by the Observatory's on-line computer. The Universal Time at which the samples were taken was also recorded, with an accuracy of about 10 μs. With this system, overall instrumental smoothing of the data amounted to about 6 ms.

The data on tape were later folded at a number of different periods close to the period expected at the time of observation. The best-fit period for each 5 minute segment of data was recorded, as was the average pulse profile. Each of these profiles was then cross-correlated with a standard profile (obtained by averaging together a number of individual profiles) to find the precise time of pulse arrival. Observations of the pulsar on a given day typically lasted for about 2 hours, so that approximately 20 periods and arrival times were normally obtained in an observing session. A total of 448 measurements were obtained in this way. The rms uncertainty of a single measurement made with system 1 was about 0.5 μs in period and about 300 μs in arrival time.

The second observing system (system 2), in use during 1975 April and May, responded only to the right-hand circular component of the input signal and used a 32×20 kHz filter-bank receiver and an all-digital dedispersing device (Boriakoff 1973). The effective instrumental smoothing with this system was only 0.4 ms, and 1024 equally spaced data samples were taken during each pulsar period. The signal averaging to produce mean pulse profiles was done in real time, with an average pulse profile being recorded on magnetic tape approximately every five minutes. As in system 1, pulse arrival times were determined by cross-correlating individual profiles with a standard profile. A total of 43 arrival times were obtained in this way during 1975 April and May, and the rms uncertainty of a single measurement was approximately 200 μs.

A third observing system (system 3) was in use from 1975 June to October, because of a malfunction in the digital dedisperser. In this mode two single-channel receivers, each of 250 kHz bandwidth, responded to opposite circular polarizations. Data samples were taken and averaged as in system 2, but independently for each of the two receivers. After the mean pulse profiles were cross-correlated with the standard profile, the arrival times computed for the two polarizations were averaged. Another 43 arrival times were obtained by this method, with an rms uncertainty of about 1 ms for a single measurement.

III. ANALYSIS OF TIMING DATA

Approximate orbital elements for PSR 1913+16 were obtained by HT, and improved values were obtained (Taylor 1975) by performing a linearized least-squares fit of a theoretical velocity curve to the period data obtained with system 1. A total of eight independent quantities were included in the fit, including the pulsar period P_0 and its derivative $\dot{P}$; the projected orbital semimajor axis $a_1 \sin i$; the eccentricity e; the binary period P_b; the longitude of periastron ω_0; the time of a reference periastron passage T_0 (which is also the time at which P_0 and ω_0 are defined); and the rate of advance of periastron, $\dot{\omega}$. The fitted values of these parameters, as computed from the period measurements, are given in Table 1.

For binary pulsars, unlike the case for ordinary spectroscopic binary stars, it is possible to analyze the orbit in terms of radial displacements instead of radial velocities. In the present instance this procedure yields considerably improved accuracy, because the uncertainty of the arrival-time measurements, expressed as a fraction of the light travel time across the orbit, is $c\sigma_t/(a_1 \sin i) \approx 1.2 \times 10^{-4}$, while the corresponding fractional uncertainty of the period changes is $\sigma_P/(P_{\max} - P_{\min}) \approx 6 \times 10^{-3}$. This use of arrival times for solution of the orbit is a straightforward extension of standard methods of analyzing timing data for single pulsars (e.g., Manchester and Peters 1972). In effect the phase of the pulsar "clock," as well as its frequency, is accurately monitored throughout the course of the data taking.

The analysis of binary orbits by means of measured arrival times has been discussed in detail by Blandford and Teukolsky (1976). One uses the best available estimates of the pulsar and orbit parameters to predict the times of pulse arrival, and then subjects the resulting arrival-time residuals to a linearized least-squares solution for improved parameters. We have used essentially the method described by Blandford and Teukolsky. The observed times of arrival were corrected to give solar system barycentric arrival times, t, measured from the time of the first pulse. Then, the phase of the pulsar (measured in periods) was predicted from the equation

$$\phi(t) = \nu t + \tfrac{1}{2}\dot{\nu}t^2 + \nu Q\left(\frac{2\pi RS}{P_b} - 1\right) - \dot{\nu}Qt\,, \quad (1)$$

where $\nu = P_0^{-1}$, $\dot{\nu} = -\dot{P}P_0^{-2}$, and we have the following shorthand notations, with c = the velocity of light:

$$x = (a_1 \sin i)/c\,, \quad f = \cos E - e\,,$$
$$g = x \sin \omega\,, \quad h = x \cos \omega (1 - e^2)^{1/2}\,,$$
$$Q = gf + h \sin E\,, \quad R = -g \sin E + h \cos E\,,$$
$$S = (1 - e \cos E)^{-1}, \quad \omega = \omega_0 + \dot{\omega}t\,. \quad (2)$$

