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SHAPIRO DELAY IN THE PSR J1640+2224 BINARY SYSTEM

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ABSTRACT

We present the results of precision timing observations of the binary millisecond pulsar PSR J1640+2224. Combining the pulse arrival time measurements made with the Effelsberg 100 m radio telescope and the Arecibo 305 m radio telescope, we have extended the existing timing model of the pulsar to search for a presence of the effect of a general relativistic Shapiro delay in the data. At the currently attainable precision level, the observed amplitude of the effect constrains the companion mass to $m_2 = 0.15^{+0.08}_{-0.05}\ M_\odot$, which is consistent with the estimates obtained from optical observations of the white dwarf companion and with the mass range predicted by theories of binary evolution. The measured shape of the Shapiro delay curve restricts the range of possible orbital inclinations of the PSR J1640+2224 system to $78^\circ \leq i \leq 88^\circ$. The pulsar offers excellent prospects to significantly tighten these constraints in the near future.

Subject headings: astrometry — binaries: general — gravitation — pulsars: individual (PSR J1640+2224) — relativity — stars: neutron

1. INTRODUCTION

Precision timing measurements of binary millisecond pulsars (Phinney & Kulkarni 1994) with sufficiently high (near edge-on) orbital inclinations make it possible to detect the effect of a general relativistic time delay of the pulsar signal in the gravitational field of the companion star. For a pulsar in a circular orbit this "Shapiro delay" (Shapiro 1964) is given by

$$\Delta t = -2m_2 T_\odot \ln\left[1 - \sin i \sin\left(\Phi - \Phi_0\right)\right], \qquad (1)$$

where Φ is the orbital phase in radians, Φ_0 is the phase of the ascending node, and $T_\odot = (GM_\odot/c^3)$. In practice, Shapiro delay is conveniently expressed in terms of two observables, the "range" $r = m_2 T_\odot$ and the "shape" $s = \sin i$ (Ryba & Taylor 1991), and the post-Keplerian orbital parameters, which allow a determination of the companion mass, m_2, and the orbital inclination, i.

Because high-inclination orbits are relatively rare, Shapiro delay has been detected in only four pulsar–white dwarf (WD) binaries, PSR J1713+0747 (Camilo et al. 1994), PSR B1855+09 (Ryba & Taylor 1991), PSR J0437−4715 (van Straten et al. 2001), PSR J1909−3744 (Jacoby et al. 2003), and possibly in PSR J0751+1807 (Nice et al. 2003). Such detections offer very useful means to measure masses of the companion stars and to calibrate the pulsar spin-down models against the cooling models of WDs. This is accomplished by comparing the spin-down age of a pulsar, obtained from timing observations, with the cooling age of a WD, estimated from its mass, an optical measurement of its temperature, and an appropriate cooling model (Kulkarni 1986). In particular, such comparisons are important in assessing the temperature-modifying effect of hydrogen left over after the WD formation (van Kerkwijk et al. 2000).

Shapiro delay has also been detected in two double neutron star (NS-NS) systems, PSR B1534+12 (e.g., Stairs et al. 2002) and PSR J0737−3039A (Burgay et al. 2003; Lyne et al. 2004). In these cases, the measured parameters r and s, together with the other two strong gravity-related post-Keplerian parameters, the periastron advance $\dot{\omega}$, and the time dilation and gravitational redshift γ, provide a clean test of general relativity and other theories of gravity, in the sense that it does not mix the relativistic strong field and the radiative effects (Damour & Taylor 1992).

Neutron stars in pulsar-WD binaries are thought to undergo extended periods of transfer of mass and angular momentum from their companions (Phinney & Kulkarni 1994). As a result, they are spun up to millisecond periods and may end up having masses significantly larger than the canonical value of 1.35 $M_\odot$ derived for stars in the NS-NS systems (Thorsett & Chakrabarty 1999). The existing mass measurements for PSR J0437−4715 ($m_1 = 1.58 \pm 0.18\ M_\odot$; van Straten et al. 2001) and PSR B1855+09 ($m_2 = 1.57^{+0.12}_{-0.11}\ M_\odot$; Nice et al. 2003, 2004) provide support for this idea. On the other hand, the recent mass measurement of $1.3 \pm 0.2\ M_\odot$ derived from precision timing observations of PSR J1713+0747 (Splaver et al. 2005) is in accord with the canonical value. Undoubtedly, more data for similar systems are needed to improve the existing statistics.

