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Progress Report on the Binary Pulsar 1913+16

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Abstract

We report on the current status of observations of the binary pulsar PSR 1913+16. The average pulse shape, polarization and spectrum have been found to be similar to those of other pulsars. We find no evidence for irregularities in the rotational frequency of the pulsar. With present measurement uncertainties, timing measurements after a few more years will yield estimates of the individual masses of the pulsar and its companion. the orbital inclination and the derivative of the orbital period. Upper limits on the last parameter are already inconsistent with theories that predict dipole gravitational waves; its measurement will test a specific prediction of general relativity theory and will indirectly demonstrate the existence of gravitational waves.

Introduction

This paper is an interim report on a continuing series of observations of the only known pulsar in a binary system, PSR 1913+16. Pulse arrival-time measurements have now been made over a span of more than three years, beginning in September 1974. Earlier papers (Hulse and Taylor 1975; Taylor 1975; Taylor *et al.* 1976) have summarized the first year's data, which showed that the measured pulse arrival times are fully consistent with those expected from a ticking clock of precisely defined period and slow down rate, moving in a Keplerian orbit with a fixed rate of apsidal advance. The identity of the companion object has not yet been ascertained; searches at radio (Taylor *et al.* 1976), optical (Kristian *et al.* 1976) and X-ray (Davidsen *et al.* 1975) wavelengths have all yielded negative results. The absence of eclipses and the measured rate of periastron advance require the companion to be a compact star of a solar mass or so, probably a white dwarf or another neutron star.

Observations

Successful observations of the binary pulsar at the Arecibo Observatory have now been made at 430, 610, 1410 and 2380 MHz. Pulse profiles obtained at 430 and 1410 MHz, where the bulk of the data have been taken, are shown in Fig. 1. These observations made use of 32×20 and $2\times 32\times 250$ kHz filter bank receivers respectively and a digital post-detection de-dispersing device (Boriakoff 1973). The effective time resolution for these observations was approximately 400 μs at 430 MHz and 150 μs at 1410 MHz. The pulse shape changes substantially with observing frequency, being both narrower and less complicated at the higher frequency. The overall pulse width (at the 10% intensity points) is 9·9 ms at 430 MHz and

8·4 ms at 1410 MHz. The separation between the two principal peaks in the profile is 7·0 and 6·6 ms at the lower and higher frequency respectively. As can be seen in Fig. 1, a third maximum situated about 5 ms after the first is present at the lower frequency only. We have found no significant dependence of pulse shape on orbit phase, nor any secular changes in the profile. Secular changes are to be expected in due course, because geodetic precession will cause the pulsar spin axis to change direction by $\sim 1° \, yr^{-1}$, thereby presenting the observer with different cuts through the radiation beam (Esposito and Harrison 1975; Barker and O'Connell 1975; Hari-Dass and Radhakrishnan 1975). Such effects will probably become observable within a few years.

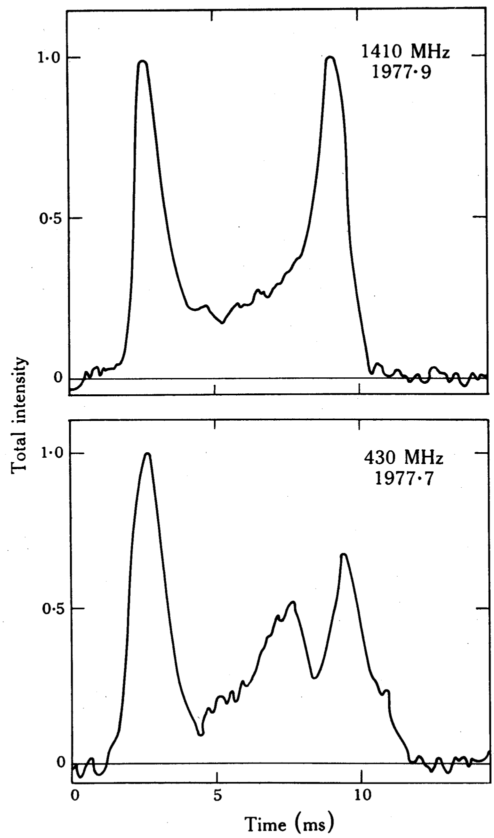

Fig. 1. Integrated total intensity profiles of the binary pulsar PSR 1913+16 at 430 and 1410 MHz. Integrations of 150 000 pulses were used.

