

HIGH-PRECISION TIMING OF MILLISECOND PULSARS. I. ASTROMETRY AND MASSES OF THE PSR 1855+09 SYSTEM

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ABSTRACT

Timing observations of several millisecond pulsars are being made on a regular basis, generally twice a month, at the Arecibo Observatory. We describe the observing method and procedures of data analysis used for one particular object, PSR 1855+09, a 5.4 ms pulsar in a 12.3 day orbit. Measurements have now been obtained on a total of 94 days over a 4.4 yr span, with timing accuracies ranging from about $2 \mu\text{s}$ to $0.4 \mu\text{s}$. We use a general relativistic timing model to obtain improved values for all previously determined parameters of the pulsar and its orbit. In addition, we find the annual parallax of the system to be $\pi = 1.2 \pm 0.5 \text{ mas}$ and the proper motion to be $\mu = 6.07 \pm 0.20 \text{ mas yr}^{-1}$, directed nearly along the galactic plane. For the first time, we present measurements of two orbital parameters quantifying the magnitude and shape of the general relativistic “Shapiro delay” in the orbiting system. The parameter values show the orbital inclination to be nearly 90° , and they provide mass estimates for the pulsar and companion star, respectively $m_1 = 1.27^{+0.23}_{-0.15} M_\odot$ and $m_2 = 0.233^{+0.026}_{-0.017} M_\odot$. Both masses are in good agreement with theoretical predictions based on neutron star physics and evolutionary models of the PSR 1855+09 system.

Subject headings: astrometry — pulsars — relativity — stars: binaries — stars: neutron — stars: individual (PSR 1855+09)

1. INTRODUCTION

Among the 500 radio pulsars discovered since 1967, some of the most rewarding to study have been those “recycled” in close binary systems. Like all radio pulsars, these objects are believed to be spinning neutron stars whose energetics are dominated by their spindown luminosities. Their evolution has been significantly modified by an episode of accretion in which mass and angular momentum were transferred from an orbiting companion star. Recycled pulsars make up a small fraction of the total (fewer than 30 are presently known), and most of them are still members of gravitationally bound binary systems. Their rotation periods are generally considerably shorter than those of “normal” pulsars.

Timing observations have always been one of the most powerful tools for studying pulsars. Recycled pulsars make especially attractive targets for such work: their short periods mean that the measurement precision can be unusually high, and orbital motion gives access to important constraints on the stellar masses. In the most favorable circumstances, the information content of long sequences of data can be surprisingly large. Timing measurements of binary and millisecond pulsars can provide unique information on a diverse range of topics including astrometry, cosmology, gravitation physics, the evolution of binary systems, and time-keeping metrology.

The period, eccentricity, and mass function of a binary pulsar’s orbit are readily determined from a first-order Doppler analysis of the velocity curve. A wide range of orbital characteristics has been found among the known binary pulsars: periods range from less than 2 hr to several years, eccentricities from less than 10^{-5} to 0.8, and mass functions from less than 10^{-5} to 0.25 solar masses. If the data quality is high enough, special- and general-relativistic effects can also be measured, and considerably more information can be extracted. In such cases one can hope to establish the masses of

one or both components of the binary, and to carry out important tests of relativistic gravity.

In this paper we present the results of a 4.4 yr series of timing observations of a particular binary millisecond pulsar, PSR 1855+09. The pulsar has proved to be one of the most stable of all known natural clocks; this stability, together with the high precision of the measurements, has provided access to information in all of the categories mentioned above. Earlier published reports have used subsets of the data to yield the basic orbital characteristics of the system (Segelstein et al. 1986), improved spin and orbital parameters and accurate celestial coordinates (Rawley, Taylor, & Davis 1988), and a significant limit on the cosmic gravitational wave background (Stinebring et al. 1990). Because the data span has increased and improvements in equipment have yielded higher precision, we can now present a more refined analysis of (1) the spin parameters of the pulsar; (2) astrometry of the system, including parallax and proper motion; and (3) orbital parameters, including masses of the two components. We also summarize some astrophysical consequences of the results. Analysis of the data has been carried out using the comprehensive and elegant relativistic timing model of Damour & Deruelle (1986, hereafter DD), which has been shown to account for all significant timing effects through terms of gravitational-radiation order—even for the much more highly relativistic binary pulsar, PSR 1913+16 (Taylor & Weisberg 1989; Damour & Taylor 1991). Our analysis is based on all available observations through 1990 June 11.

2. ARRIVAL TIME MEASUREMENTS

PSR 1855+09 has a period $P = 5.4 \text{ ms}$, dispersion measure $DM = 13.3 \text{ cm}^{-3} \text{ pc}$, and mean flux density of only 2 mJy at 1.4 GHz. High-precision timing measurements therefore require a large telescope, the best possible receiver, and a spectrometer adequate to permit dispersion removal and exploit-

ation of intensity fluctuations caused by interstellar scintillation. In addition, one needs data acquisition hardware designed for high time resolution and means for accurate time transfer from the best available atomic clocks. Our data have all been obtained with the 305 m radio telescope of the Arecibo Observatory,¹ usually observing at a frequency near 1408 MHz. From 1986 January through 1988 December, observations were made with equipment dubbed our “Mark II” pulsar timing system (Rawley 1986; Rawley, Taylor, & Davis 1988; Taylor & Weisberg 1989, hereafter TW). This equipment, designed explicitly for observing millisecond pulsars, uses a dual polarization 32×250 kHz filter-bank spectrometer followed by a bank of 32 concurrently operating signal averagers synchronized with the topocentric pulsar period. Since 1989 January we have used a “Mark III” system, similar in many ways to the Mark II but permitting use of a wider variety of spectrometer resolutions and de-dispersing hardware. In observations of PSR 1855+09, the principal advantage of the Mark III system is that it has twice as many data channels and uses a broader, 32×1.25 MHz filter bank in addition to the one with 250 kHz resolution.

On a given observing day we have usually looked at PSR 1855+09 for about 40 minutes. With the Mark II system, we stepped the central observing frequency until a strongly focused feature (caused by diffractive interstellar scintillation) was found. Our exact observing frequency therefore varied, generally falling in the range 1380–1425 MHz. The scintillation characteristics of PSR 1855+09 are such that at these observing frequencies a strong feature usually lasts for 30 minutes or so; the fade-out of a good scintillation band usually marked the practical end of our run. With the Mark III system, we leave the 32×1.25 MHz filter bank tuned to a standard frequency, normally 1408 MHz. After the observations have started, the 250 KHz filters are retuned to the strongest scintillation feature found in the passband of the wide filter bank. The enhanced signal-to-noise ratios obtained in this way largely compensate for the much smaller total bandwidth of the narrow filter bank. In practice, however, we find that suitably weighted averages of data from the broad filter bank provide the best data on PSR 1855+09, and we have used these data in the analysis presented here.

