Binary pulsars and relativistic gravity*

Joseph H. Taylor, Jr.

Princeton University, Princeton, New Jersey 08544

I. SEARCH AND DISCOVERY

Work leading to the discovery of the first pulsar in a binary system began more than twenty years ago, so it seems reasonable to begin with a bit of history. Pulsars burst onto the scene (Hewish *et al.*, 1968) in February 1968, about a month after I completed my Ph.D. at Harvard University. Having accepted an offer to remain there on a post-doctoral fellowship, I was looking for an interesting new project in radio astronomy. When *Nature* announced the discovery of a strange new rapidly pulsating radio source, I immediately drafted a proposal, together with Harvard colleagues, to observe it with the 92 m radio telescope of the National Radio Astronomy Observatory. By late spring we had detected and studied all four of the pulsars which by then had been discovered by the Cambridge group, and I began thinking about how to find further examples of these fascinating objects, which were already thought likely to be neutron stars. Pulsar signals are generally quite weak, but have some unique characteristics that suggest effective search strategies. Their otherwise noise-like signals are modulated by periodic, impulsive waveforms; as a consequence, dispersive propagation through the interstellar medium makes the narrow pulses appear to sweep rapidly downward in frequency. I devised a computer algorithm for recognizing such periodic, dispersed signals in the inevitable background noise, and in June 1968 we used it to discover the fifth known pulsar (Huguenin *et al.*, 1968).

Since pulsar emissions exhibited a wide variety of new and unexpected phenomena, we observers put considerable effort into recording and studying their details and peculiarities. A pulsar model based on strongly magnetized, rapidly spinning neutron stars was soon established as consistent with most of the known facts (Gold, 1968). The model was strongly supported by the discovery of pulsars inside the glowing, gaseous remnants of two supernova explosions, where neutron stars should be created (Large, *et al.*, 1968; Staelin and Reifenstein, 1968), and also by an observed gradual lengthening of pulsar periods (Richards and Comella, 1969) and polarization measurements that clearly suggested a rotating source (Radhakrishnan and Cooke, 1969). The electrodynamical properties of a spinning, magnetized neutron star were studied theoretically (Goldreich and Julian, 1969) and shown to be plausibly capable of generating broadband ratio noise detectable over interstellar distances. However, the rich diversity of the observed radio pulses suggested magnetospheric complexities far beyond those readily incorporated in theoretical models. Many of us suspected that detailed understanding of the pulsar emission mechanism might be a long time coming—and that, in any case, the details might not turn out to be fundamentally illuminating.

In September 1969 I joined the faculty at the University of Massachusetts, where a small group of us planned to build a large, cheap radio telescope especially for observing pulsars. Our telescope took several years to build, and during this time it became clear that whatever the significance of their magnetospheric physics, pulsars were interesting and potentially important to study for quite different reasons. As the collapsed remnants of supernova explosions, they could provide unique experimental data on the final stages of stellar evolution, as well as an opportunity to study the properties of nuclear matter in bulk. Moreover, many pulsars had been shown to be remarkably stable natural clocks (Manchester and Peters, 1972), thus providing an alluring challenge to the experimenter, with consequences and applications about which we could only speculate at the time. For such reasons as these, by the summer of 1972 I was devoting a large portion of my research time to the pursuit of accurate timing measurements of known pulsars, using our new telescope in western Massachusetts, and to planning a large-scale pulsar search that would use bigger telescopes at the national facilities.

I suspect it is not unusual for an experiment's motivation to depend, at least in part, on private thoughts quite unrelated to avowed scientific goals. The challenge of a good intellectual puzzle, and the quiet satisfaction of finding a clever solution, must certainly rank highly among my own incentives and rewards. If an experiment seems difficult to do, but plausibly has interesting consequences, one feels compelled to give it a try. Pulsar searching is the perfect example: it's clear that there must be lots of pulsars out there, and, once identified, they are not so very hard to observe. But finding each one for the first time is a formidable task, one that can become a sort of detective game. To play the game you invent an efficient way of gathering clues, sorting, and assessing them, hoping to discover the identities and celestial locations of all the guilty parties.

Most of the several dozen pulsars known in early 1972 were discovered by examination of strip-chart records, without benefit of further signal processing. Nevertheless, it was clear that digital computer techniques would

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be essential parts of more sensitive surveys. Detecting new pulsars is necessarily a multidimensional process; in addition to the usual variables of two spatial coordinates, one must also search thoroughly over wide ranges of period and dispersion measure. Our first pulsar survey, in 1968, sought evidence of pulsar signals by computing the discrete Fourier transforms of long sequences of intensity samples, allowing for the expected narrow pulse shapes by summing the amplitudes of a dozen or more harmonically related frequency components. I first described this basic algorithm (Burns and Clark, 1969) as part of a discussion of pulsar search techniques, in 1969. An efficient dispersion-compensating algorithm was conceived and implemented soon afterward (Manchester *et al.*, 1972; Taylor, 1974), permitting extension of the method to two dimensions. Computerized searches over period and dispersion measure, using these basic algorithms, have by now accounted for discovery of the vast majority of nearly 600 known pulsars, including forty in binary systems (Taylor *et al.*, 1993; Camilo, 1994).