TABLE 1

PARAMETERS OF PSR 1913+16 FROM TIMING OBSERVATIONS

Parameter	Value Obtained from Period Data	Value Obtained from Arrival-Time Data
α (1950.0)	...	$19^h13^m12^s.484 \pm 0^s.008$
δ (1950.0)	...	$+16°01'08''.4 \pm 0''.2$
P_0 (s)	0.0590301 ± 2	0.059029995272 ± 5
$\dot{P}$	$<10^{-13}$	$(8.8 \pm 0.3) \times 10^{-18}$
$a_1 \sin i$ (cm)	$(7.015 \pm 0.016) \times 10^{10}$	$(7.0043 \pm 0.0004) \times 10^{10}$
e	0.616 ± 0.001	0.61717 ± 0.00005
P_b (s)	27906.96 ± 0.06	27906.980 ± 0.002
ω_0 (degrees)	178.7 ± 0.3	178.861 ± 0.007
T_0 (JD)	2,442,321.4327 ± 0.0002	2,442,321.433210 ± 0.000004
$\dot{\omega}$ (degrees yr^{-1})	4.0 ± 1.5	4.22 ± 0.04
$\dot{x}$ (cm s^{-1})	...	(−0.2 ± 1.2)
$\dot{e}$ (s^{-1})	...	$(1 \pm 1) \times 10^{-11}$
$\dot{P}_b$	...	$(2 \pm 6) \times 10^{-10}$
RMS residual	0.4 μs (in period)	300 μs (in arrival time)
Data span	1974 Sept. 12–Dec. 1 (80 days)	1974 Sept. 29–1975 Oct. 23 (390 days)

The parameter E is the eccentric anomaly, defined by

$$2\pi(t - T_0)/P_b = E - e \sin E\,. \qquad (3)$$

If the pulsar behaved as a perfect clock, if the measurements were error-free, and if the assumed orbital elements were exactly correct, then the phases predicted by equation (1) would be integers. In practice, therefore, timing residuals are defined as $(\phi - n)$ periods or $(\phi - n)/\nu$ seconds, where n is the closest integer to ϕ. Improvements to the pulsar and orbit parameters are fitted to the observed residuals by the method of least squares, using the equation

$$\begin{aligned}\frac{(\phi - n)}{\nu} &= \frac{\phi_0}{\nu} - \frac{1}{\nu}[t - Q][\Delta\nu + \tfrac{1}{2}t\Delta\dot{\nu} + \tfrac{1}{6}t^2\ddot{\nu}] \\ &+ A(\Delta\alpha + \mu_\alpha t) + B(\Delta\delta + \mu_\delta t) \\ &+ [f \sin\omega + (1 - e^2)^{1/2}\cos\omega \sin E][\Delta x + t\dot{x}] \\ &+ x[f\cos\omega - (1 - e^2)^{1/2}\sin\omega\sin E][\Delta\omega + t\Delta\dot{\omega}] \\ &- SR\left[\frac{2\pi}{P_b}\Delta T_0 + \frac{2\pi t}{P_b{}^2}(\Delta P_b + \tfrac{1}{2}t\dot{P}_b)\right] \\ &- S[g(1 + \sin^2 E - e\cos E) \\ &\quad - (hf\sin E)(1 - e^2)^{-1}][\Delta e + t\dot{e}] + \gamma\sin E\,. \qquad (4)\end{aligned}$$