Integrated pulse profiles for each channel of each filter bank are recorded every 2 minutes, along with time tags corresponding to the first digitized sample in a period near the midpoint of the integration. The phase of the pulsar waveform at the nominal time is obtained by template matching with a standard profile in the Fourier transform domain (Rawley 1986; Taylor 1990b). For purposes of illustration, Figure 1 shows the standard profile for Mark III data using the 32×1.25 MHz filter bank. One day it may be interesting to relate our absolute pulse arrival times to some altogether different ones—perhaps from gamma-ray observations, or radio data obtained at some epoch far in the future. Toward this end we have marked in Figure 1 the pulse phase that we define as the TOA: the highest point in the main pulse component.

The phases for all 32 filter-bank channels for each integration in an observing session are combined to form a single equivalent topocentric time of arrival, or TOA, for the day's observations. As part of the template-matching procedure,

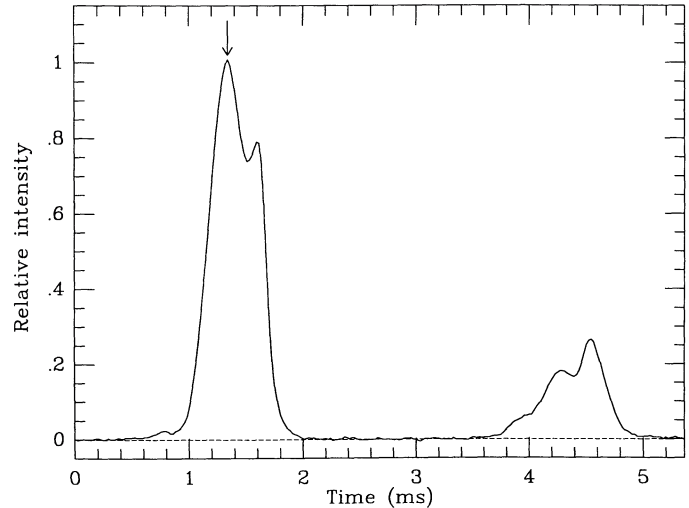


FIG. 1.—Standard profile of PSR 1855+09 at 1408 MHz, used to obtain pulse times of arrival with the Mark III system. The phase defined as the TOA is marked with an arrow.

uncertainties are estimated for each phase measurement, and reduction of these values to a daily normal point yields another uncertainty estimate derived from the scatter of the individual phases. We find that the daily average TOA's from the Mark II and Mark III data have typical uncertainties of $1.9 \mu\text{s}$ and $1.2 \mu\text{s}$, respectively. For our best data, obtained with the Mark III system on 13 days in 1990 April, the observing time was extended to ~ 2 hr per day and the uncertainty reduced to $0.4 \mu\text{s}$. Note that even 2 hr of observing time collapsed into a single TOA represents less than 1% of the 12.3 day orbital period of PSR 1855+09. Consequently, the data-averaging procedure does not significantly compromise our ability to measure effects that depend on orbital phase.

3. FITTING A RELATIVISTIC TIMING MODEL

Pulse arrival times are measured in the reference frame of the moving observatory and must ultimately be related to proper times at the pulsar. As an intermediate step, it is convenient to transform first to the inertial reference frame of the solar system barycenter (SSB). If t is a measured topocentric TOA, the equivalent infinite-frequency barycentric arrival time can be written as

$$t_b = t + (\mathbf{r} \cdot \hat{\mathbf{n}})/c + [(\mathbf{r} \cdot \hat{\mathbf{n}})^2 - |\mathbf{r}|^2]/2cd - D/f^2 + \Delta_C + \Delta_{E_0} - \Delta_{S_0}. \quad (1)$$

In this equation t is measured in units of terrestrial time (TT), while t_b is in units of barycentric dynamical time (TDB). The pulsar is assumed to lie at vector distance $\hat{\mathbf{n}}d$ from the SSB, where $\hat{\mathbf{n}}$ is a unit vector; the vector $\mathbf{r}$ points from the SSB to the phase center of the telescope; c is the speed of light; D is the “dispersion constant” of the pulsar, measured in Hz and conventionally related to dispersion measure by $DM \equiv (2.41 \times 10^{-16} \text{ cm}^{-3} \text{ pc s}) D$; f is the observing frequency, expressed in the reference frame of the SSB; Δ_C is the offset between the observatory's master clock and the reference atomic time standard; Δ_{E_0} is the solar system “Einstein delay,” or combined effect of changes in gravitational redshift and time dilation caused by the Earth's motion; and Δ_{S_0} is the “Shapiro delay,” caused by propagation of the pulsar signal through curved spacetime near the Sun (Shapiro 1964).

¹ The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, operated by Cornell University under a cooperative agreement with the National Science Foundation.

In practice, we determine the position and velocity of the telescope by interpolating a solar system ephemeris and adding terms that account for measured irregularities in the Earth's rotation. We use the Center for Astrophysics PEP740R ephemeris, or the Jet Propulsion Laboratory DE200 ephemeris, together with Earth rotation data from the Bulletin of the International Earth Rotation Service. Clock corrections Δ_c are obtained from measurements made at the time of observation, using satellites in the Global Positioning System, in common view from Arecibo Observatory and the National Institute of Standards and Technology in Boulder, Colorado. Further corrections are ultimately obtained from published offsets of UTC(NIST) relative to primary atomic time scales. The solar system Einstein delay, $\Delta_{E\odot}$, is evaluated by interpolating a table included with the distribution of the CfA ephemeris—or, when using the DE200 ephemeris, by means of a semianalytical model developed by Fairhead, Bretagnon, & Lestrade (1988). Finally, the solar-system Shapiro delay is computed from

$$\Delta_{S\odot} = \frac{2GM_{\odot}}{c^3} \log(1 + \cos \theta), \quad (2)$$

safely ignoring the eccentricity of the Earth's orbit. In this expression θ is the pulsar–Sun–Earth angle, and we take the constant $GM_{\odot}/c^3$ to be $4.925490947 \mu\text{s}$. Further details on all of the terms in equation (1) can be found in Rawley, Taylor & Davis (1988) and TW.

A similar procedure is required in order to transform from the SSB to the proper reference frame of the pulsar. In the model of DD, the necessary operation can be summarized as

$$T = t_b - t_0 - \Delta_R - \Delta_E - \Delta_S - \Delta_A, \quad (3)$$

where T is proper time at the pulsar; t_0 is a reference epoch (measured in TDB units) from which all pulses will be numbered; Δ_R is the “Roemer” time delay caused by orbital motion, analogous to the solar-system term $(\mathbf{r} \cdot \hat{\mathbf{n}})/c$ in equation (1); Δ_E and Δ_S are the orbital Einstein and Shapiro delays, analogous to $\Delta_{E\odot}$ and $\Delta_{S\odot}$ in the solar system; and Δ_A is a time delay associated with aberration caused by rotation of the pulsar. Equations defining the various Δ 's in terms of Keplerian and “post-Keplerian” orbital parameters of the pulsar have been derived by DD. Our implementation of the entire timing model is described in detail by TW.

