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Shapiro Delay in the Binary Millisecond Pulsar PSR J1909−3744

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Abstract. PSR J1909−3744, a 2.95 millisecond pulsar in a nearly circular 1.53 day orbit, was discovered in a recent survey for pulsars at high galactic latitude using the 64-m Parkes telescope. Its narrow pulse width of 43 μs allows pulse arrival times to be determined with great accuracy. Analysis of arrival times clearly shows strong Shapiro delay. We expect that further timing observations, combined with the companion's radial velocity obtained through optical spectroscopy, will allow a very accurate determination of the pulsar's mass. Weighted rms timing residuals of only 270 ns indicate that this pulsar will be very useful for high-precision timing experiments.

1. Introduction

PSR J1909−3744 was discovered during the Swinburne High Latitude Pulsar Survey, a large-area search using the 13-beam multibeam receiver on the 64-m Parkes radio telescope (Jacoby 2003). This survey, which uncovered 26 new pulsars, is an extension of the highly-successful Swinburne Intermediate Latitude Pulsar Survey (Edwards et al. 2001).

After its discovery in 2001, we began timing observations of this pulsar with the 512-channel Parkes filterbank. These observations yielded a weighted rms residual of only 330 ns over more than two years (Jacoby et al. 2003). Most interesting was a statistically significant detection of Shapiro delay; unfortunately, the pulsar's strong scintillation meant that the orbital phase coverage of high-quality arrival time measurements was rather limited. Moreover, as quality TOAs from a given region of orbital phase often depended heavily on observations from a single epoch, there was some covariance between the Shapiro delay and astrometric parameters.

2. Shapiro Delay

More recently, we began observing PSR J1909−3744 with the Caltech-Parkes-Swinburne Recorder II coherent dedispersion system (CPSR2; Bailes 2003). This instrument's high time resolution revealed an unusually narrow pulse profile (43 μs FWHM; Fig. 1). The improvement in timing precision allowed by this new instrument, combined with more complete orbital phase coverage, reveals the unmistakable signature of Shapiro delay.

Arrival time residuals from 21 cm CPSR2 data are shown in Figure 2. Observations were divided into 10-minute segments, and only arrival times with uncertainty less than 600 ns have been included. Since the CPSR2 data set spans less than one year, all astrometric parameters were held fixed at values derived from filterbank data. The weighted rms residual is 270 ns, among the best ever achieved.

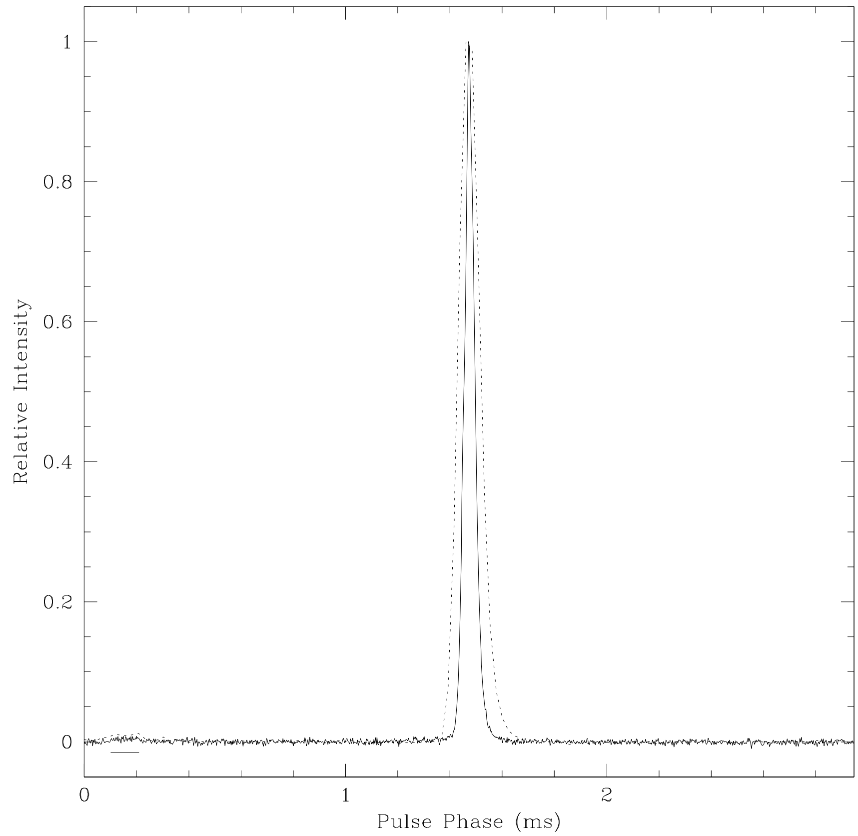

Figure 1. Average pulse profile of PSR J1909−3744 at 1.4 GHz as measured by CPSR2 coherent dedispersion system (solid line) and $2 \times 512 \times 0.5$ MHz Parkes filterbank (dotted line). The location of a very weak interpulse is indicated by the underscore at left.

3. Discussion

A trustworthy measurement of companion and pulsar masses awaits further timing observations which will give more complete orbital phase coverage and allow all model parameters to be determined from the higher-quality CPSR2 data. Our current data suggest an orbital inclination near 90°, a typical low-mass white dwarf companion of about $0.2\,M_\odot$, and a neutron star mass somewhat greater than the canonical $1.35\,M_\odot$ inferred from double neutron star systems (Thorsett & Chakrabarty 1999). Because of the edge-on orientation and exceptional timing precision afforded by its narrow pulse profile, we expect that PSR J1909−3744 will allow a more precise millisecond pulsar mass measurement than has been possible for objects such as PSR J0437−4715 (van Straten et al. 2001) and PSR B1855+09 (Nice, Splaver, & Stairs 2003).