The dispersion measure has been determined from timing measurements at 430 and 1410 MHz to be $171 \cdot 61 \pm 0 \cdot 02 \, cm^{-3} \, pc$. The uncertainty of the dispersion measure brackets any variation with orbital phase, from which a limit of $10^6 \, cm^{-3}$ can be placed on the electron density inside the orbit. This result places a strong limit on the density of any stellar wind from the companion star (Smarr and Blandford 1976) and is further evidence of the compact nature of the companion.

Table 1. Parameters of PSR 1913+16 from timing observations

Measured parameter	Symbol	Sept. 1974 to Dec. 1977	July 1977 to Dec. 1977
	(a) Astrometric and pulsar 'clock' effects		
Right ascension	$\alpha(1950)$	$19^{h}\,13^{m}\,12^{s}{\cdot}482\pm0^{s}{\cdot}003$	—
Declination	$\delta(1950)$	$16°\,01'\,08''{\cdot}24\pm0''{\cdot}06$	—
Period	P (s)	$0{\cdot}059\,029\,995\,269\,9\pm5$	$0{\cdot}059\,029\,995\,271\,7\pm9$
Derivative of P	$\dot{P}$ (s s^{-1})	$(8{\cdot}64\pm0{\cdot}02)\times10^{-18}$	—
	(b) Classical orbit effects		
Projected semimajor axis	$x \equiv a_1 \sin i$ (s)	$2{\cdot}344\,2\pm0{\cdot}000\,2$	$2{\cdot}344\pm0{\cdot}007$
Orbital eccentricity	e	$0{\cdot}617\,22\pm0{\cdot}000\,06$	$0{\cdot}617\,13\pm0{\cdot}000\,03$
Binary period	P_b (s)	$27\,906{\cdot}981\,2\pm0{\cdot}000\,4$	$27\,906{\cdot}981\,3\pm0{\cdot}000\,6$
Periastron longitude	ω (deg)	$178{\cdot}864\pm0{\cdot}005$	$178{\cdot}84\pm0{\cdot}03$
Periastron passage time	T_0 (JD)	$2\,442\,321{\cdot}433\,209\pm4$	$2\,442\,321{\cdot}433\,206\pm6$
	(c) Relativistic orbit effects		
Periastron advance rate	$\dot{\omega}$ (deg yr^{-1})	$4{\cdot}221\pm0{\cdot}002$	—
Second-order Doppler	γ (s)	—	$0{\cdot}006\pm0{\cdot}005$
Orbital inclination	$\sin i$	—	$-0{\cdot}5\pm0{\cdot}9$
Derivative of P_b	$\dot{P}_b$ (s s^{-1})	$(3\pm6)\times10^{-12}$	—
	(d) Other possible effects		
Derivative of x	$\dot{x}$ (s s^{-1})	$(-2\pm2)\times10^{-12}$	—
Derivative of e	$\dot{e}$ (s^{-1})	$(-1{\cdot}1\pm0{\cdot}7)\times10^{-12}$	—
RMS residual	σ (μs)	300	160
Data span	t (yr)	3·2	0·4

The radio frequency spectrum of the pulsar is similar to that of many pulsars. The data from all four frequencies are described adequately by a power law with a slope of about unity. Polarization observations at 430 MHz show the presence of $\sim$25% mean linear polarization and no circular polarization exceeding 10%.

Analysis of Results

Astrometric and Orbit Parameters

As described by Taylor *et al.* (1976), analysis of the observed pulse arrival times is done by correcting for the propagation time from the observatory to the solar system barycentre and then fitting the data, by the method of least squares, to a multiparameter timing equation. Parameters to be determined include the pulsar coordinates (α and δ), the period and its derivative of the pulsar 'clock' (P and $\dot{P}$), and the five 'Keplerian' orbit parameters ($x \equiv a_1 \sin i$, e, ω, P_b and T_0). Solutions for these parameters are listed in sections (*a*) and (*b*) of Table 1; for interest, we have included both a weighted fit to all of the available data and a fit to a limited set of parameters based solely on 1977 data, which are of higher and more uniform quality. The parameters already discussed have all been determined to high accuracy, in most cases to four or more significant figures.