After the best available parameters have been used to carry out the transformations defined by equations (1) and (3), the pulsar rotational phase corresponding to each TOA can be evaluated from

$$\phi(T) = \nu T + \frac{1}{2}\dot{\nu}T^2 + \frac{1}{6}\ddot{\nu}T^3. \quad (4)$$

In this expression $\nu = 1/P$ is the pulsar spin frequency and $\dot{\nu}$ and $\ddot{\nu}$ its first and second time derivatives. A statistic measuring goodness of fit of the model to the data is computed from

$$\chi^2 = \sum_{i=1}^N \left[\frac{\phi(T_i) - n_i}{\sigma_i/P} \right]^2, \quad (5)$$

where N is the total number of TOAs, n_i is the closest integer to each computed $\phi(T_i)$, and σ_i is the estimated uncertainty of T_i . Partial derivatives of ϕ with respect to each of the model parameters are also computed, so that standard linearized least-squares techniques can be used to minimize χ^2 with respect to small corrections to any or all of the model parameters. It is worth noting that the very high precisions obtainable for many of the model parameters are possible because the

large integers n_i are known exactly: for example, precisely 26,031,636,392 rotations of PSR 1855+09 elapsed between the first and last TOA in our present data set. Additional details of the model-fitting procedure can be found in TW.

Our implementation of the Damour-Deruelle model provides an excellent fit to the available data on PSR 1855+09. Significant parameters include right ascension α , declination δ , proper motion components $\mu_\alpha \equiv \dot{\alpha} \cos \delta$ and $\mu_\delta \equiv \dot{\delta}$, parallax π , a reference epoch t_0 , the pulsar frequency ν and its derivatives, and the dispersion measure DM. In addition there are five Keplerian parameters of the binary orbit: the projected semimajor axis $x \equiv a_1 \sin i$, eccentricity e , time of periastron passage T_0 (measured in the TDB system), period P_b , and longitude of periastron ω . Finally, with the present data quality there are two measurable post-Keplerian parameters, describing the shape and magnitude of the dependence of Shapiro delay on orbital phase. In the DD model the shape parameter is $s \equiv \sin i$, where i is the inclination between the plane of the orbit and the plane of the sky; the magnitude or “range” parameter is $r \equiv Gm_2/c^3$, where G is Newton's constant and m_2 is the mass of the companion star.

Post-fit residuals from a 16-parameter solution are plotted as a function of date in Figure 2. To a good approximation the residuals have the character of uncorrelated white noise, with a magnitude consistent with the measurement uncertainties. Detailed spectral analysis of the residuals (Taylor 1990a; Stinebring et al. 1990) has failed to reveal any significant contributions with nonwhite spectra. Additional details on the robustness of the multiparameter solution and our method of assigning parameter uncertainties are given in the Appendix.

4. ASTROMETRIC, SPIN, AND DISPERSION PARAMETERS

The astrometric, spin, and dispersion parameters of the fitted model are listed in Table 1. For purposes of comparison we quote the parameter values from two independent solutions: one based on the PEP740R ephemeris, with coordinates given in the B1950 system, and one based on the DE200 ephemeris and J2000 coordinates. For the reference epoch t_0 , we list a TDB Julian ephemeris date near the weighted centroid of our data set for which $\phi[T(t_0)] = 0$. Thus, t_0 represents a nominal infinite-frequency barycentric TOA corresponding to the pulse phase marked in Figure 1, as well as a reference epoch for the remaining astrometric and spin parameters.

Table 1 lists the pulsar's spin parameters in terms of both period and frequency. The second derivatives are indistinguishable from zero, as expected on the basis of standard electromagnetic braking models (see, for example, Manchester & Taylor 1977). The first derivatives are now determined to five significant figures, and $\dot{P}$ for PSR 1855+09 is the second smallest period derivative known for any pulsar. The values of ν and P listed for the B1950 and J2000 solutions differ by considerably more than their measurement uncertainties, because of what amounts to different definitions of the TDB second in each system. Most of the difference arises from the use of different averaging intervals to specify the mean gravitational potential at the Earth; see TW (especially eq. [2]) for further details.

In the coordinate systems of PEP740R and DE200, the position of PSR 1855+09 is now determined to an accuracy of about 0.2 mas and the proper motion to about 0.2 mas yr^{-1} . These are among the most precise astrometric measurements ever made, by any method. When combined with timing measurements of other millisecond pulsars, and with VLA or VLBI

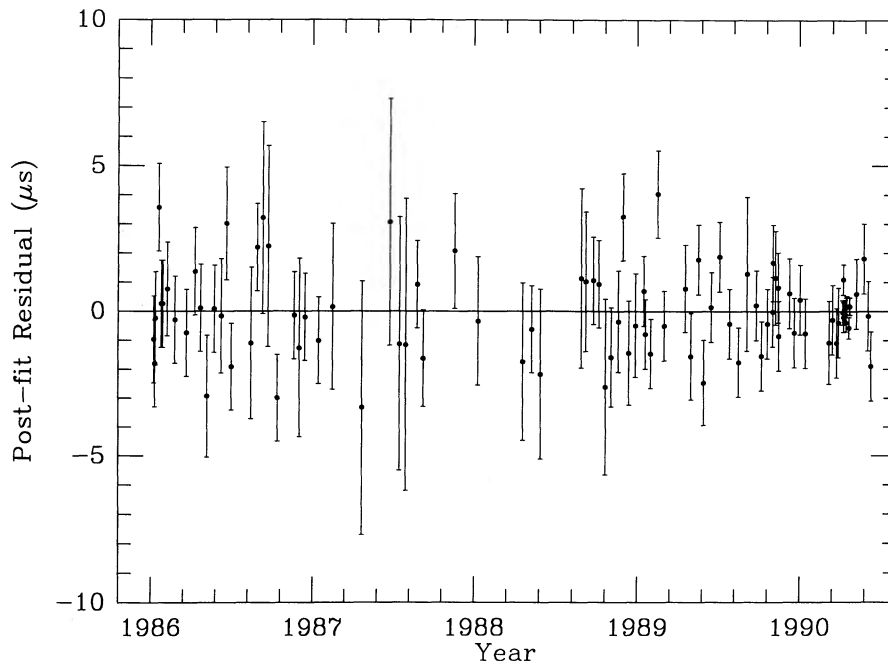


FIG. 2.—Post-fit timing residuals plotted as a function of date. A 16-parameter model has been removed from the data.

positions for the same sources, they should help to tie the solar-system reference frame to a more fundamental extragalactic frame based on quasars.