In addition to private stimuli related to "the thrill of the chase," my outwardly expressed scientific motivation for planning an extensive pulsar survey in 1972 was a desire to double or triple the number of known pulsars. I had in mind the need for a more solid statistical basis for drawing conclusions about the total number of pulsars in the Galaxy, their spatial distribution, how they fit into the scheme of stellar evolution, and so on. I also realized (Taylor, 1972) that it would be highly desirable ". . . to find even *one* example of a pulsar in a binary system, for measurement of its parameters could yield the pulsar mass, an extremely important number." Little did I suspect that just such a discovery would be made, or that it would have much greater significance that anyone had foreseen! In addition to its own importance, the binary pulsar PSR 1913+16 is now recognized as the harbinger of a new class of unusually short-period pulsars with numerous important applications.

An up-to-date map of known pulsars on the celestial sphere is shown in Fig. 1. The binary pulsar PSR 1913+16 is found in a clump of objects close to the Galactic plane around longitude 50°, a part of the sky that passes directly overhead at the latitude of the Arecibo Observatory in Puerto Rico. Forty of these pulsars, including PSR 1913+16, were discovered in the survey that Russell Hulse and I carried out with the 305 m Arecibo telescope (Hulse and Taylor, 1974, 1975a, 1975b). Figure 2 illustrates the periods and spin-down rates of known pulsars, with those in binary systems marked by larger circles around the dots. All radio pulsars slow down gradually in their own rest frames, but the slowdown rates vary over nine orders of magnitude. Figure 2 makes it clear that binary pulsars are special in this regard. With few exceptions, they have unusually small values of both period and period derivative—an important factor which helps to make them especially suitable for high-precision timing measurements.

Much of the detailed implementation and execution of our 1973–74 Arecibo survey was carried out by Russell Hulse. He describes that work, and particularly the discovery of PSR 1913+16, in his accompanying lecture (Hulse, 1994). The significant consequences of our discovery have required accurate timing measurements extending over many years, and since 1974–76 I have pursued these with a number of other collaborators. I shall now turn to a description of these observations.

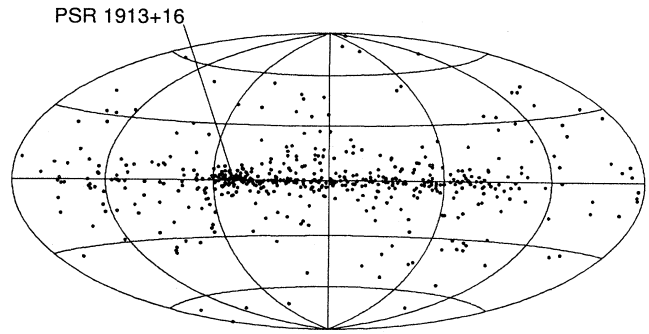

FIG. 1. Distribution of 558 pulsars in Galactic coordinates. The Galactic center is in the middle, and longitude increases to the left.

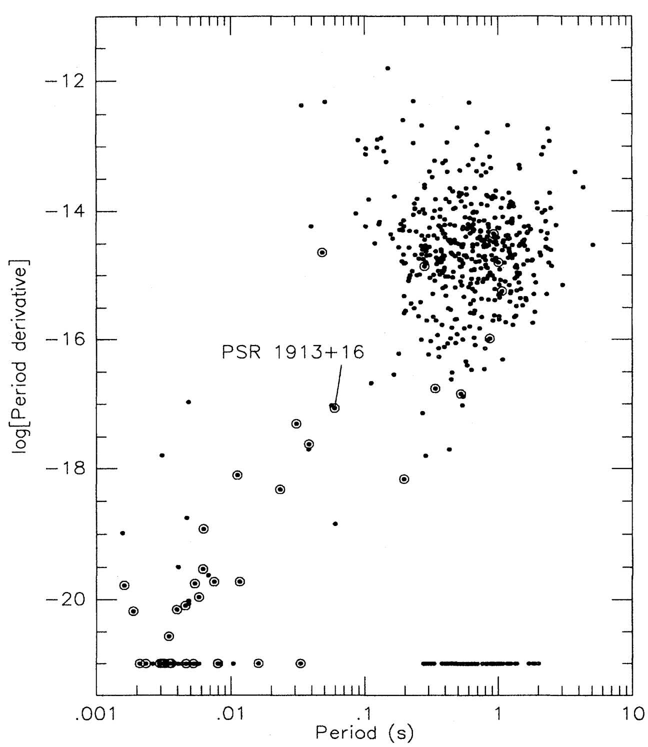

FIG. 2. Periods and period derivatives of known pulsars. Binary pulsars, denoted by larger circles around the dots, generally have short periods and small derivatives. Symbols aligned near the bottom represent pulsars for which the slowdown rate has not yet been measured.