In this paper, we report new results of timing measurements of the PSR J1640+2224 binary system. A tentative detection of

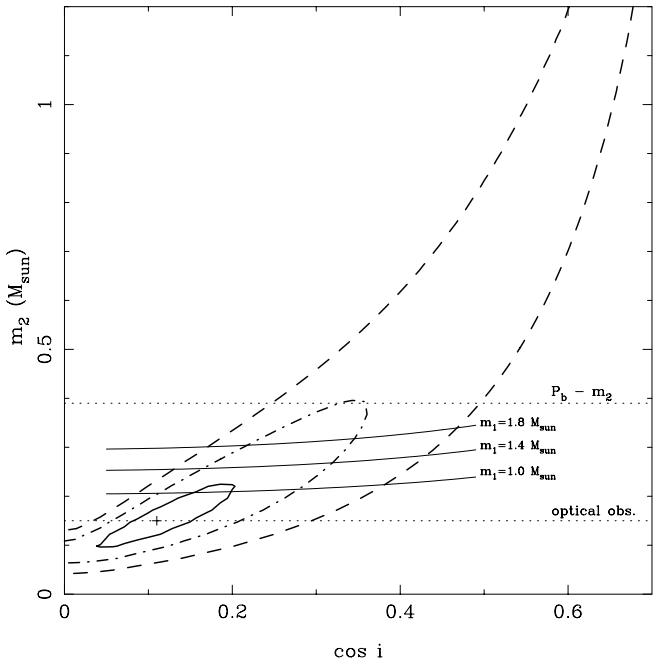


FIG. 1.—Constraints on m_2 and cos i in the PSR J1640+2224 system from a χ^2 search for the best-fit Shapiro delay parameters. The global χ^2 minimum is indicated by a plus sign. The contours of $\Delta\chi^2 = 1.0$ (*solid line*), $\Delta\chi^2 = 4.0$ (*dashed-dotted line*), and $\Delta\chi^2 = 9.0$ (*dashed lines*) have extrema respectively corresponding to 1, 2, and 3 σ errors on the individual parameters cos i and m_2. Lines of constant m_1 are indicated. Horizontal lines denote the m_2 range bounded by a lower limit obtained from optical observations ($m_2 \geq 0.15\ M_\odot$) and an upper limit allowed by the P_b-m_2 relationship ($m_2 \leq 0.39\ M_\odot$).

the Shapiro delay in the pulse arrival times from the pulsar allows us to set preliminary constraints on the orbital inclination of the system and the mass of the pulsar companion. In § 2 we describe the timing observations made at Effelsberg and Arecibo, present the timing analysis, and summarize the resulting best-fit timing model for PSR J1640+2224. In § 3 we discuss the new findings and their implications. In particular, we use simulated timing observations to demonstrate the expected potential of a future submicrosecond timing of PSR J1640+2224 to verify the validity of the current best-fit model and to improve the estimates of the masses of the pulsar and its WD companion.

2. OBSERVATIONS AND TIMING ANALYSIS

We have conducted systematic, high-precision timing observations of PSR J1640+2224 with the 100 m Effelsberg radio telescope of the Max-Planck-Institut für Radioastronomie in Bonn, Germany, and the 305 m Arecibo radio telescope of the National Astronomy and Ionosphere Center in Puerto Rico, over a 7 yr period from 1996 until 2003.