For the first time with timing data on any pulsar, our observations of PSR 1855+09 yield a marginally significant measurement of the annual parallax of the source, and hence its distance. Parallax information can in principle be extracted from pulsar timing data because of the term $(\mathbf{r} \cdot \hat{\mathbf{n}})^2/2cd$ in equation (1). The measurement is extremely difficult, however, because the magnitude of this term is so small—approximately $1.2 \mu\text{s}$ for a pulsar in the ecliptic at a distance $d = 1 \text{ kpc}$. Figure 3 illustrates the significance of the present measurement by showing the functional dependence of $\Delta\chi^2$ (the difference $\chi^2 - \chi_0^2$, where χ_0^2 is the global minimum found in the least-squares solution) on parallax. The fitted value, $\pi = 1.2 \pm 0.5$

mas (68% confidence), corresponds to a pulsar distance of about 0.8 kpc and implies a rather small average electron density along the line of sight, namely

$$\langle n_e \rangle \equiv DM/d = DM\pi = 0.016 \pm 0.007 \text{ cm}^{-3}. \quad (6)$$

The proper motion of PSR 1855+09, although only about 6 mas yr^{-1} , has a large and unmistakable effect on the timing data, as illustrated in Figure 4. In the past, some published proper motions based on timing observations have been shown to have large systematic errors (Lyne, Anderson, & Salter 1982). The errors were caused by sparse and irregularly sampled data, together with unrecognized intrinsic timing noise in the pulsars. We have no reason to expect such problems with the present data, because many observations are available throughout each year and there is no evidence for

TABLE 1
ASTROMETRIC AND SPIN PARAMETERS OF THE PSR 1855+09 SYSTEM

PARAMETER	EPOCHS	
	PEP740R	DE200
	EQUINOX	
	B1950	J2000
α	18 ^h 55 ^m 13 ^s .682738(10)	18 ^h 57 ^m 36 ^s .393521(10)
δ	09°39'13".3111(3)	09°43'17".3233(3)
μ_α (mas yr^{-1})	-3.00 ± 0.12	-2.92 ± 0.12
μ_δ (mas yr^{-1})	-5.26 ± 0.19	-5.32 ± 0.19
π (mas)	1.1 ± 0.5	1.2 ± 0.5
P (ms)	5.36210045404849(10)	5.36210045404065(10)
$\dot{P}$ (10^{-20})	1.7738(3)	1.7835(3)
$\ddot{P}$ (10^{-31} s^{-1})	-1.2 ± 1.9	-1.0 ± 1.9
ν (s^{-1})	186.494081669988(3)	186.494081670261(3)
$\dot{\nu}$ (10^{-16} s^{-2})	$-6.1693(10)$	$-6.2034(10)$
$\ddot{\nu}$ (10^{-27} s^{-3})	4 ± 7	4 ± 7
t_0 JD 2447526+	0.0000565829(3)	0.0000566171(3)
DM ($\text{cm}^{-3} \text{ pc}$)	13.306(9)	13.306(9)

NOTE.—Figures in parentheses are uncertainties in the last digit quoted.

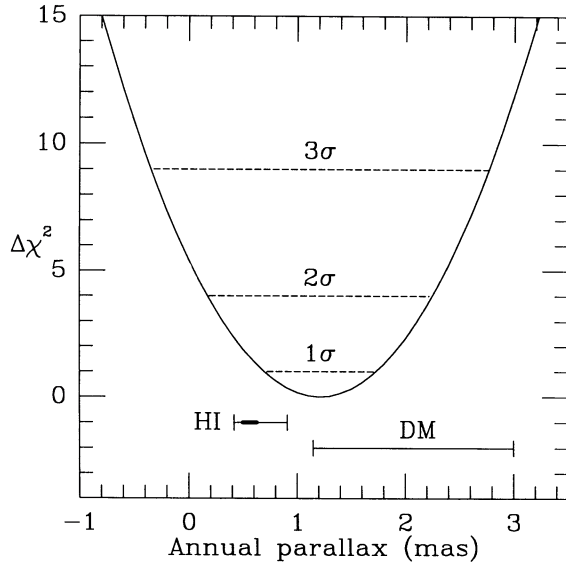


FIG. 3.—The smooth curve represents values of $\Delta\chi^2$ obtained in least-squares solutions with the annual parallax held fixed at a number of values throughout the plotted range, and all other parameters allowed to vary. The expected parallax values based on distance estimates from neutral hydrogen absorption and dispersion measure are indicated at the bottom. The thickened portion of the bar giving H I distance limits corresponds to the range preferred by Frail & Weisberg (1990; see text).

detectable timing noise (Stinebring et al. 1990). Nevertheless, as a safeguard we have measured the proper motion by two methods. In the first of these, the proper motion components μ_α and μ_δ are explicitly included in the multiparameter solution. The fitted values obtained in this way are listed in Table 1. In the second method, we divided the data set into four intervals, each about 1.1 yr long. For each subsequence we determined the best-fitting values of α and δ , with μ_α and μ_δ held

fixed. As illustrated in Figure 5, the results of the two methods are in excellent agreement.

5. KEPLERIAN AND POST-KEPLERIAN ORBITAL PARAMETERS

Except for some increased precision, the Keplerian orbital parameters of the PSR 1855+09 system are not much changed from those published by Rawley, Taylor, & Davis (1988). The new values, listed at the top of Table 2, are determined with precisions ranging from four to 12 significant digits. The projected semimajor axis and orbital period can be combined to form the mass function,

$$f_1(m_1, m_2, \sin i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} \\ = (5.5573943 \pm 0.0000007) \times 10^{-3} M_\odot, \quad (7)$$

TABLE 2
ORBITAL PARAMETERS OF THE PSR 1855+09 SYSTEM

Parameter	Value
x (light s)	9.2307807 ± 0.0000003
P_b (s)	$1065067.59082 \pm 0.00012$
e	$(2.167 \pm 0.004) \times 10^{-5}$
T_0 (JED)	$2447530.39335870 \pm 0.003^a$
ω	$276^\circ 299335 \pm 0.09^a$
r (μ s)	$1.15^{+0.13}_{-0.08}$
s	$0.99955^{+0.00030}_{-0.00061}$
$\dot{x}$	$(-3 \pm 7) \times 10^{-5}$
$\dot{P}_b$	$(-5 \pm 8) \times 10^{-12}$
$\dot{e}$ (s^{-1})	$(-1.3 \pm 1.5) \times 10^{-15}$

^a We intentionally quote several more digits for T_0 and ω than are significant. These two parameters are highly covariant in the least-squares solution, greatly reducing their measurability when both are estimated simultaneously (see Appendix). Some observations will benefit from using the full quoted precisions.

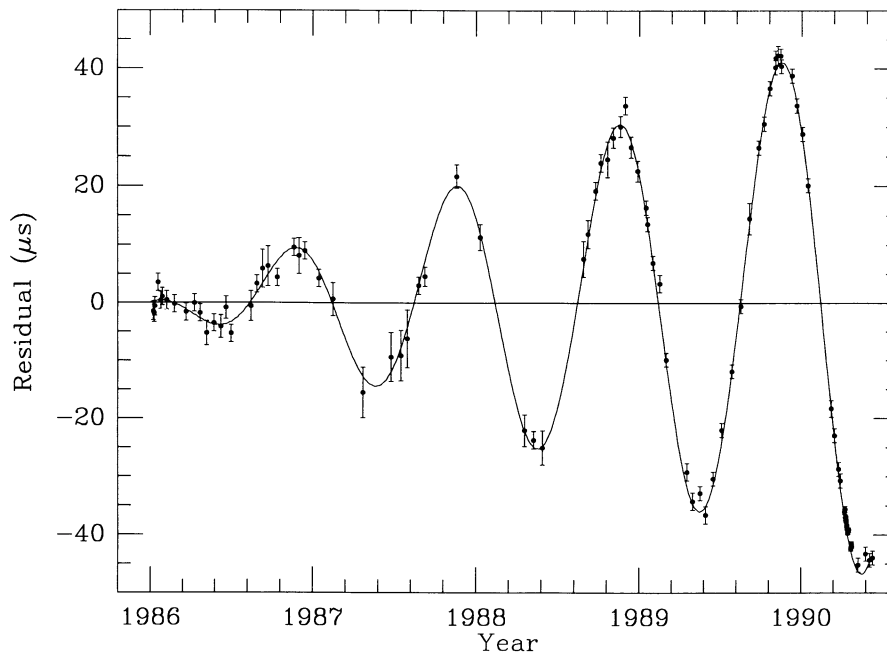


FIG. 4.—Timing residuals illustrating the “signal” caused by the proper motion of PSR 1855+09 as the pulsar moves away from its fitted position at epoch 1986.0. The plotted curve, closely approximating an annual sinusoid with linearly increasing amplitude, corresponds to the proper motion of 6.07 mas yr^{-1} given in Table 1.