II. CLOCK-COMPARISON EXPERIMENTS

Pulsar timing experiments are straightforward in concept: one measures pulse times of arrival (TOAs) at the telescope, and compares them with time kept by a stable reference clock. A remarkable wealth of information about a pulsar's spin, location in space, and orbital motion can be obtained from such simple measurements. For binary pulsars, especially, the task of analyzing a sequence of TOAs often assumes the guise of another intricate detective game. Principal clues in this game are the recorded TOAs. The first and most difficult objective is the assignment of unambiguous pulse numbers to each TOA, despite the fact that some of the observations may be separated by months or even years from their nearest neighbors. During such inevitable gaps in the data, a pulsar may have rotated through as many as 10^7-10^{10} turns, and in order to extract the maximum information content from the data, these integers must be recovered *exactly*. Fortunately, the correct sequence of pulse numbers is easily recognized, once attained, so you can tell when the game has been "won."

A block diagram of equipment used for recent pulsar timing observations (Taylor, 1991) at Arecibo is shown in Fig. 3. Incoming radio-frequency signals from the antenna are amplified, converted to intermediate frequency, and passed through a multichannel spectrometer equipped with square-law detectors. A bank of digital signal averagers accumulates estimates of a pulsar's periodic wave form in each spectral channel, using a precomputed digital ephemeris and circuitry synchronized with the observatory's master clock. A programmable synthesizer, its output frequency adjusted once a second in a phase-continuous manner, compensates for changing Doppler shifts caused by accelerations of the pulsar and the telescope. Average profiles are recorded once every few minutes, together with appropriate time tags. A log is kept of small measured offsets (typically of order 1 μs) between the observatory clock and the best available standards at national time-keeping laboratories, with time transfer accomplished via satellites in the Global Positioning System.

An example of pulse profiles recorded during timing observations of PSR 1913+16 is presented in Fig. 4, which shows intensity profiles for 32 spectral channels spanning the frequency range 1383–1423 MHz, followed by a "de-dispersed" profile at the bottom. In a five-minute observation such as this, the signal-to-noise ratio is just high enough for the double-peaked pulse shape of PSR 1913+16 to be evident in the individual channels. Pulse arrival times are determined by measuring the phase offset between each observed profile and a long-term average with much higher signal-to-noise ratio. Differential dispersive delays are removed, the adjusted offsets are averaged over all channels, and the resulting mean value is added to the time tag to obtain an equivalent TOA. Nearly 5000 such five-minute measurements have been obtained for PSR 1913+16 since 1974, suing essentially this technique. Through a number of improvements in the data-taking systems (Taylor *et al.*, 1976; McCulloch *et al.*, 1979; Taylor *et al.*, 1979; Taylor and Weisberg, 1982, 1989; Stinebring *et al.*, 1992), the typical uncertainties have been reduced from around 300 μs in 1974 to 15–20 μs since 1981.

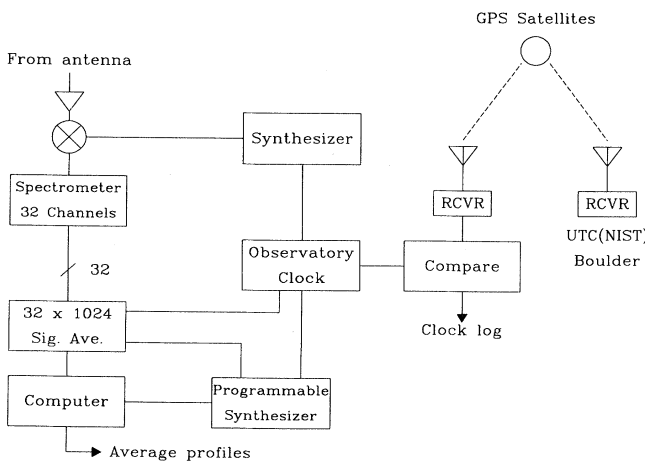

FIG. 3. Simplified block diagram of equipment using for timing pulsars at Arecibo.

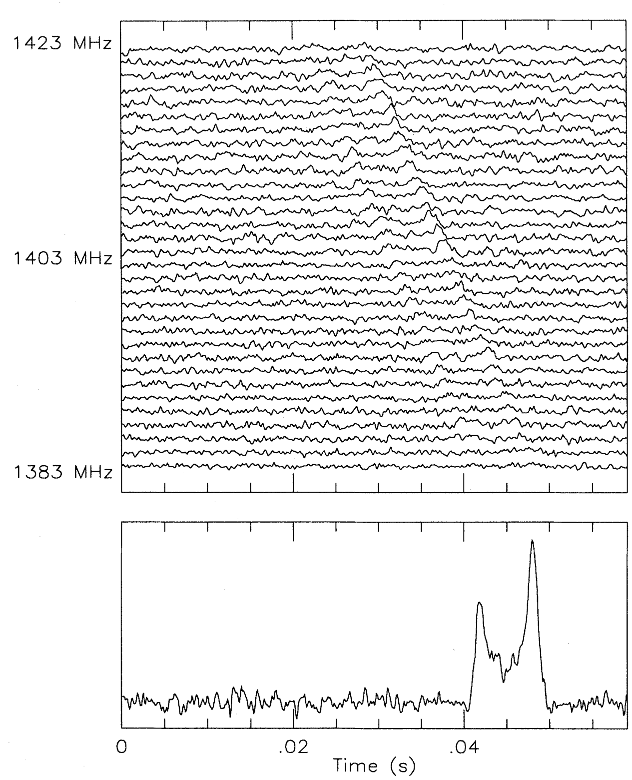

FIG. 4. Pulse profiles obtained on April 24, 1992 during a five-minute observation of PSR 1913+16. The characteristic double-peaked shape, clearly seen in the de-dispersed profile at the bottom, is also discernible in the 32 individual spectral channels.