Relativistic Effects

It has been known since shortly after the discovery of this pulsar that, because of its tightly bound, highly eccentric orbit with $v/c \approx 10^{-3}$, a number of interesting relativistic effects should eventually be observable. The first (and by far the largest) of these is the advance-of-periastron effect, analogous to the well-known prediction of general relativity for planets in the solar system. For two objects of ~ 1 solar mass moving in an orbit similar to that of the binary pulsar, the magnitude of the effect is expected to be $\sim 4° \text{yr}^{-1}$ (Hulse and Taylor 1975); in fact, as shown in Table 1*c*, the value measured is $\dot{\omega} = 4°{\cdot}221 \pm 0°{\cdot}002 \text{yr}^{-1}$. The effect of this large apsidal motion on the pulsar timing observations is vividly illustrated in Fig. 2, which shows the orbital time delay curve and its derivative, the velocity curve, as observed in September 1974 and March 1978. The changes between the two curves amount to several thousand times the measurement uncertainties, as shown by the single datum point plotted with thousand-fold error bars. The actual deviations between measurements and a theoretically computed timing equation are plotted on a magnified scale in Fig. 3.

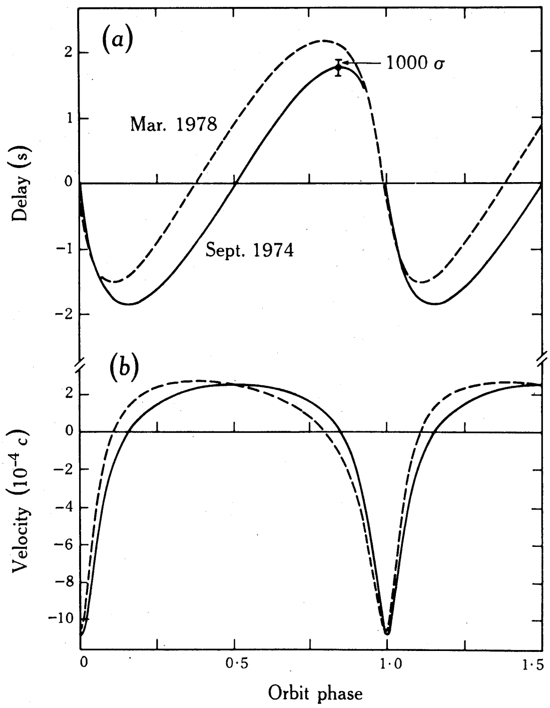

Fig. 2. Time delay curves (*a*) and velocity curves (*b*) for PSR 1913+16 as observed in September 1974 and March 1978. The lone datum point bears error bars 1000 times larger than the present measurement uncertainties.

The next three parameters listed in Table 1*c*, namely γ, $\sin i$ and $\dot{P}_b$, represent additional effects of relativistic origin that should become measureable in the near future. The terms γ and $\sin i$ can be identified with terms of order $(v/c)^2$ and $(v/c)^3$ respectively in the timing equation. To be more specific, γ measures the combined effects of second-order Doppler shift and gravitational redshift, while $\sin i$ is determined from the effects of gravitational propagation delay and the largest post-Newtonian

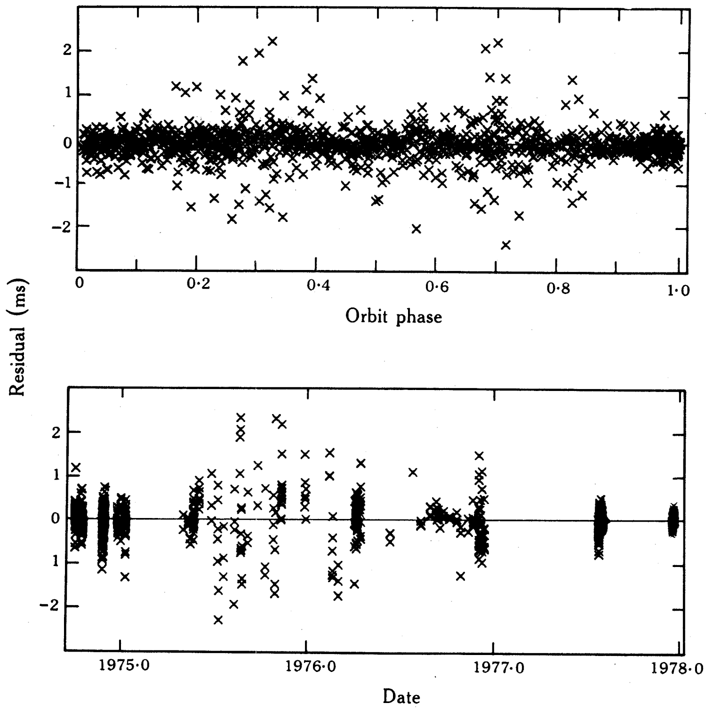

Fig. 3. Timing measurement residuals for PSR 1913+16, defined as observed minus predicted arrival times, plotted as functions of orbit phase and date.