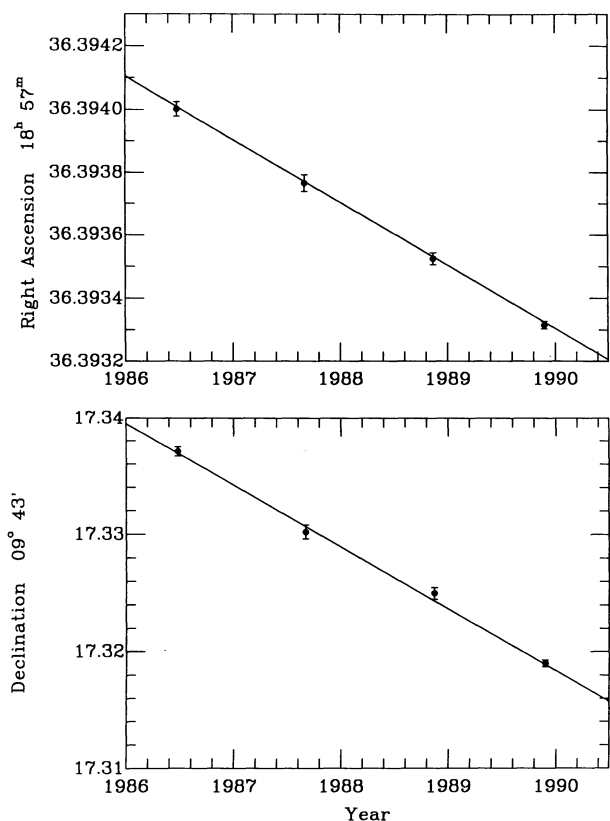


FIG. 5.—Fitted positions of PSR 1855+09 at four epochs, in J2000 coordinates. Each measurement is based on about 1.1 yr of timing data. Straight lines correspond to the proper motion given in Table 1, which was obtained from a global fit to the entire data set.

where m_1 and m_2 are the masses of the pulsar and the companion star. As was clear immediately after the discovery of PSR 1855+09 (e.g., Taylor 1987), the mass function, together with a reasonable assumption for the pulsar mass, makes it highly probable that the companion has a mass in the range 0.2–0.4 $M_\odot$.

The only post-Keplerian measurables in our present data set are r and s , parameters that define the range and shape of the Shapiro delay curve. The signature of this general-relativistic effect in our data is illustrated in the top panel of Figure 6. Although the signal amplitude is much larger than the uncertainties in the TOA's, the fact that two parameters must be determined, and that they have significant covariances with the other fitted parameters, reduces their detectability considerably. In fact, the coefficients of r and s in the timing formula (see eq. [10] of TW) are small enough that curvature of the χ^2 surface over the parameter ranges of interest cannot be treated as constant. Consequently, the customary assumptions used to estimate parameter uncertainties in a linearized least-squares solution are not valid. In order to determine the acceptable range of parameter values for r and s , we therefore mapped out the interesting region of χ^2 space. Contours of $\Delta\chi^2(r, s) \equiv \chi^2(r, s) - \chi_0^2$ are plotted in Figure 7, using a horizontal scale in which $\cos i$, rather than $s \equiv \sin i$, is the linear quantity (compare Fig. 7 of TW). The figure shows contours for $\Delta\chi^2 = 2.3, 6.2$, and 11.8, which correspond to regions of 68.3%, 95.4%, and 99.73% confidence, respectively, for r and s ; the 68% or “1 σ ” limits are presented in Table 2. Note that in general relativity, our measured value of r implies a companion mass

$$m_2 = rc^3/G = 0.233^{+0.026}_{-0.017} M_\odot. \quad (8)$$

Inserting this value and that of $\sin i$ into equation (7), we

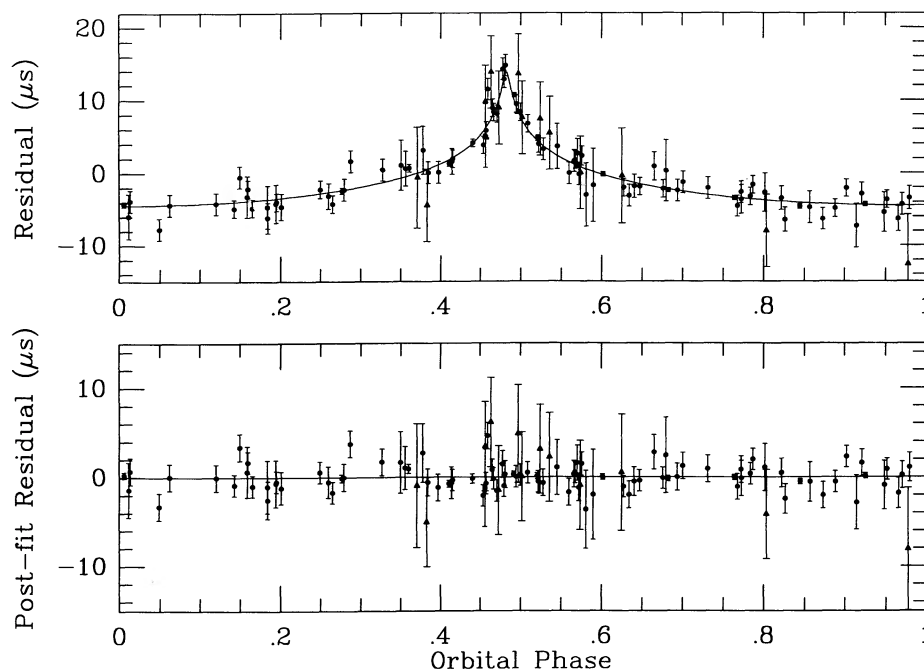


FIG. 6.—Timing measurements of PSR 1855+09 plotted as a function of orbital phase. The top panel illustrates the effect of the general relativistic Shapiro time delay, with all other timing effects removed. Filled triangles represent data taken at 430 MHz; all other measurements were made at frequencies near 1408 MHz. The smooth curve is the theoretical prediction based on parameters listed in Table 2. The lower panel shows the post-fit residuals after the full timing model has been removed.