At Effelsberg, PSR J1640+2224 was observed approximately once a month using a 1300–1700 MHz tunable HEMT receiver at a center frequency of 1410 MHz. In order to monitor changes of the dispersion measure (DM), we occasionally collected data at 860 MHz. As a back end, we used the Effelsberg-Berkeley Pulsar Processor (EBPP), which corrects for the dispersion smearing of the signal by employing a coherent dedispersion technique (Hankins & Rickett 1975). In the total power mode, the EBPP provided 32 channels for both senses of circular polarization, with a maximum total bandwidth of

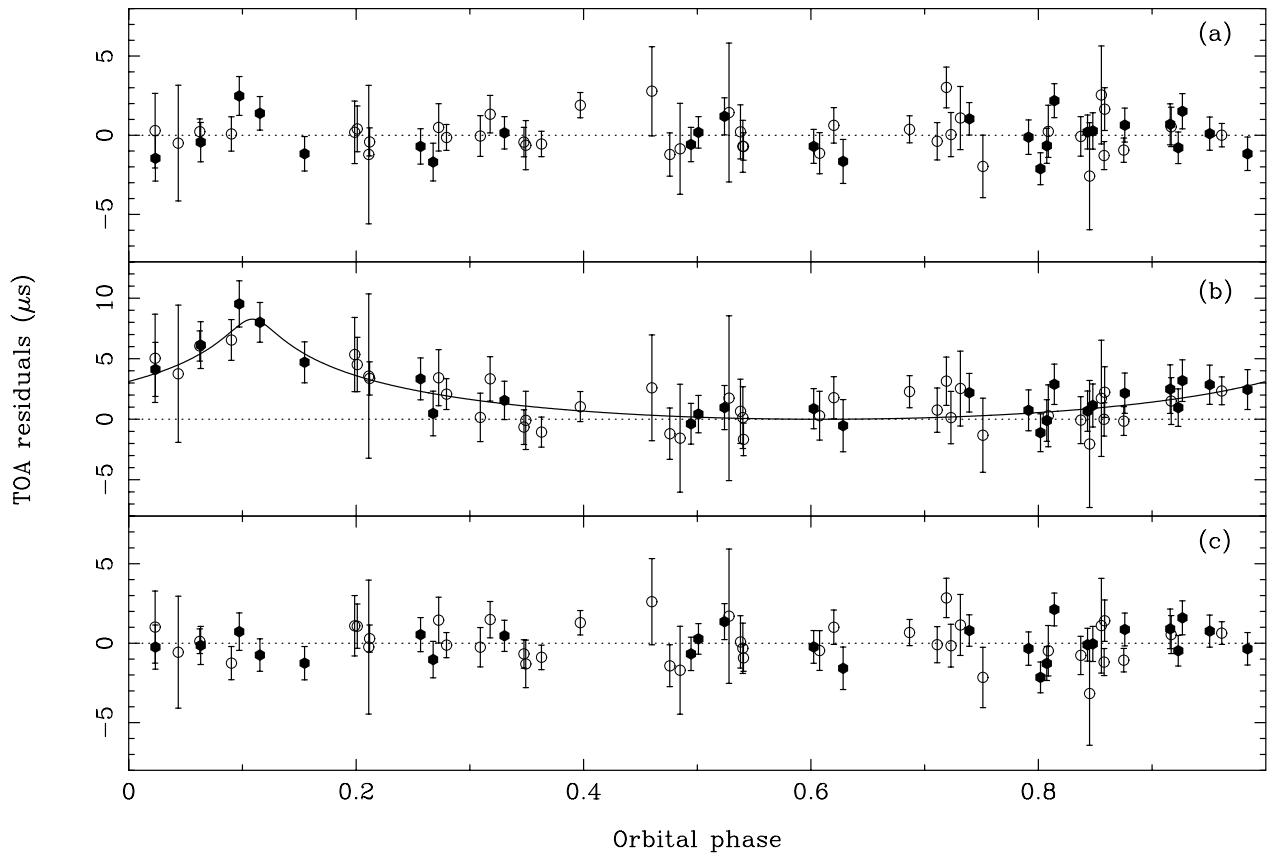


FIG. 2.—Timing residuals for PSR J1640+2224 observed with the Arecibo telescope at 1130 and 1410 MHz (*filled circles*) and with the Effelsberg telescope at 1410 MHz (*open circles*), as a function of orbital phase. (*a*) Post-fit residuals for the best-fit model involving only the five Keplerian parameters. (*b*) The effect of Shapiro delay on the TOA residuals calculated with sin i and m_2 set to zero and all other parameters fixed at their best-fit values. The solid curve represents the delay predicted by general relativity for the best-fit Shapiro parameters. (*c*) Post-fit residuals for the best-fit model including the sin i and m_2 parameters (see also Table 1).