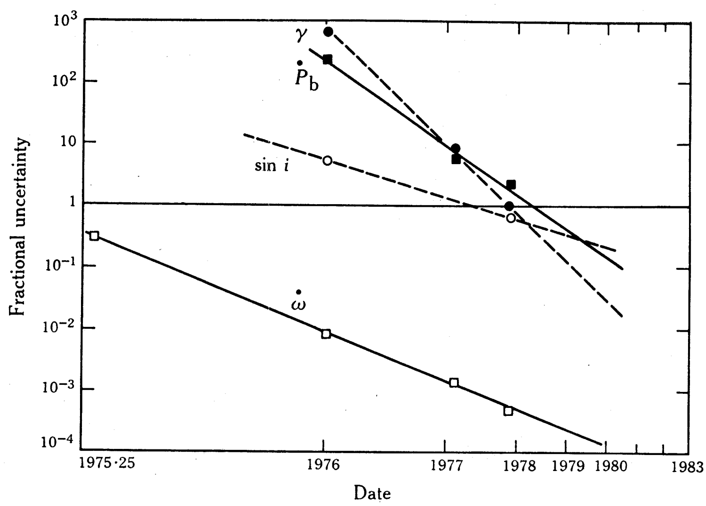

Fig. 4. Empirical fractional uncertainties in the data for the four orbital parameters $\dot{\omega}$, γ, $\dot{P}_b$ and sin i, estimated from relativistic effects, plotted as a function of date. Values assumed for the three undetermined quantities are $\gamma = 0{\cdot}006$ s, $|\dot{P}_b| = 3\times10^{-12}$ s s^{-1} and sin $i = 1$.

orbit corrections (Blandford and Teukolsky 1976; Epstein 1977). The second-order term has an effect on the pulse arrival times of order 5 ms, many times larger than the measurement uncertainty. However, its coefficient depends on orbit phase in almost the same way as the first-order term, and it becomes separately measurable only after a non-negligible fraction of the 85 yr apsidal period has elapsed. The third-order term has a smaller amplitude of only ~ 20 μs but, because its functional dependence on orbit phase is quite unlike any of the other terms, it can in principle be measured over a single orbit. General relativity also predicts that this system should lose orbital energy in the form of gravitational waves, thereby causing a rate of change of orbit period $\dot{P}_b \approx -3 \times 10^{-12}$ s s^{-1} (Wagoner 1975). As shown in Table 1*c*, none of these three effects has yet been measured; however, the quoted uncertainties in the estimates given there show that the improvement in accuracy required to determine them to $\sim 10\%$ is only about an order of magnitude.

A tempting glimpse into a crystal ball may be had by looking at Fig. 4, which is a graph of the best obtainable fractional uncertainties in the 'relativistic' parameters $\dot{\omega}$, γ, $\sin i$ and $\dot{P}_b$ from our data collected over the past three years, plotted as a function of date. It should be noted that many unpredictable factors go into determining details of the decreasing fractional uncertainties, such as improvements in equipment, frequency of observations and so on. However, the graph suggests strongly that all of the parameters under discussion will be measured to useful accuracies within only a few more years.

It is interesting to remark in passing that (1) determination of the binary system masses by measuring γ and $\sin i$ would be the first practical application of general relativity as a tool for precise astronomical measurement; (2) a determination of $\sin i$ would constitute the first detection of gravitational time-delay and post-Newtonian orbital effects outside the solar system; (3) the upper limit already obtained for $|\dot{P}_b|$ is essentially inconsistent with any theory of gravity (such as the Brans–Dicke scalar–tensor theory) that predicts *dipole* gravitational radiation (Eardley 1975); and (4) measurement of $\dot{P}_b \approx -3 \times 10^{-12}$ s s^{-1} would confirm a prediction of general relativity and would furnish an indirect proof of the existence of gravitational waves. For these reasons the observations of PSR 1913+16 are being actively continued.

Note added in proof. Since the writing of this paper, observations with considerably improved time resolution (50 μs) have revealed circular polarization as large as 30% at 430 MHz. The relativistic parameters in Table 1*c* are determined to $\sim 20\%$ accuracy (see Taylor *et al.* 1979).

Acknowledgments

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