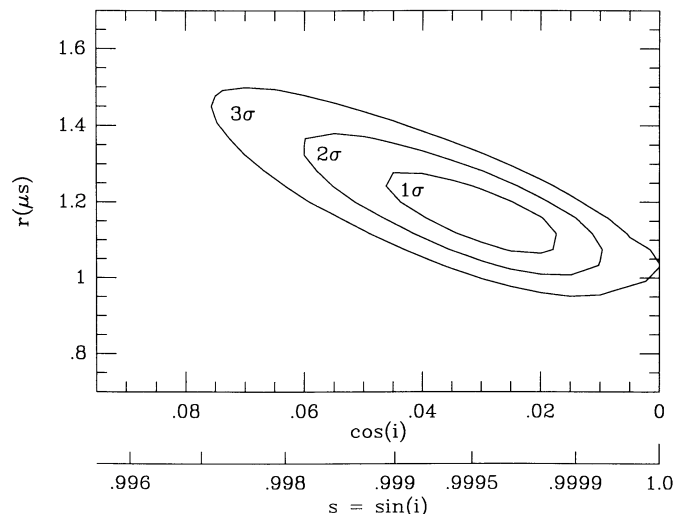


FIG. 7.—Contours of χ^2 near its global minimum, plotted as a function of r and s . The three contours enclose regions of 68.3%, 95.4%, and 99.73% confidence for measurements of r and s .

obtain

$$m_1 = 1.27^{+0.23}_{-0.15} M_{\odot} \quad (9)$$

for the mass of the pulsar.

One can imagine a model in which the excess TOA delays near superior conjunction of the pulsar (orbital phase 0.4823 ± 0.0003) are caused by dispersive propagation of the signal through an atmosphere surrounding the companion star, as in the PSR 1957+20 system (Fruchter et al. 1990), rather than the general relativistic Shapiro delay. If such a mechanism were the correct explanation of the signal seen at the top of Figure 6, the delays would be expected to scale with observing frequency as f^{-2} . We therefore measured a few additional TOAs at the much lower frequency of 430 MHz, using similar observing procedures and the 32×250 kHz filter bank. These data, plotted as filled triangles in Figure 6, have much larger uncertainties but essentially the same dependence on orbital phase as the 1408 MHz observations. The excess delay is certainly not larger at the lower frequency by a factor $(1408/430)^2 \approx 11$. We conclude that the observed non-Keplerian delays are independent of frequency and that we have, indeed, measured the Shapiro delay in the PSR 1855+09 system.

With our measured values for the Keplerian parameters and the values quoted above for the stellar masses, we can estimate the values of additional post-Keplerian parameters. Equations (15)–(17) of TW, which are valid in general relativity, yield for $\dot{\omega}$, the rate of advance of the longitude of periastron, and γ , the variable part of time dilation and gravitational redshift, the values

$$\dot{\omega} = 0.004 \text{ deg yr}^{-1}, \quad (10)$$

$$\gamma = 8 \times 10^{-8} \text{ s}. \quad (11)$$

These quantities are far too small to be measurable with our present data, and the consequences of ignoring γ are negligible. However, note that by assuming $\dot{\omega} = 0$ we knowingly impose a bias on the fitted value of orbital period. The quoted value of P_b is smaller than the true value by approximately 0.4 parts per million, because it has absorbed most of the effect of the unmeasured $\dot{\omega}$. Nevertheless we quote the biased value of P_b in Table 2, because it is much more useful observationally and, in

any event, the bias is insignificant for most theoretical purposes. (Note, however, that for this reason the true dynamical mass function is about 6 standard deviations smaller than the phenomenological value given in eq. [7].)

For any plausible orbital damping mechanisms, including gravitational radiation, the expected values of $\dot{x}$, $\dot{P}_b$, and $\dot{e}$ —the rates of change of orbital size, period, and eccentricity—are utterly negligible. For completeness, however, and as a test of the general assumptions underlying the preferred neutron-star/white-dwarf model of the system, we have carried out solutions in which $\dot{x}$, $\dot{P}_b$, and $\dot{e}$ were permitted to vary. The results, which are included in Table 2, are in all cases consistent with zero.

6. DISCUSSION OF THE ASTROPHYSICAL CONSEQUENCES

Current theory holds that binary pulsars like PSR 1855+09—those in wide, nearly circular orbits with low mass functions—are descended from low-mass X-ray binaries (see, for example, Webbink, Rappaport, & Savonije 1983; van den Heuvel 1987). These systems are fed by mass transfer on a nuclear time scale, as the companion evolves through a sub-giant phase, filling its Roche lobe. Mass transfer ceases when the companion's envelope is exhausted, leaving a helium white-dwarf core and terminating the orbital evolution. Detailed tracing of such an evolutionary path for PSR 1855+09 has lead to theoretical mass estimates for the two stars. Joss, Rappaport, & Lewis (1987) predict $m_2 = 0.20 \pm 0.03 M_{\odot}$, while Savonije (1987) calculates $m_2 \approx 0.22 M_{\odot}$ and $m_1 \lesssim 1.2 M_{\odot}$.

Our most important new results are experimental measurements of just these quantities, the masses of the two stars. Simultaneous measurements of the shape and range of the Shapiro delay, plus the assumption of general relativity theory, yield the orbital inclination and companion mass. The well-determined mass function then gives a value for the pulsar mass as well. Our measurements show that $s = \sin i$ is extremely close to 1 (see Fig. 7). One should keep in mind that the a priori probability of orbital inclinations greater than i is $\cos i$; therefore, values of s as close to unity as we have measured have a nonnegligible probability, about 4%. We note that Dewey et al. (1988), using independent arguments based on interstellar scintillation data, have also concluded that $i \approx 90^\circ$ for this binary system. Because the orbital inclination is so close to 90° , masses consistent with our measured value of r occupy a narrow band in the (m_1, m_2) -plane. The allowable region, illustrated in Figure 8, is centered on masses remarkably close to those predicted on evolutionary grounds.

We note that the pulsar mass given in equation (9) is only the third example of a neutron star mass measured to better than about 30% (see, for example, Nagase 1989). The nominal value is smaller than those of two neutron stars in the PSR 1913+16 system, which have been found to be 1.442 ± 0.003 and $1.386 \pm 0.003 M_{\odot}$, respectively (TW). However, the uncertainties of the present measurement are large enough that the acceptable ranges overlap. All three neutron stars are reasonably close to the Chandrasekhar limiting mass for electron-degenerate matter, which of course is a critical parameter in the events leading up to their formation. Recall that the “baryonic” or precollapse masses are 10%–15% larger than the gravitational masses we measure, the remainder having been carried away by neutrinos during the collapse to neutron star status (Burrows & Woosley 1986).