Owing to its strong optical absorption lines, we will be able to measure the companion's radial velocity as a function of orbital phase (Fig. 3); this measurement will give the system's mass ratio and, with sufficient precision, allow a test of general relativity.

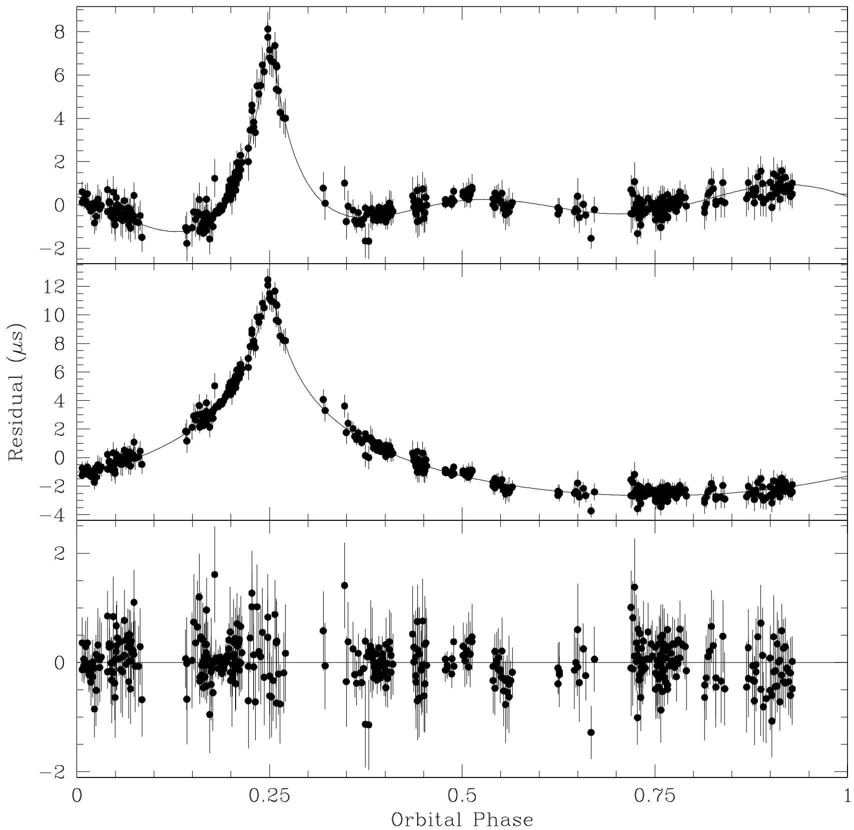

Figure 2. Timing residuals of PSR J1909−3744 with respect to the best-fit Keplerian model (top), a model with physically correct orbital parameters but neglecting Shapiro delay (middle), and a model taking Shapiro delay fully into account (bottom). In each case the solid line represents the timing model from the bottom panel.

This binary system appears to have an extremely small orbital eccentricity, $\sim 2 \times 10^{-7}$, which gives it the highest figure of merit for tests of Lorentz invariance ($P_b^{1/3}/e$) of all known binary pulsars. Along with the parallax and proper motion already determined through pulse timing, measurement of the companion's absolute radial velocity will give the system's 3-D space velocity. Therefore, this system should allow us to improve current constraints on the existence of a preferred reference frame (Lange et al. 2001).

In addition to these interesting physical measurements of this system, the pulsar itself is an extremely good clock, and is widely separated on the sky from the traditional precision timing pulsars. We expect it to be an important component of pulsar timing array experiments designed to detect low-frequency gravitational waves (Lommen et al. 2003).

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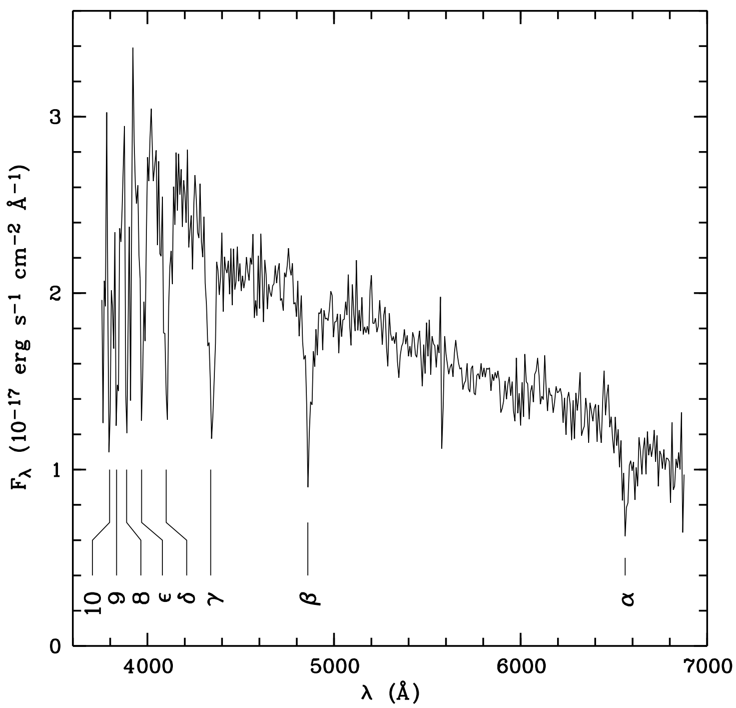

Figure 3. Spectrum of the companion of PSR J1909−3744 obtained with the LDSS2 on the 6.5 m Clay telescope, showing that it is a low-mass white dwarf. The Balmer lines from Hα to H10 are indicated.

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