III. MODEL FITTING

In the process of data analysis, each measured topocentric TOA, say $t_{\rm obs}$, must be transformed to a corresponding proper time of emission T in the pulsar frame. Under the assumption of a deterministic spin-down law, the rotational phase of the pulsar is given by

$$\phi(T)=\nu T+\frac{1}{2}\dot{\nu}T^2 , \qquad (1)$$

where ϕ is measured in cycles, $\nu\equiv 1/P$ is the rotation frequency, P the period, and $\dot{\nu}$ the slowdown rate. Since a topocentric TOA is a relativistic space-time event, it must be transformed as a four-vector. The telescope's location at the time of a measurement is obtained from a numerically integrated solar-system model, together with published data on the Earth's unpredictable rotational variations. As a first step one normally transforms to the solar-system barycenter, using the weak-field, slow-motion limit of general relativity. The necessary equations include terms depending on the positions, velocities, and masses of all significant solar-system bodies. Next, one accounts for propagation effects in the interstellar medium; and finally, for the orbital motion of the pulsar itself.

With presently achievable accuracies, all significant terms in the relativistic transformation can be summarized in the single equation

$$\begin{aligned} T=t_{\rm obs}-t_0+\Delta_C-D/f^2+\Delta_{R\odot}(\alpha,\delta,\mu_\alpha,\mu_\delta,\pi) \\ +\Delta_{E\odot}-\Delta_{S\odot}(\alpha,\delta) \\ -\Delta_R(x,e,P_b,T_0,\omega,\dot{\omega},\dot{P}_b)-\Delta_E(\gamma)-\Delta_S(r,s) . \qquad (2)\end{aligned}$$

Here t_0 is a nominal equivalent TOA at the solar-system barycenter; Δ_C represents measured clock offsets; D/f^2 is the dispersive delay for propagation at frequency f through the interstellar medium; $\Delta_{R\odot}$, $\Delta_{E\odot}$, and $\Delta_{S\odot}$ are propagation delays and relativistic time adjustments within the solar system; and Δ_R, Δ_E, and Δ_S are similar terms for effects within a binary pulsar's orbit. Subscripts on the various Δ's indicate the nature of the time-dependent delays, which include "Römer," "Einstein," and "Shapiro" delays in the solar system and in the pulsar orbit. The Römer terms have amplitudes comparable to the orbital periods times $v/2\pi c$, where v is the orbital velocity and c the speed of light. The Einstein terms, representing the integrated effects of gravitational redshift and time dilation, are smaller by another factor ev/c, where e is the orbital eccentricity. The Shapiro time delay is a result of reduced velocities that accompany the well-known bending of light rays propagating close to a massive object. The delay amounts to about 120 μs for one-way lines of sight grazing the Sun, and the magnitude depends logarithmically on the angular impact parameter. The corresponding delay within a binary pulsar orbit depends on the companion star's mass, the orbital phase, and the inclination i between the orbital angular momentum and the line of sight.

Figure 5 illustrates the combined orbital delay $\Delta_R+\Delta_E+\Delta_S$ for PSR 1913+16, plotted as a function of orbital phase. Despite the fact that the Einstein and Shapiro effects are orders of magnitude smaller than the Römer delay, they can still be measured separately if the precision of available TOAs is high enough. In fact, the available precision is very high indeed, as one can see from the lone data point shown in Fig. 5 with 50 000σ error bars.

Equations (1) and (2) have been written to show explicitly the most significant dependences of pulsar phase on as many as nineteen *a priori* unknowns. In addition to the rotational frequency ν and spin-down rate $\dot{\nu}$, these phenomenological parameters include a reference arrival time t_0, the dispersion constant D, celestial coordinates α and δ, proper-motion terms μ_α and μ_δ, and annual parallax π. For binary pulsars the terms on the third line of Eq. (2), with as many as ten significant orbital parameters, are also required. The additional parameters include five that would be necessary even in a purely Keplerian analysis of orbital motion: the projected semimajor axis $x\equiv a_1 \sin i/c$, eccentricity e, binary period P_b, longitude of periastron ω, and time of periastron T_0. If the experimental precision is high enough, relativistic effects can yield the values of five further "post-Keplerian" parameters: the secular derivatives $\dot{\omega}$ and $\dot{P}_b$, the Einstein parameter γ, and the range and shape of the orbital Shapiro delay, r and $s\equiv \sin i$. Several earlier versions of this formalism for treating timing measurements of binary pulsars exist (Blandford and Teukolsky, 1976; Epstein, 1977; Haugan, 1985), and have been historically important to our progress with the PSR 1913+16 experiment. The elegant framework outlined here was derived during 1985–86 by Damour and Deruelle (1985, 1986).