A full understanding of the PSR 1855+09 system, including

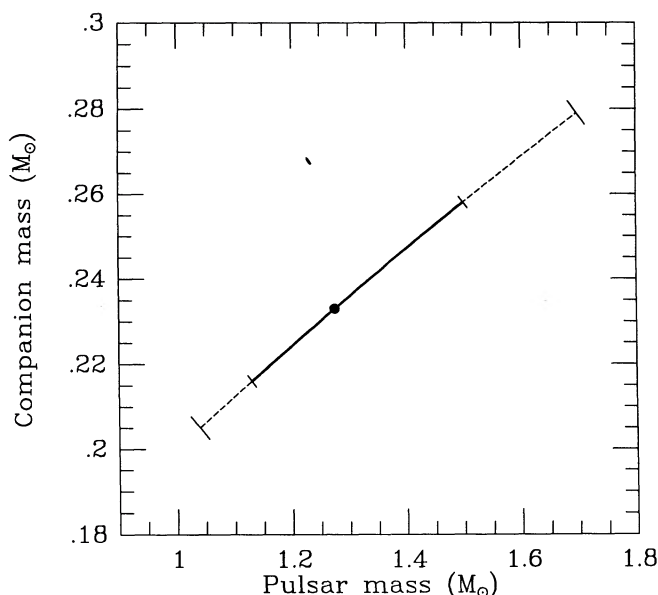


FIG. 8.—Range of permissible masses for the pulsar and companion star. The heavy band corresponds to the 68% confidence region, and the dashed line to 95% confidence.

the age, structure, and temperature of the companion, requires a reliable distance estimate. A neutral hydrogen absorption spectrum obtained by Kulkarni, Djorgovski, & Klemola (1991) shows prominent features at 3–12 and 19–23 km s⁻¹, but none at slightly higher velocities where strong emission is seen. In a thorough discussion of H I absorption data for many pulsars, Frail & Weisberg (1990) show that these results imply lower and upper distance limits of 1.6 ± 0.5 and 2.0 ± 0.4 kpc for PSR 1855+09. (The uncertainties correspond to random velocities of ± 7 km s⁻¹ added to the galactic rotation model used to convert velocities to distances.) On the other hand, with customary assumptions about the distribution of interstellar free electrons, the pulsar's low dispersion measure of 13.3 cm⁻³ pc suggests a distance well under a kiloparsec, though with fairly large uncertainty (Lyne et al. 1985). Our own measurement of annual parallax favors a distance of nearly a kiloparsec, and certainly no less than 0.6 kpc (68% confidence) or 0.45 kpc (95% confidence). The recently favored galactic distance scale with solar galactocentric radius $R_0 = 7.7$ kpc (Reid 1989) would reduce the H I-based estimates by about 10%. On the basis of all three techniques (see Fig. 3), we conclude that PSR 1855+09 probably lies at a distance of 0.8–1.4 kpc. We use $d = 1.1$ kpc in the following discussion.

The equatorial proper motion components listed in Table 1, which have a normalized covariance of -0.2828 (see Appendix and Table 4), correspond to angular motion in galactic coordinates

$$\mu_l = -6.07 \pm 0.20 \text{ mas yr}^{-1}, \quad (12)$$

$$\mu_b = +0.11 \pm 0.11 \text{ mas yr}^{-1}. \quad (13)$$

The pulsar's apparent transverse motion is thus directed almost parallel to the galactic plane, and amounts to some 32 km s⁻¹. The net angular motion can be decomposed into contributions due to the circular galactic orbits of matter in the solar and pulsar neighborhoods, the peculiar motion of the Sun relative to its local standard of rest (approximately 20 km s⁻¹ toward $\alpha = 18.1^\circ$, $\delta = 30^\circ$), and peculiar motion of the

TABLE 3
CONTRIBUTIONS TO THE OBSERVED PROPER MOTION
OF PSR 1855+09

Origin	μ_l (mas yr ⁻¹)	μ_b (mas yr ⁻¹)
Solar motion	-0.93	-1.25
Galactic rotation	-3.23	+0.00
Peculiar motion of pulsar	-1.91	+1.36
Total observed	-6.07	+0.11

pulsar with respect to its local standard of rest. Table 3 illustrates this decomposition for $d = 1.1$ kpc; in obtaining the quoted values we have used a flat galactic rotation curve (Fich, Blitz, & Stark 1989), solar galactocentric distance $R_0 = 7.7$ kpc (Reid 1989), and solar circular velocity $v_0 = 220$ km s⁻¹ (Kerr & Lynden-Bell 1986). We conclude that about 60% of the observed proper motion is the result of solar motion and galactic rotation. The PSR 1855+09 system appears to move relative to its local standard of rest with a two-dimensional transverse velocity of only about 12 km s⁻¹. This low velocity is consistent with the somewhat model-dependent value obtained by Dewey et al. (1988) from scintillation data. It tends to favor accretion-induced collapse models (e.g., Taam & van den Heuvel 1986; Popham & Narayan 1991) for creation of the neutron star, since such models do not involve the impulsive ejection of a massive and possibly asymmetric supernova shell.

The characteristic spin-down age of the pulsar, generally considered to be an upper bound on the true age (Manchester & Taylor 1977), is 5×10^9 yr. Attempts at detecting the white dwarf optically, which may or may not have been successful, conclude from cooling arguments that the age of the system in its present configuration is at least 10^9 yr (Wright & Loh 1987; Callanan et al. 1989; Kulkarni, Djorgovski, & Klemola 1990). This lower age limit provides strong support for the concept of a nondecaying residual magnetic field in pulsars, or at least a field which decays much more slowly than exponentially (Sang & Channugam 1987, 1990). We believe it is now well established that pulsars like PSR 1855+09 can remain active millisecond pulsars for a Hubble time or longer—which is an important consideration in establishing their galactic statistics (Kulkarni & Narayan 1988).

Damour, Gibbons, & Taylor (1988) have called attention to the fact that binary pulsars provide an excellent means for testing the constancy of Newton's gravitational "constant," G . Fifteen years of timing observations of PSR 1913+16 now yield the interesting result $\dot{G}/G = (1.1 \pm 1.1) \times 10^{-11} \text{ yr}^{-1}$ (Damour & Taylor 1991). The present data set on PSR 1855+09 yields a weaker limit,

$$\frac{\dot{G}}{G} = -\frac{1}{2P_b} (\dot{P}_b^{\text{obs}} - \dot{P}_b^{\text{exp}}) = (7 \pm 12) \times 10^{-11} \text{ yr}^{-1}. \quad (14)$$

(Here $\dot{P}_b^{\text{obs}}$ is the observed value of the orbital period derivative, and $\dot{P}_b^{\text{exp}}$ is the expected value, in the present case essentially zero.) With continued observations, the limit from PSR 1855+09 should improve as the inverse 2.5 power of the total time span. After a decade or so, the experimental uncertainties in $\dot{P}_b/P_b$ should be comparable to or smaller than those for PSR 1913+16; furthermore, the relative proximity of PSR 1855+09 will make it much less subject to systematic errors in $\dot{P}_b$ caused by effects of galactic dynamics (Damour & Taylor 1991). For this and other reasons it seems well worthwhile to

continue making timing observations of this pulsar, and we plan to do so.