The parameters A and B depend on the direction cosines of the observatory and the pulsar as seen from the solar system barycenter (see Manchester and Peters 1972; Manchester, Taylor, and Van 1974). Quantities in equation (4) preceded by Δ, such as $\Delta\nu$, are differential corrections to the initial values used to predict the pulsar phase. Initial values are not required for the parameters ϕ_0, $\ddot{\nu}$, μ_α, μ_δ, $\dot{x}$, $\dot{P}_b$, $\dot{e}$, and γ. Note that equation (4) is linear in the 18 parameters to be solved for, which include all of the 13 parameters in Table 1 as well as the initial pulsar phase ϕ_0, the second derivative $\ddot{\nu}$, the proper motion terms μ_α and μ_δ, and the quantity γ. (For computational convenience, ν, $\dot{\nu}$, and $\ddot{\nu}$ are explicitly solved for instead of P_0, $\dot{P}$, and $\ddot{P}$.) The parameter γ is the term which measures the combined effects of $O(v/c)^2$ Doppler shift and gravitational redshift; in our notation it is defined by

$$\gamma = \frac{2\pi a_1{}^2 e}{c^2 P_b}\left(2 + \frac{M_1}{M_2}\right), \qquad (5)$$

where M_1 and M_2 are the masses of the pulsar and the companion (see Blandford and Teukolsky 1976). It is difficult to determine γ from a short span of observations, because its coefficient depends on orbital phase in nearly the same way as do the coefficients of Δx and $\Delta\omega$. However, after several years the orbit will have rotated through a sufficient angle to decouple these terms and allow an evaluation of γ. In view of the large estimated distance of the pulsar, about 6 kpc, and the very small value of $\dot{P}$, it is very unlikely that μ_α, μ_δ, or $\ddot{\nu}$ will be measurable even after 10 years or more.

The results of a least-squares solution for 14 of the 18 parameters are given in column (3) of Table 1. The value of ϕ_0, which depends on our standard profile, is not listed. The final residuals after the fit are plotted as functions of both orbit phase and date in Figure 1. The graphs make it clear that the remaining residuals do not contain systematic orbital, annual, or secular dependences, and evidently the physics underlying equation (4) provides an accurate description of

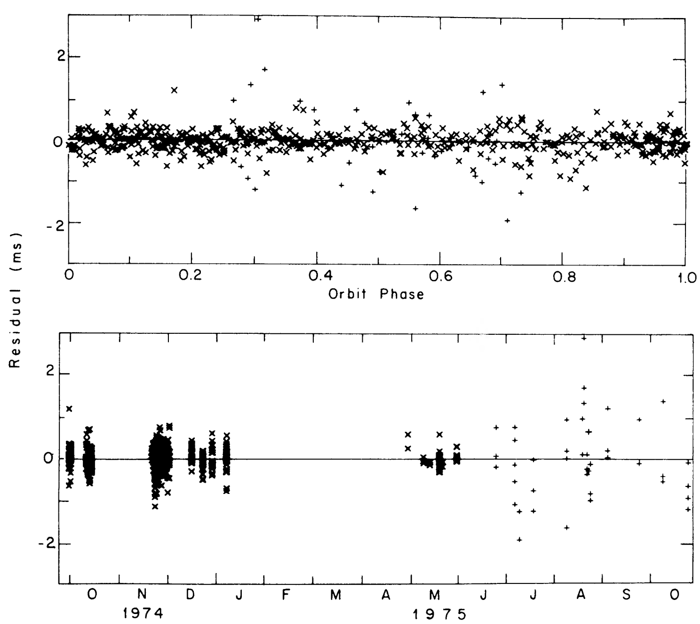

Fig. 1.—Timing residuals for PSR 1913+16, defined as observed minus predicted pulse arrival time, plotted as a function of orbit phase (*upper*) and date (*lower*). Observations taken with the aid of dispersion-removing equipment (×××) have an rms deviation of about 300 μs. The other measurements (*plus signs*) have an rms value of 1 ms.

the pulsar and its orbit. We note also that the uncertainties quoted in Table 1, which are twice the formal standard errors, are in good agreement with the error analysis in § III of Blandford and Teukolsky's (1976) paper.

One should be aware that the true values of P_0, $a_1 \sin i$, P_b, and $\dot{\omega}$ differ from the numbers quoted in Table 1 by a systematic fractional error v_r/c, where v_r is the (unmeasurable) radial component of the relative motion between the binary and solar system barycenters. Furthermore, equation (4) shows that at the current $\omega \sim \pi$, the quoted value of $a_1 \sin i$ has "absorbed" most of the undetermined γ term, and is therefore too large by a factor of approximately $1 + \gamma c\,(a_1 \sin i)^{-1}(1 - e^2)^{-1/2} \sim 1.002$. This should serve as a warning that other significant effects could possibly have been overlooked if their functional forms mimic one of the terms included explicitly.