Model parameters are extracted from a set of TOAs by calculating the pulsar phases $\phi(T)$ from Eq. (1) and minimizing the weighted sum of squared residuals,

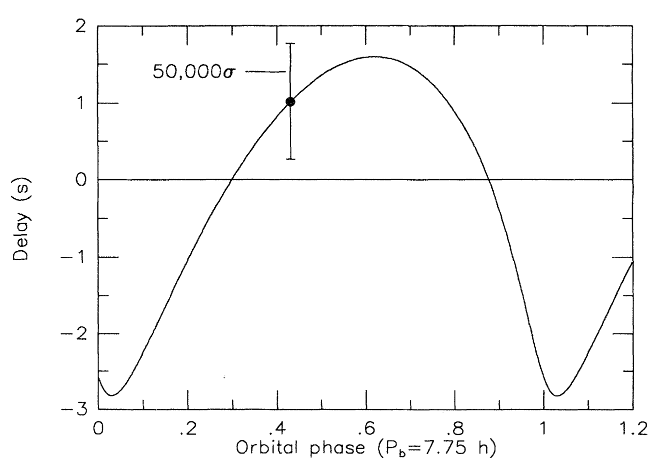

FIG. 5. Orbital delays observed for PSR 1913+16 during July, 1988. The uncertainty of an individual five-minute measurement is typically 50 000 times smaller than the error bar shown.

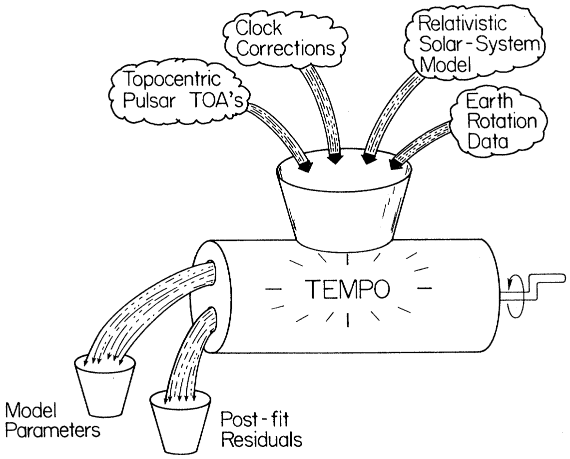

FIG. 6. Schematic diagram of the analysis of pulsar timing measurements carried out by the computer program TEMPO. The essential functions are all described in the text.

$$\chi^2=\sum_{i=1}^{N}\left[\frac{\phi(T_i)-n_i}{\sigma_i/P}\right]^2, \tag{3}$$

with respect to each parameter to be determined. In this equation, n_i is the closest integer to $\phi(T_i)$, and σ_i is the estimated uncertainty of the ith TOA. In a valid and reliable solution the value of χ^2 will be close to the number of degrees of freedom, i.e., the number of measurements N minus the number of adjustable parameters. Parameter errors so large that the closest integer to $\phi(T_i)$ may not be the correct pulse number are invariably accompanied by huge increases in χ^2; this is the reason for my earlier statement that correct pulse numbering is easily recognizable, once attained. In addition to providing a list of fitted parameter values and their estimated uncertainties, the least-squares solution produces a set of post-fit residuals, or differences between measured TOAs and those predicted by the model (see Fig. 6). The post-fit residuals are carefully examined for evidence of systematic trends that might suggest experimental errors, or some inadequacy in the astrophysical model, or perhaps deep physical truths about the nature of gravity.

Necessarily some model parameters will be easier to measure than others. When many TOAs are available, spaced over many months or years, it generally follows that at least the pulsar's celestial coordinates, spin parameters, and Keplerian orbital elements will be measurable with high precision, often as many as 6–14 significant digits. As we will see, the relativistic parameters of binary pulsar orbits are generally much more difficult to measure—but the potential rewards for doing so are substantial.

IV. THE NEWTONIAN LIMIT

Thirty-five binary pulsar systems have now been studied well enough to determine their basic parameters, including the Keplerian orbital elements, with good accuracy. For each system the orbital period P_b and projected semimajor axis x can be combined to give the mass function.

$$f_1(m_1,m_2,s)=\frac{(m_2 s)^3}{(m_1+m_2)^2}=\frac{x^3}{T_\odot(P_b/2\pi)^2}. \tag{4}$$

Here m_1 and m_2 are the masses of the pulsar and companion in units of the Sun's mass, $M_\odot$; I use the shorthand notations $s\equiv\sin i$, $T_\odot\equiv GM_\odot/c^3=4.925\,490\,947\times10^{-6}$ s, where G is the Newtonian constant of gravity. In the absence of other information, the mass function cannot provide unique solutions for m_1, m_2, or s. Nevertheless, likely values of m_2 can be estimated by assuming a pulsar mass close to $1.4M_\odot$ (the Chandrasekhar limit for white dwarfs) and the median value $\cos i=0.5$, which implies $s=0.87$. With this approach one can distinguish three categories of binary pulsars, which I shall discuss by reference to Fig. 7: a plot of binary pulsar companion masses versus orbital eccentricities.