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APPENDIX

ANALYSIS OF EXPERIMENTAL ERRORS

In this Appendix we offer some additional details on the data analysis for this project, especially concerning the assignment of uncertainties to the measured parameter values. The overall robustness of the fitted model can be characterized by its matrix of parameter covariances. We reproduce the most significant parts of this matrix in Table 4. The triangular portion at the top includes all covariances among the astrometric parameters and those involving pulsar rotation and interstellar dispersion; the triangle at the bottom does the same for orbital parameters. Together, these two submatrices include all of the parameter covariances with absolute values greater than 0.3. Table 4 also includes for each parameter the global correlation coefficient, ρ , which is a measure of the maximum covariance with all possible linear combinations of the other variables. The measurability of a parameter is reduced by a factor $(1 - \rho^2)^{1/2}$ because of flexibility in the rest of the model. Thus, values of ρ very close to unity represent problem areas. Our model of the PSR 1855+09 system has one such problem area, the near-degeneracy of T_0 and ω . Note that despite the appearance of the tabulated version, our matrix is not (quite) singular. Footnotes to the table give higher precision values for the covariance between T_0 and ω , and their global correlations. In these two cases, $(1 - \rho^2)^{1/2} \approx 10^{-5}$, and this fact accounts for our quoting, for the convenience of observers, five “insignificant” digits for T_0 and ω in Table 2. All of the other model parameters have global correlations with reasonable values. We hasten to point out that the full matrix was accumulated and inverted with sufficient precision to avoid numerical problems with its near singularity.

The total uncertainty of each model parameter is a combination of a statistical component (based on the usual assumption of measurement errors with random, Gaussian statistics), and our best estimate of possible contributions from systematic errors. As always, the systematic errors are the more difficult ones to quantify. We have sought evidence of their presence by examining the post-fit residuals for any evidence of non-Gaussian statistics, and by carrying out a number of fits to the data using widely varying weighting schemes—including the deletion of whole sections of data.

Figure 9 presents a histogram of the normalized postfit residuals (i.e., the residuals divided by their estimated uncertainties) for all of our data. The shape of the histogram is a reasonable approximation to a Gaussian (within counting statistics), although there may be slightly more outlying points than expected. As a second test, we started with the list of normalized residuals, ordered by observing date; we then computed averages of consecutive sets of 1, 2, 4, 8 and 16 residuals, and plotted the standard deviations within each group as illustrated in Figure 10. In such a test, random Gaussian measurement errors would produce standard deviations inversely proportional to the square root of the number of residuals averaged, and the points in Figure 10 would

TABLE 4
SIGNIFICANT PORTIONS OF THE NORMALIZED COVARIANCE MATRIX

	α	δ	μ_α	μ_δ	π	ν	$\dot{\nu}$	DM
α	1.0000							
δ	-0.2352	1.0000						
μ_α	-0.1151	-0.1465	1.0000					
μ_δ	-0.0994	0.1482	-0.2828	1.0000				
π	-0.1799	-0.1586	-0.2141	0.2415	1.0000			
ν	-0.4567	-0.0329	-0.2706	-0.1439	-0.2315	1.0000		
$\dot{\nu}$	-0.4825	-0.0403	0.0301	-0.3260	-0.1333	0.8112	1.0000	
DM	0.1597	0.0697	-0.0007	-0.0116	-0.2422	-0.1297	-0.2363	1.0000
ρ	0.7926	0.6155	0.7843	0.5920	0.7650	0.9269	0.8884	0.4611
	x	P_b	e	T_0	ω_0	r	s	
x	1.0000							
P_b	0.0639	1.0000						
e	-0.5665	-0.1365	1.0000					
T_0	0.4670	0.1337	-0.2679	1.0000				
ω	0.4670	0.1337	-0.2679	1.0000 ^a	1.0000			
r	-0.8815	-0.0060	0.6638	-0.2994	-0.2994	1.0000		
s	0.5484	-0.0960	-0.3182	0.1165	0.1165	-0.7156	1.0000	
ρ	0.9204	0.6365	0.7534	1.0000 ^b	1.0000 ^b	0.9549	0.8069	

^a Actual value is 0.99999999921.

^b Actual value is 0.99999999950.

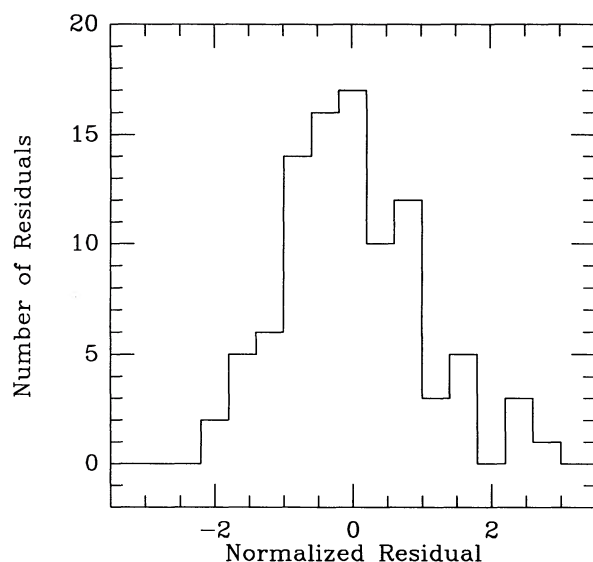


FIG. 9

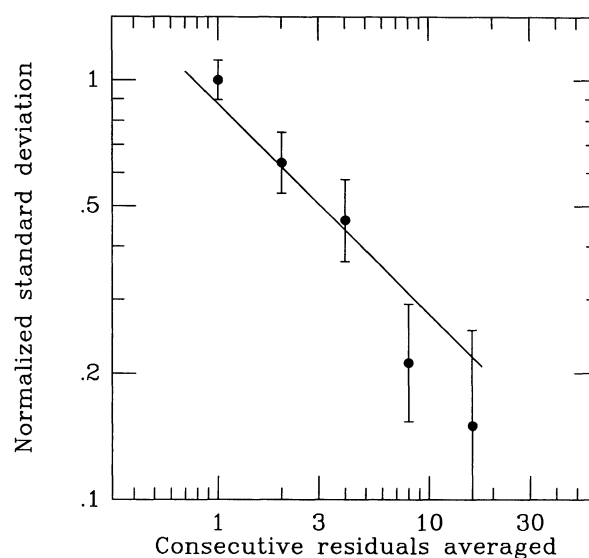


FIG. 10

FIG. 9.—Histogram showing the distribution of post-fit residuals for all of our data, normalized by dividing each value by its estimated uncertainty.

FIG. 10.—Standard deviations among averages of consecutively ordered normalized residuals. Positive correlations among adjacent residuals would cause the points to show a shallower slope than that of the $n^{-1/2}$ line plotted.

therefore follow a slope of -0.5 . Correlations among adjacent measurements would cause the slope to be flatter than -0.5 . As the figure shows, our observed slope appears to be slightly steeper than the nominal value, though the difference is probably not significant. We conclude that these tests have revealed no suggestive evidence of systematic errors in the TOAs.

Our preferred solution, which gave rise to the parameter estimates quoted in Tables 1 and 2, weighted the data by the inverse squares of their estimated uncertainties. Other weighting schemes make arguably plausible alternatives, however. For example, we carried out solutions in which all data taken with the Mark II system received the same weights—and likewise for the normal Mark III data and the concentrated Mark III observations in 1990 April. As another test, we replaced all of the Mark III data with TOAs obtained with the 32×250 kHz filter bank, which otherwise had not been used in the fits. Most of these and other similar tests produced parameter values that agreed with the quoted ones within the statistical errors. For the few cases where this was not true, we have increased the estimated uncertainty (always by a factor of 2 or less) to allow for possible systematic errors. The uncertainties quoted in the tables represent our best estimates of realistic 68% confidence intervals for the model parameters.

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