112 MHz, depending on the DM and the observing frequency (Backer et al. 1997). For PSR J1640+2224, total bandwidths of 54 and 27 MHz were available at 1410 and 860 MHz, respectively. The output signals of each channel were fed into the dedisperser boards for coherent online dedispersion and were synchronously folded at the pulse period over a 7 minute integration time.

At Arecibo, the timing observations of PSR J1640+2224 were made with the dual-circular-polarization receiving systems at 430, 1130, and 1410 MHz and the Penn State Pulsar Machine (PSPM). The PSPM pulsar back end is a computer-controlled processor with a $2 \times 128 \times 60$ kHz filter bank designed to conduct fast-sampled pulsar searches and precision timing measurements. Technical details of the back end are given in Cadwell (1997). For our timing observations, the two signals of opposite circular polarizations were added together, smoothed with a 32 μs time constant, 4 bit quantized, folded synchronously with the topocentric pulse period, and stored for further processing. The pulse integration times were 3 minutes at 430 MHz and 5 minutes at both 1130 and 1410 MHz.

Both Effelsberg and Arecibo data were time stamped using the observatory hydrogen maser clocks and later synchronized to UTC (NIST) using the signals from the Global Positioning System (GPS). In order to calculate the pulse time-of-arrival (TOA), high signal-to-noise ratio template profiles of the pulse were constructed for each back end and observing frequency, and least-squares fitted to the observed profiles in frequency domain (Taylor 1991). A theory-independent timing model for binary pulsars, devised by Damour & Deruelle (1986), was least-squares fitted to the combined TOAs, weighted by their individual uncertainties using the software package TEMPO[1] and the DE200 planetary ephemeris (Standish 1990).

In the fitting procedure, the TOA segments obtained with the EBPP and the PSPM were fitted for an unknown offset between the two data sets resulting from different templates and TOA reference points in the profiles. Using the full TOA set at all frequencies, we determined the DM of the pulsar. In the subsequent analysis, we fixed the best-fit value for the DM and used only the 1410 MHz TOAs from Effelsberg and the 1130 and 1410 MHz TOAs from Arecibo, as these high-frequency data were not significantly affected by the observed DM variations. A determination of an initial best-fit model for the PSR J1640+2224 timing data involved a set of 12 parameters, including the astrometric and rotational parameters of the pulsar and the orbital parameters of the binary system. In order to achieve a uniform reduced $\chi^2 = 1$ for each data segment, we increased the TOA uncertainties by a constant amount, approximately equal to the post-fit rms noise, by adding it in quadrature to the actual TOA values.

In order to examine the timing data for a possible presence of the Shapiro delay, we employed a grid-search procedure used by Ryba & Taylor (1991). We searched the $m_2 - \cos i$ plane for a global χ^2 minimum, by fixing the Shapiro parameters r and s at nodes of an appropriately defined two-dimensional grid and repeatedly fitting for all other parameters for each set of (r,s) values. As displayed in Figure 1, the grid search produces a well-defined global $\Delta\chi^2$ minimum, equivalent to the best-fit $\cos i = 0.11^{+0.09}_{-0.07}$ ($i \sim 84^{+4}_{-6}$ deg) and $m_2 = 0.15^{+0.08}_{-0.05}\ M_\odot$ (1 σ uncertainties). Clearly, the inclusion of a Shapiro delay in the timing model for PSR J1640+2224 leads to astrophysically plausible estimates of both the companion mass and the inclination of the pulsar orbit. In Figure 2, the timing residuals for the combined Arecibo and Effelsberg observations are plotted as a function of orbital phase. Because the observed Shapiro delay is weak and both r and s are strongly covariant with other model parameters, the effect is not detectable in residuals from the best fit involving the Keplerian orbit alone, as seen in Figure 2*a*. On the other hand, in Figure 2*b*, showing a Shapiro delay signature extracted from the grid search with all other timing effects removed (see also Ryba & Taylor 1991; Camilo et al. 1994), the amplitude of the effect in the PSR J1640+2224 TOA residuals significantly exceeds the TOA uncertainties, as expected from the result of the χ^2 search displayed in Figure 1.