Twenty-eight of the binary systems in Fig. 7 have orbital eccentricities $e<0.25$ and low-mass companions likely to be degenerate dwarfs. Most of these have nearly circular orbits; indeed, the only ones with eccentricities more than a few percent are located in globular clusters, and their orbits have probably been perturbed by near collisions with other stars. Five of the binaries have much larger eccentricities and likely companion masses of $0.8M_\odot$ or more; these systems are thought to be pairs of neutron stars, one of which is the detectable pulsar. The large orbital eccentricities are almost certainly the result of rapid ejection of mass in the supernova explosion creating the second neutron star. Finally, at the upper right of Fig. 7 we find two binary pulsars that

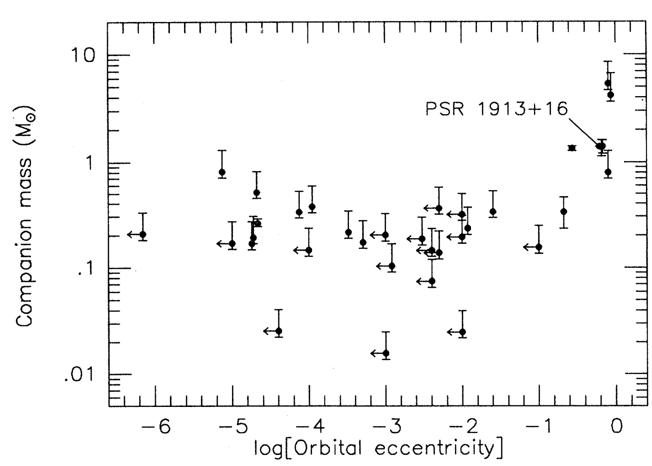

FIG. 7. Masses of the companions of binary pulsars, plotted as a function or orbital eccentricity. Near the marked location of PSR 1913+16, three distinct symbols have merged into one; these three binary systems, as well as their two nearest neighbors in the graph, are thought to be pairs of neutron stars. The two pulsars at the upper right are accompanied by high-mass main-sequence stars, while the remainder are believed to have white-dwarf companions.

move in eccentric orbits around high-mass main-sequence stars. These systems have not yet evolved to the stage of a second supernova explosion. Unlike the binary pulsars with compact companions, these two systems have orbits that could be significantly modified by complications such as tidal forces or mass loss.

V. GENERAL RELATIVITY AS A TOOL

As Russell Hulse and I suggested in the discovery paper for PSR 1913+16 (Hulse and Taylor, 1975a), it should be possible to combine measurements of relativistic orbital parameters with the mass function, thereby determining masses of both stars and the orbital inclination. In the post-Keplerian (PK) framework outlined above, each measured PK parameter defines a unique curve in the (m_1,m_2) plane, valid within a specified theory of gravity. Experimental values for any two PK parameters (say, $\dot{\omega}$ and γ, or perhaps r and s) establish the values of m_1, m_2, and s unambiguously. In general relativity the equations for the five most significant PK parameters are as follows (Damour and Deruelle, 1986; Taylor and Weisberg, 1989; Damour and Taylor, 1992):

$$\dot{\omega}=3\left[\frac{P_b}{2\pi}\right]^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}\ , \tag{5}$$

$$\gamma=e\left[\frac{P_b}{2\pi}\right]^{1/3}T_\odot^{2/3}M^{-4/3}m_2(m_1+2m_2)\ , \tag{6}$$

$$\dot{P}_b=-\frac{192\pi}{5}\left[\frac{P_b}{2\pi}\right]^{-5/3}\left[1+\frac{73}{24}e^2+\frac{37}{96}e^4\right]\times(1-e^2)^{-7/2}T_\odot^{5/3}m_1m_2M^{-1/3}\ , \tag{7}$$

$$r=T_\odot m_2\ , \tag{8}$$

$$s=x\left[\frac{P_b}{2\pi}\right]^{-2/3}T_\odot^{-1/3}M^{2/3}m_2^{-1}\ . \tag{9}$$

Again the masses m_1, m_2, and $M\equiv m_1+m_2$ are expressed in solar units. I emphasize that the left-hand sides of Eqs. (5) through (9) represent directly measurable quantities, at least in principle. Any two such measurements, together with the well-determined values of e and P_b, will yield solutions for m_1 and m_2, as well as explicit predictions for the remaining PK parameters.