IV. SEARCH FOR A COMPANION PULSAR

About 20 hours of data acquired with system 1 were subjected to further analysis in the hope that the invisible companion might also be a detectable radio pulsar. The data sampled at 2 ms intervals were summed in pairs and in groups of eight to form long sequences of samples at 4 and 16 ms intervals. Discrete power spectra were computed for sequences of 16,384 such data points, and the resulting spectra were summed into 10 different arrays according to the orbital phase of the known pulsar. Only data taken near the maximum of the velocity curve, where the radial velocity is changing slowly, were used. The 10 spectral arrays were adjusted to compensate for the Doppler shifts expected for companion pulsars of mass such that $0 < M_1/M_2 < 10$. They were then summed to form "grand average" spectral arrays, and plotted for visual inspection. No evidence of periodic signals was found in any of the plots, except at the frequencies of PSR 1913+16 and the 60 Hz power line and their harmonics. A companion pulsar with a period in the range 8 ms to 4 s would have been detectable in this way if its average flux density exceeded 60 μJy and if its mass was not less than one-tenth the mass of PSR 1913+16. We show below on dynamical grounds that if the companion star is as compact as a neutron star, its mass cannot be less than 0.56 times that of the pulsar. We conclude that the companion either is not an active pulsar or is oriented so that its beamed emission does not pass over the Earth.

V. DISCUSSION

In order to gain a complete dynamical understanding of this orbiting system, one would need to determine independently the masses M_1 and M_2, the orbital semimajor axis a_1, and the orbit inclination i. Two relations between these four quantities are immediately available, because the projected semimajor axis,

$$a_1 \sin i = 7.0043 \times 10^{10}\ \text{cm}\,, \tag{6}$$

and the mass function,

$$\frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{4\pi^2}{G}\frac{(a_1 \sin i)^3}{P_b{}^2} = 0.13126 \pm 0.00002\ M_\odot\,, \tag{7}$$

are determined by existing observations. In order to proceed further, it is necessary to know something about the unseen companion. If it is sufficiently compact to behave dynamically as a point mass, then the general-relativistic prediction for $\dot{\omega}$ provides a third relation between the four unknown quantities which, upon inserting known values of the orbital elements, reduces to

$$\dot{\omega} = 2.11 \left(\frac{M_1 + M_2}{M_\odot}\right)^{2/3} \text{deg yr}^{-1}\,. \tag{8}$$

This equation, together with the mass function and the observed value $\dot{\omega} = 4.22$ deg yr^{-1}, shows that the total mass is $M_1 + M_2 = 2.83\ M_\odot$ and that the orbital inclination must satisfy $21° < i < 90°$. The distribution of the total mass between M_1 and M_2 is defined by choosing a particular value of i in this range, as illustrated in Figure 2.

A fourth relationship among the four quantities will be provided by a measurement of γ, the second-order Doppler and gravitational redshift term. With the aid of known values of $a_1 \sin i$, e, P_b, and $\dot{\omega}$, and using equations (7) and (8), one can rewrite equation (5) in the form (Blandford and Teukolsky 1976)

$$\gamma = 2.07 \times 10^{-3} \left(\frac{M_2}{M_\odot}\right)\left(1 + \frac{M_2}{2.83 M_\odot}\right) \text{s}\,. \tag{9}$$

The restrictions already placed on M_2 (Fig. 2) require γ to fall in the range $0.003\ \text{s} < \gamma < 0.012$ s.

We can summarize the preceding discussion by writing explicit equations for M_1, M_2, a_1, and i in terms

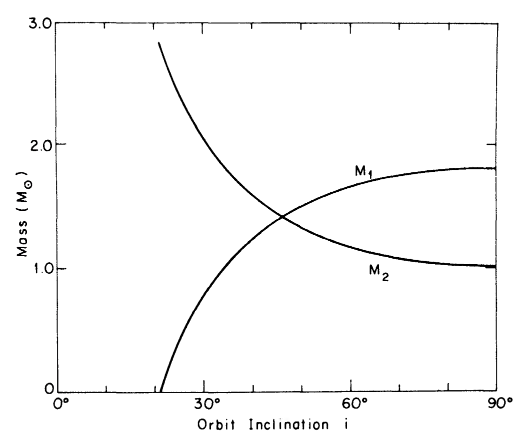

FIG. 2.—The masses of PSR 1913+16, M_1, and its unseen companion, M_2, plotted as a function of orbit inclination i. It is assumed that both objects behave as point masses, so that the only significant contribution to $\dot{\omega}$ is the general-relativistic one.