In principle, the observed signature could be induced by DM variations over the pulsar orbit. If the pulsar's WD companion had an extended envelope created by the pulsar wind and

[1] TEMPO is available at http://pulsar.princeton.edu/tempo.

TABLE 1

Timing Model for PSR J1640+2224

Parameter	Value
Measured Parameters[a]	
Right ascension, α (J2000.0)	$16^h40^m16^s.742307(10)$
Declination, δ (J2000.0)	$22^\circ24'08''.9413(3)$
Proper motion, μ_α	1.66(12) mas yr^{-1}
Proper motion, μ_δ	$-11.3(2)$ mas yr^{-1}
Pulse frequency, ν	316.123984313238(2) s^{-1}
Pulse frequency derivative, $\dot{\nu}$	$-2.8257(9) \times 10^{-16}$ s^{-2}
Pulse period, P	3.16331581791380(2) ms
Period derivative, $\dot{P}$	$0.28276(9) \times 10^{-20}$ s s^{-1}
Epoch (MJD)	51700.0
Dispersion measure, DM	18.4260(8) pc cm^{-3}
Orbital period, P_b	175.46066194(7) days
Projected semimajor axis, x	55.3297198(4) lt-s
Eccentricity, e	0.000797262(14)
Epoch of periastron,[b] T_0 (MJD)	51626.1785(5)
Longitude of periastron,[b] ω	$50^\circ.7308(10)$
Shape of Shapiro delay,[c] s	0.99 ± 0.01
Range of Shapiro delay,[c] r	$0.74^{+0.39}_{-0.25}$ μs
Measured Upper Limits[d]	
Parallax, π	<3.7 mas
Pulse frequency second derivative, $\lvert\ddot{\nu}\rvert$	$<4 \times 10^{-27}$ s^{-3}
DM derivative, $\lvert d(\mathrm{DM})/dt\rvert$	$<1.3 \times 10^{-3}$ pc cm^{-3} yr^{-1}
Orbital period derivative, $\lvert\dot{P}_b\rvert$	$<3 \times 10^{-10}$ s s^{-1}
Derivative of projected semimajor axis, $\lvert\dot{x}\rvert$	$<1.7 \times 10^{-14}$ lt-s s^{-1}
Periastron rate of change, $\lvert\dot{\omega}\rvert$	$<1.1 \times 10^{-3}$ deg yr^{-1}
Derived Parameters	
Galactic longitude, l	$41^\circ.051$
Galactic latitude, b	$38^\circ.271$
DM distance[e]	1.16 kpc
Composite proper motion, μ	11.4(2) mas yr^{-1}
Companion mass, m_2	$0.15^{+0.08}_{-0.05}\ M_\odot$
Orbital inclination angle, i	84^{+4}_{-6} deg
Mass function, f_m	0.0059074304(2) $M_\odot$
Number of TOAs	314
Timing rms	2.0 μs

[a] Values in parentheses are 2 σ uncertainties in the last digits quoted (twice the formal TEMPO errors).

[b] ω and T_0 are highly covariant. Observers should use $\omega = 50.730834835740$ and $T_0 = 51626.178534099$.

[c] Uncertainties are 1 σ errors derived from the χ^2 analysis (see § 2).

[d] Upper limits represent 95% confidence level.

[e] From the Cordes & Lazio (2002) model of the Galactic electron density distribution, with typical uncertainties of 10%.

