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DISCOVERY OF A PULSAR IN A BINARY SYSTEM

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ABSTRACT

We have detected a pulsar with a pulsation period that varies systematically between $0^{\rm s}.058967$ and $0^{\rm s}.059045$ over a cycle of $0^{\rm d}.3230$. Approximately 200 independent observations over 5-minute intervals have yielded a well-sampled velocity curve which implies a binary orbit with projected semimajor axis $a_1 \sin i = 1.0\, R_\odot$, eccentricity $e = 0.615$, and mass function $f(m) = 0.13\, M_\odot$. No eclipses are observed. We infer that the unseen companion is a compact object with mass comparable to that of the pulsar. In addition to the obvious potential for determining the masses of the pulsar and its companion, this discovery makes feasible a number of studies involving the physics of compact objects, the astrophysics of close binary systems, and special- and general-relativistic effects.

Subject headings: binaries — black holes — neutron stars — pulsars — relativity

I. INTRODUCTION

We wish to report the detection of an unusual pulsar discovered during the course of a systematic survey for new pulsars being carried out (Hulse and Taylor 1974) at the Arecibo Observatory in Puerto Rico. The object has a pulsation period of about 59 ms—shorter than that of any other known pulsar except the one in the Crab Nebula—and periodic changes in the observed pulsation rate indicate that the pulsar is a member of a binary system with an eccentric orbit of $0^{\rm d}.3230$ period. Thus for the first time it is possible to observe the gravitational interactions of a pulsar and another massive object, and additional observations should make it possible to determine the masses of the two objects unambiguously.

II. DISCOVERY OF THE BINARY PULSAR

The equipment and searching method used in the pulsar survey have been described previously (Hulse and Taylor 1974). Forty pulsars have now been detected in this work, of which 32 were not previously known; the parameters of the 21 most recently discovered will be given in another paper (Hulse and Taylor 1975). The 59-ms pulsar, PSR 1913+16, was first detected in 1974 July. Attempts to measure its period to an accuracy of $\pm 1\ \mu$s were frustrated by apparent changes in period of up to $\sim 80\ \mu$s from day to day, and sometimes by as much as $8\ \mu$s over 5 minutes. Such behavior is quite uncharacteristic of other pulsars: the largest known secular changes of period are of order $10\ \mu$s per *year*, and irregular changes of period are many orders of magnitude smaller (Manchester and Taylor 1974). It soon became clear that Doppler shifts resulting from orbital motion of the pulsar could account for the observed period changes, and by the end of September an accurate velocity curve of this "single-line spectroscopic binary" had been obtained (see figure 1).

The parameters of the pulsar are given in table 1. In the table, celestial and galactic coordinates are followed by $P_{\rm cm}$, the "center of mass" pulsar period (corrected for the orbital motion of the pulsar and for the motion of the observer in the solar system); an upper limit for $dP_{\rm cm}/dt$, the first derivative of the period; DM, the dispersion measure; S_{430}, the average flux density at 430 MHz; and an upper limit to W_e, the effective pulse width. (The pulses observed at 430 MHz are probably significantly broadened by multipath scattering in the interstellar medium.)

The elements of the binary orbit are given in table 2. K_1 is the semiamplitude of radial velocity variation of the pulsar with respect to the center of mass of the system; P_b is the period of the binary orbit, corrected for the motion of the observatory; e is the eccentricity of the orbit; ω is the longitude of periastron; T is the time of periastron passage; $a_1 \sin i$ is the projected semimajor axis of the pulsar orbit, i being the inclination between the orbit and the plane of the sky; and $f(m) = (M_2 \sin i)^3/(M_1 + M_2)^2$ is the mass function. These quantities were evaluated from the velocity measurements shown as filled circles in figure 1. The

TABLE 1

Parameters of the Binary Pulsar

$\alpha(1950.0) = 19^{\rm h}13^{\rm m}13^{\rm s} \pm 4^{\rm s}$
$\delta(1950.0) = +16^\circ 00' 24'' \pm 60''$
$l = 49^\circ.9$
$b = 2^\circ.1$
$P_{\rm cm} = 0^{\rm s}.059030 \pm 0^{\rm s}.000001$
$dP_{\rm cm}/dt < 1 \times 10^{-12}$
$\mathrm{DM} = 167 \pm 5\ \mathrm{cm^{-3}\,pc}$
$S_{430} = 0.006 \pm 0.003\ \mathrm{Jy}$
$W_e < 10\ \mathrm{ms}$