The binary systems most likely to yield measurable PK parameters are those with large masses and high eccentricities and which are astrophysically "clean," so that their orbits are overwhelmingly dominated by the gravitational interactions between two compact masses. The five pulsars clustered near PSR 1913+16 in Fig. 7 would seem to be especially good candidates, and this has been borne out in practice. In the most favorable circumstances, even binary pulsars with low-mass companions and nearly circular orbitals can yield significant post-Keplerian measurements. The best present example is PSR 1855+09: its orbital plane is nearly parallel to the line of sight, greatly magnifying the orbital Shapiro delay. The relevant measurements (Rawley *et al.*, 1988; Ryba and Taylor, 1991; Kaspi *et al.*, 1994) are illustrated in Fig. 8, together with the fitted function $\Delta_S(r,s)$, in this case closely approximated by

$$\Delta_S=-2r\log(1-s\cos[2\pi(\phi-\phi_0)])\ , \tag{10}$$

where ϕ is the orbital phase in cycles and $\phi_0=0.4823$ the phase of superior conjunction. The fitted values of r and s yield the masses $m_1=1.50^{+0.26}_{-0.14}$, $m_2=0.258^{+0.028}_{-0.016}$. In a

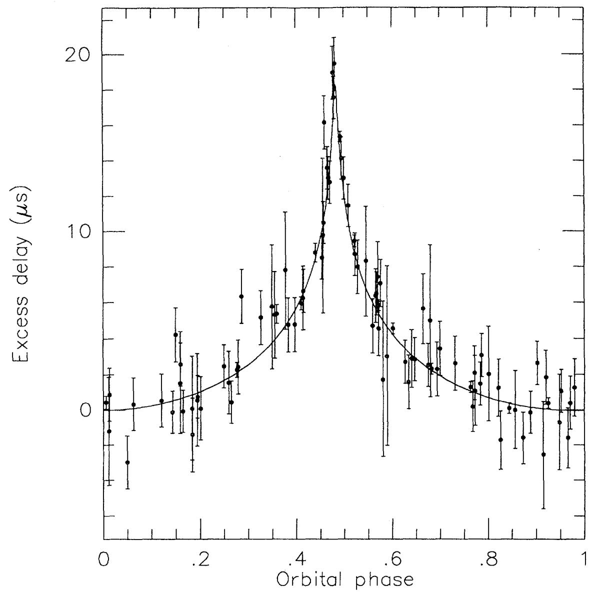

FIG. 8. Measurements of the Shapiro time delay in the PSR 1855+09 system. The theoretical curve corresponds to Eq. (10), and the fitted values of r and s can be used to determine the masses of the pulsar and companion star.

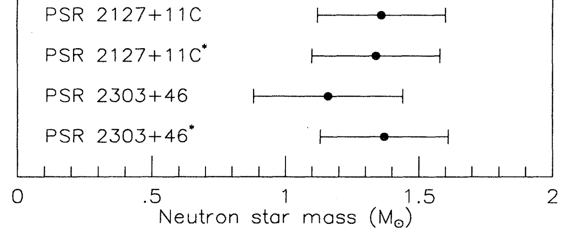

FIG. 9. The masses of ten neutron stars, measured by observing relativistic effects in binary pulsar orbits. Asterisks after pulsar names denote companions to the observed pulsars.

similar way, all binary pulsars with two measurable PK parameters yield solutions for their component masses. At present, most of the experimental data on the masses of neutron stars (see Fig. 9) come from such timing analyses of binary pulsar systems (Taylor and Dewey, 1988; Thorsett *et al.*, 1993, and references therein).

VI. TESTING FOR GRAVITATIONAL WAVES

If three or more post-Keplerian parameters can be measured for a particular pulsar, the system becomes over-determined, and the extra experimental degrees of freedom transform it into a calibrated laboratory for testing relativistic gravity. Each measurable PK parameter beyond the first two provides an explicit, quantitative test. Because the velocities and gravitational energies in a high-mass binary pulsar system can be significantly relativistic, strong-field and radiative effects come into play. Two binary pulsars, PSRs 1913+16 and 1534+12, have now been timed well enough and long enough to yield three or more PK parameters. Each one provides significant tests of gravitation beyond the weak-field, slow-motion limit (Damour and Taylor, 1982; Taylor *et al.*, 1992).

PSR 1913+16 has an orbital period $P_b \approx 7.8$ h, eccentricity $e \approx 0.62$, and mass function $f_1 \approx 0.13 M_\odot$. With the available data quality and time span, the Keplerian orbital parameters are actually determined with fractional accuracies of a few parts per million, or better. In addition, the PK parameters $\dot{\omega}$, γ, and $\dot{P}_b$ are determined with fractional accuracies better than 3×10^{-6}, 5×10^{-4}, and 4×10^{-3}, respectively (Taylor and Weisberg, 1989; Taylor, 1993). Within any viable relativistic theory of gravity, the values of $\dot{\omega}$ and γ yield the values of m_1 and m_2 and a corresponding prediction for $\dot{P}_b$ arising from the damping effects of gravitational radiation. At present levels of accuracy, a small kinematic correction (approximately 0.5% of the observed $\dot{P}_b$) must be included to account for accelerations of the solar system and the binary pulsar system in the Galactic gravitational field (Damour and Taylor, 1991). After doing so, we find that Einstein's theory passes this extraordinarily stringent test with a fractional accuracy better than 0.4% (see Figs. 10 and 11). The clock-comparison experiment for PSR 1913+16 thus provides direct experimental proof that changes in gravity propagate at the speed of light, thereby creating a dissipative mechanism in an orbiting system. It necessarily follows that gravitational radiation exists and has a quadrupolar nature.