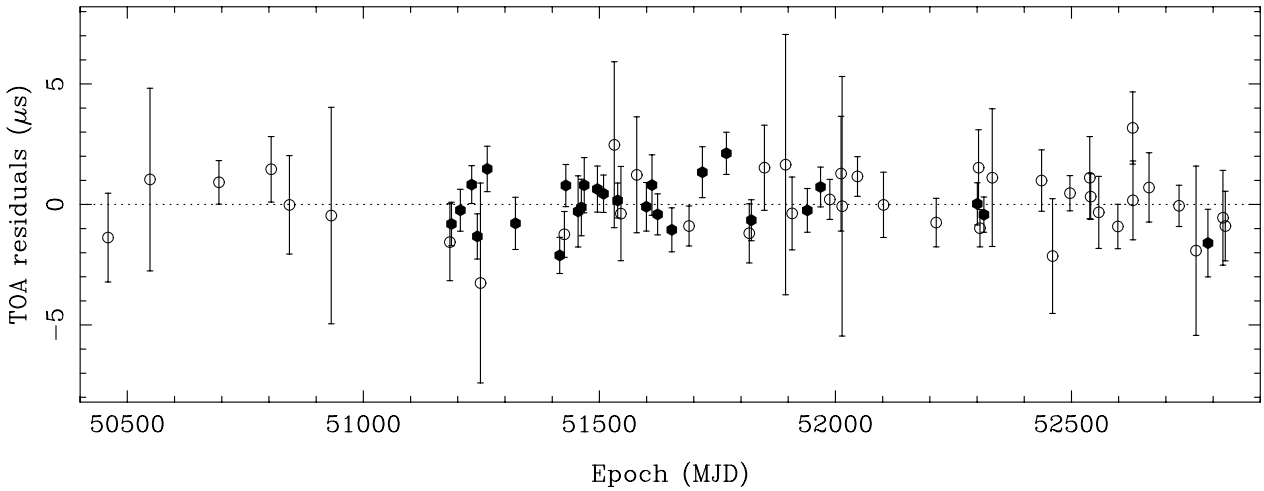


FIG. 3.—Best-fit timing residuals for PSR J1640+2224 as a function of observing epoch. See Fig. 2 for further explanation.

the high-energy photon flux, as observed in eclipsing binary systems (e.g., Nice et al. 2000), the electron column density would fluctuate periodically as a function of orbital phase. For highly inclined orbits, this would obviously cause periodic, frequency-dependent TOA variations that could mimic the effect of Shapiro delay. We have ruled out this possibility by verifying that the effect has the same amplitude in the TOA measurements made at four different frequencies.

In the case of binary pulsars with nearly circular, low-inclination orbits, Shapiro delay becomes covariant with Roemer delay and cannot be measured (Lange et al. 2001). PSR J1640+2224 has the most eccentric orbit among the pulsar-WD binaries (see Table 1 and Edwards & Bailes 2001), and its inclination angle of $i = 84^\circ \pm 6^\circ$ derived from our analysis appears to be high enough to allow the inclusion of Shapiro delay in the timing model (Fig. 2*b*). In any case, further observations of the pulsar with higher timing precision are clearly necessary to fully assess the statistical significance of our detection.

The parameters of the best-fit timing model for PSR J1640+2224 are listed in Table 1 along with the ones for which only upper limits could be determined. In this case, the upper limits were obtained by allowing the parameters to vary, one at a time, in the global fit. Also included in the table are the most important parameters derived from the final model. Finally, the behavior of the postfit timing residuals as a function of time, spanning a 7 yr period, is shown in Figure 3. Evidently, the best-fit model that includes the Shapiro delay leaves no additional systematic effects above the current postfit rms residual of 2.0 μs.

3. DISCUSSION

A new timing model for the binary millisecond pulsar PSR J1640+2224 discussed in this paper is entirely consistent with the previous models published by Wolszczan et al. (2000) and Potapov et al. (2003). In addition, owing to a higher timing precision, the new model provides further reduction of the parameter estimation errors and, above all, it includes astrophysically sensible estimates of the Shapiro delay parameters.