TABLE 2

Elements of the Orbit

$K_1 = 199 \pm 5\ \mathrm{km\ s^{-1}}$
$P_b = 27908 \pm 7\ \mathrm{s}$
$e = 0.615 \pm 0.010$
$\omega = 179^\circ \pm 1^\circ$
$T = \mathrm{JD}\ 2{,}442{,}321.433 \pm 0.002$
$a_1 \sin i = 1.00 \pm 0.02\ R_\odot$
$f(m) = 0.13 \pm 0.01\ M_\odot$

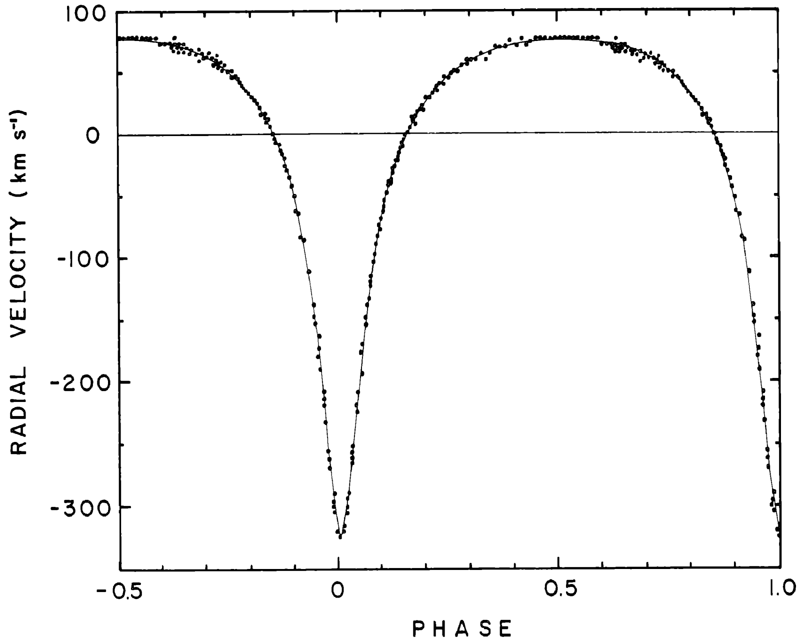

FIG. 1.—Velocity curve for the binary pulsar. Points represent measurements of the pulsar period distributed over parts of 10 different orbital periods. The curve corresponds to equations (1)–(4), with parameters from table 2.

velocity curve also shown in the figure was then computed from the elements using the equations (Aitken 1964)

$$V_{r_1} = K_1[\cos(\theta + \omega) + e\cos\omega]\,, \tag{1}$$

$$\tan\tfrac{1}{2}\theta = [(1+e)/(1-e)]^{1/2}\tan\tfrac{1}{2}E\,, \tag{2}$$

$$M = E - e\sin E\,, \tag{3}$$

$$\phi = M/2\pi = (t - T)/P_b\,, \tag{4}$$

where V_{r_1} is the radial velocity of the pulsar (the "visible" member of the binary pair); M, E, and θ are respectively the mean, eccentric, and true anomaly of the orbit of the pulsar about the center of mass; ϕ is the orbital phase; and t is the time.

The orbital elements given in table 2 were obtained from direct measurements of the pulsar period over about 200 different 5-minute intervals distributed over 10 days. The 5-minute intervals are long enough that the period can be measured to an accuracy of about 1 μs, but short enough that the period does not change too drastically within the interval.

III. PHYSICAL PARAMETERS OF THE BINARY PAIR

The mass of the pulsar is, of course, a quantity of great interest, as is the size and mass of the unseen companion. The observed mass function permits a wide range of values for M_1 and M_2. However, if we restrict attention to values of M_1 thought to be reasonable for neutron stars, the picture becomes clearer. Table 3 gives the required values for V_1, the maximum velocity of the pulsar, and M_2, the mass of the companion, for assumed inclinations i = 90°, 60°, 30°, 20°, and 10°, and pulsar masses $M_1 = 0.3$, 1.0, and 1.5 $M_\odot$. Evidently the mass ratio M_1/M_2 cannot be very different from unity unless the inclination i is rather small, which seems unlikely in view of the large observed radial velocity ($\sim 10^{-3}c$). Furthermore, the orbit is such that if the inclination were close to 90° and the size of the companion were large enough, eclipses of the pulsar would occur at orbital phase $\phi = 0.93$. No eclipses are observed, which requires the radius of the companion to be less than