PSR 1534+12 was discovered just three years ago, in a survey by Aleksander Wolszczan (1991) that again used the huge Arecibo telescope to good advantage. This pulsar promises eventually to surpass the results now available from PSR 1913+16. It has orbital period $P_b \approx 10.1$ h, eccentricity $e \approx 0.27$, and mass function $f_1 \approx 0.31 M_\odot$. Moreover, with a stronger signal and narrower pulse than PSR 1913+16, its TOAs have considerably smaller measurement uncertainties, around 3 μs for five-minute

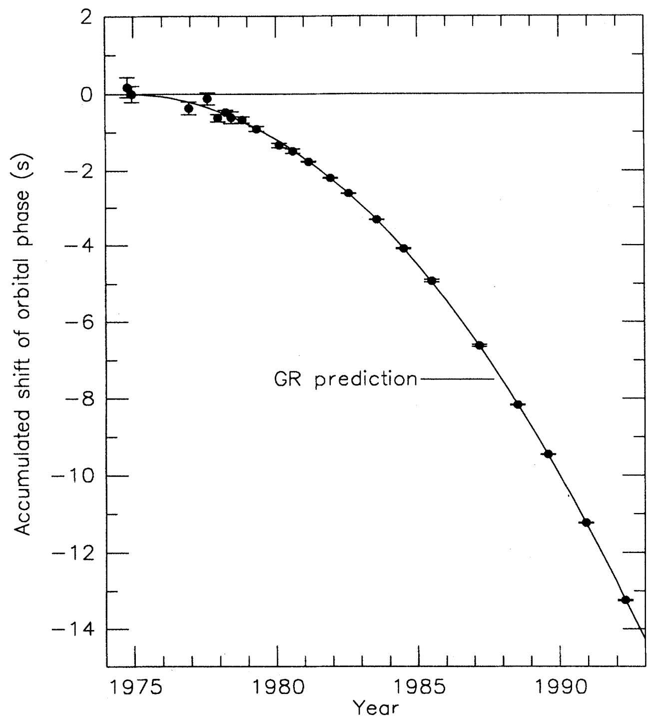

FIG. 10. Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

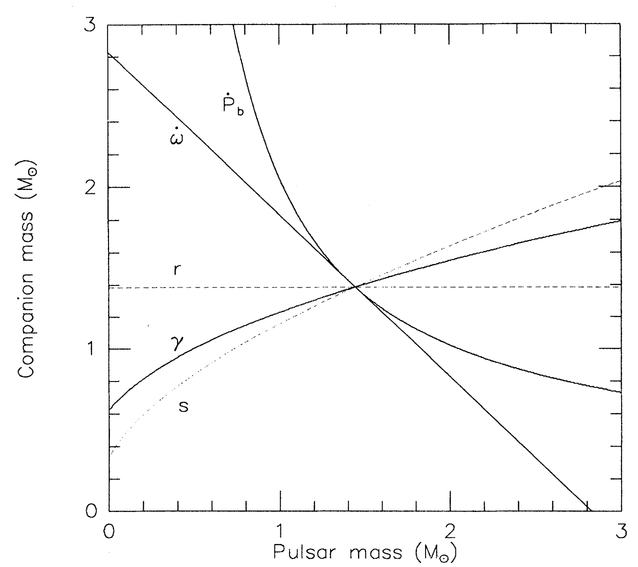

FIG. 11. Solid curves correspond to Eqs. (5)–(7) together with the measured values of $\dot{\omega}$, γ, and $\dot{P}_b$. Their intersection at a single point (within the experimental uncertainty of about 0.35% in $\dot{P}_b$), establishes the existence of gravitational waves. Dashed curves correspond to the *predicted* values of parameters *r* and *s*; these quantities should become measurable with a modest improvement in data quality.

observations. Results based on 15 months of data (Taylor *et al.*, 1992) have already produced significant measurements of four PK parameters: $\dot{\omega}$, γ, r, and s. In recent work not yet published, Wolszczan and I have measured the orbital decay rate, $\dot{P}_b$, and found it to be in accord with general relativity at about 20% level. In fact, *all* measured parameters of the PSR 1534+12 system are consistent within general relativity, and it appears that when the full experimental analysis is complete, Einstein's theory will have passed three more very stringent tests under strong-field and radiative conditions.

I do not believe that general relativity necessarily contains the last valid words to be written about the nature of gravity. The theory is not, of course, a quantum theory, and at its most fundamental level the universe appears to obey quantum-mechanical rules. Nevertheless, our experiments with binary pulsars show that, whatever the precise directions of future theoretical work may be, the correct theory of gravity must make predictions that are asymptotically close to those of general relativity over a vast range of classical circumstances.

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