The binary companion to PSR J1640+2224 is a white dwarf with the estimated cooling age of 7 ± 2 Gyr and mass of $0.25 \pm 0.10\ M_\odot$, as determined from the *Hubble Space Telescope* observations (Lundgren et al. 1996). A range of masses predicted by the relationship of the binary period to the companion mass (P_b-m_2), based on the theory of low- and intermediate-mass binary evolution, is $0.35 \leq m_2 \leq 0.39\ M_\odot$ (Tauris & Savonije 1999), and the minimum companion mass from the mass function,

$$f(m_1, m_2) = (m_2 \sin i)^3 (m_1 + m_2)^{-2} = (2\pi/P_b)^2 x^3 / T_\odot = 0.0059\ M_\odot,$$

is $m_2 = 0.25\ M_\odot$ for a $m_1 = 1.4\ M_\odot$ neutron star. At the currently attainable level of accuracy, the best-fit companion mass of $m_2 = 0.15^{+0.08}_{-0.05}\ M_\odot$ derived from our data is consistent with the above estimates, as illustrated in Figure 1.

Among the pulsar-WD binaries with a detectable Shapiro delay, only PSR J0437−4715, PSR J1713+0747, and PSR B1855+09 have values of m_2 and sin i determined with an accuracy that is high enough to make them usable in setting a tight constraint on the pulsar mass (van Straten et al. 2001; Nice et al. 2003, 2004; Splaver et al. 2005) and in investigating the details of the evolution of the pulsar's WD companion (van Kerkwijk et al. 2000). We have examined the potential of PSR J1640+2224 timing to become comparably useful in future by generating artificial TOAs according to the model of Table 1 and analyzing the data over

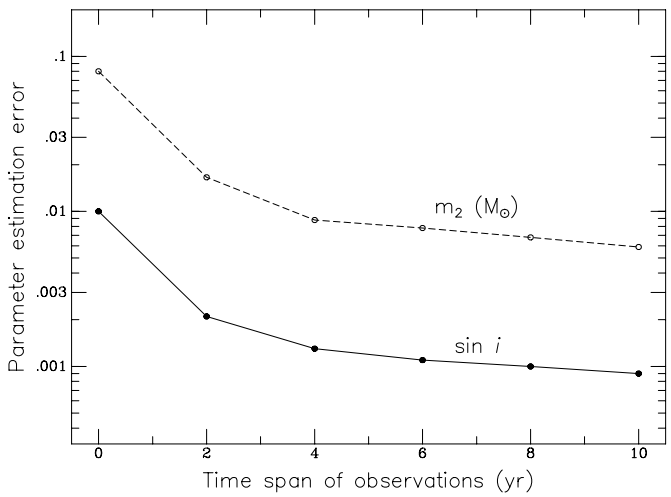


FIG. 4.—Estimation errors of the companion mass and orbital inclination from the simulated TOA measurements of PSR J1640+2224 with a 0.5 μs precision. The initial error values are equal to those currently observed.

progressively longer periods of time for several reasonable values of the timing precision. Encouragingly, as shown in Figure 4, in only 4 yr of monthly timing measurements with a 0.5 μs precision, the estimation errors of m_2 and cos i approach the respective levels of 0.01 $M_\odot$ and 0.001. Since the Arecibo timing measurements using the PSPM and an 8 MHz receiver bandwidth are characterized by a $\sim$1 μs long-term residual, it is quite conceivable that the required $\leq$0.5 μs precision can be achieved with a new generation of broadband, 100 MHz bandwidth back ends already available at the telescope. Further observations at this level of precision could quite conceivably allow a verification of the timing model presented in this paper. PSR J1640+2224 is also likely to become a valuable member of a set of the most accurate pulsar clocks that can be timed either individually or as an array to detect a low-frequency background of gravitational radiation (e.g., Thorsett & Dewey 1996; Jaffe & Backer 2003).

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