TABLE 3

POSSIBLE PARAMETERS OF BINARY PULSAR SYSTEM

i (degrees)	V_1 (max)	$M_1 = 0.3$		$M_1 = 1.0$		$M_1 = 1.5$	
		M_2	R_2	M_2	R_2	M_2	R_2
90......	0.0011c	0.4	0	0.7	0	0.9	0
60......	0.0012c	0.5	<0.6	0.9	<0.8	1.1	<0.8
30......	0.0021c	1.5	<1.3	2.2	<1.6	2.6	<1.8
20......	0.0031c	3.8	<1.9	4.8	<2.1	5.4	<2.3
10......	0.0061c	26	<3.5	27	<3.7	28	<3.7

$$\begin{aligned} R_{2,\max} &= (a_1 + a_2)(1 - e^2)\sin i/\tan i \\ &= R_\odot(1 + M_1/M_2)(1 - e^2)/\tan i\,, \end{aligned} \tag{5}$$

where a_2 is the semimajor axis of the orbit of the companion about the center of mass and M_1 and M_2 are the masses of the two objects. Comparison of these upper limits for R_2 with the corresponding values of M_2, together with the known dependence of radius on mass for main-sequence stars (Allen 1973), virtually rules out the possibility that the companion is a main-sequence star. We conclude that the companion must be a compact object, probably a neutron star or a black hole. A white dwarf companion cannot be ruled out, but seems unlikely for evolutionary reasons.

IV. ADDITIONAL OBSERVATIONS

We cannot at present rule out the possibility that the unseen companion is also a radiofrequency pulsar. If pulsations from the companion can be found, the system will be in effect a "double-line" spectroscopic binary and the mass ratio of the two bodies will be directly measurable. This is an exciting possibility, because then only the inclination would have to be determined in order to solve for the two masses.

Timing data much more accurate than that already available can in principle be obtained by recording the absolute time of arrival of the pulses. Observations of this sort done on other pulsars yield absolute arrival times accurate to $\sim 10^{-4}$ s. Measurements of comparable quality are now being acquired for PSR 1913+16, and in due course the data will yield greatly improved accuracies for the celestial coordinates and for the orbital elements of the binary system. This in turn will allow a number of interesting gravitational and relativistic phenomena to be studied. The binary configuration provides a nearly ideal relativity laboratory including an accurate clock in a high-speed, eccentric orbit and a strong gravitational field. We note, for example, that the changes of both v^2/c^2 and GM/c^2r during the orbit are sufficient to cause changes in observed period of several parts in 10^6. Therefore, both the relativistic Doppler shift and the gravitational redshift will be easily measurable. Furthermore, the general-relativistic advance of periastron should amount to about 4° per year, which will be detectable in a short time. The measurements of these effects, not usually observable in spectroscopic binaries, would allow the orbit inclination and the individual masses to be obtained.

The star field in the direction of the pulsar is crowded, and the observed dispersion measure suggests that PSR 1913+16 is about 5 kpc distant. Probably there are some 5 to 10 mag of optical absorption along the line of sight, so we should expect the apparent visual magnitude of the pulsar (and its companion) to be some 18 to 23 mag fainter than the absolute magnitudes. Thus, the prospects for optical observations do not seem good unless a large fraction of the observed dispersion is the result of ionized material close to the pulsar. No changes in dispersion measure exceeding $\pm 20\ \mathrm{cm}^{-3}$ pc have been observed over the binary period, so it is clear that at most a small fraction of the dispersion can arise from electrons within the binary orbit.

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REFERENCES

Aitken, R. G. 1964, *The Binary Stars* (New York: Dover), pp. 79, 158.
Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press), p. 209.
Hulse, R. A., and Taylor, J. H. 1974, *Ap. J.* (*Letters*), **191**, L59.
———. 1975, in preparation.
Manchester, R. N., and Taylor, J. H. 1974, *Ap. J.* (*Letters*), **191**, L63.

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