of the unknown value of γ. First, we define

$$Z = \left(2.01 + \frac{\gamma}{7.33 \times 10^{-4}\,\mathrm{s}}\right)^{1/2} . \qquad (10)$$

Then the desired equations are:

$$M_1 = (4.25 - Z)\, M_\odot , \qquad (11)$$

$$M_2 = (Z - 1.42)\, M_\odot , \qquad (12)$$

$$a_1 = 6.89 \times 10^{10}(Z - 1.42)\ \mathrm{cm} , \qquad (13)$$

$$i = \sin^{-1}\left(\frac{1.017}{Z - 1.42}\right) . \qquad (14)$$

It has not yet been shown conclusively that the unseen companion of PSR 1913+16 is sufficiently compact to ensure that classical contributions to the apsidal advance will be negligible, and therefore that equations (8)–(14) will be valid. However, there exists only a small class of possible companions which would be both small enough to produce no more than the observed rate of advance of periastron (and also to avoid eclipsing the pulsar) and large enough that they cannot be treated as point masses (HT; Roberts, Masters, and Arnett 1976). Smarr and Blandford (1976) have shown that only a helium main-sequence star or a rapidly rotating white dwarf fit into this category, and Webbink (1975) has argued on evolutionary grounds that a neutron star is the most likely companion. We note in passing that if the companion were a helium star, it would probably be as bright as $m_v \approx 20$ (Smarr and Blandford 1976); however, no object is visible on the Sky Survey prints at the position quoted in Table 1.

If the "point mass" nature of the companion can be demonstrated, then timing measurements of PSR 1913+16 will probably provide some heretofore unavailable tests of gravitation theories. Several such tests have been suggested that appear to be both observationally feasible and theoretically illuminating. Most theories of gravity predict a secular decrease of the binary period due to a loss of energy in the form of gravitational waves. For example, general relativity predicts a value (Wagoner 1975*a*, *b*)

$$\dot{P}_b = -0.85 \times 10^{-12}\left(\frac{m^{4/3}}{\sin i}\right)\left(1 - \frac{0.51}{m^{1/3}\sin i}\right)$$
$$\sim -3 \times 10^{-12} , \qquad (15)$$

where $m = (M_1 + M_2)/M_\odot$ is the total mass in solar units. For comparison, Eardley (1975) has pointed out that Brans-Dicke theory allows dipole as well as quadrupole gravitational radiation and predicts a value of $\dot{P}_b$ as much as three orders of magnitude larger. In a few years the accuracy with which $\dot{P}_b$ and i can be determined should be sufficient to allow tests of both the Brans-Dicke and the general-relativistic predictions.

Will (1976) has pointed out that according to some metric theories of gravity, the center of mass of a binary system may be accelerated toward periastron because of a violation of post-Newtonian momentum conservation. Observations of secular changes of the pulsar period can be used to place limits on any such acceleration, and hence on the parametrized post-Newtonian (PPN) parameter ζ_2. The contribution to $\dot{P}$ from this cause would be (Will 1976)

$$\dot{P} \approx -4 \times 10^{-16}\zeta_2 \frac{X(1 - X)}{(1 + X)^2} m^{2/3} T , \qquad (16)$$

where $X = M_1/M_2$ is the mass ratio and T is the time spanned by the observations, in years since 1974 September. From the values $\dot{P} = 8.8 \times 10^{-18}$, $m = 2.83$, and $T = 1$, we obtain

$$|\zeta_2| < 0.01\, \frac{(1 + X)^2}{X(1 - X)} . \qquad (17)$$

Unless i happens to be very close to 46°, we will have $|1 - X| > 0.1$, and the limit imposed by inequality (17) would become at least as restrictive as $|\zeta_2| < 0.4$. The best independently available limit is $|\zeta_2| < 100$, obtained from gravitational redshift data for white dwarfs (Shapiro and Teukolsky 1976).

Other possible uses of PSR 1913+16 to test gravitational theories have been discussed by Esposito and Harrison (1975), Hari-Dass and Radhakrishnan (1975), Smarr and Blandford (1976), and others. The most promising of these involve measurements of $O(v/c)^3$ terms in the timing data and spin precession of the pulsar axis, both of which may be feasible with improved observations.

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