TIMING OF ISERVNI'1ONS OF THE SMC BINARY PSR J0045- 7310

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Abstract.
We describe radio timing observations of the binary pulsar PSR J0045–7319 made over the past 3.3 yr. We show that a simple timing model involving a standard Keplerian orbit well-describes the data, however significant low-level systematic residuals never before seen in other binary pulsars remain. We consider various possible origins of the residuals.

1. Introduction

PSR J0045-7319 (PSR 110042- 73) was discovered in a systematic search of the Magellanic Clouds for radio pulsars (McConnell et al. 1 991). The pulsar's association with the SMC is evidenced by its high dispersion measure of 105 pc cIIl^{-3}, since models of the galactic electron distribution account for no more than $\sim$25 pc cm^{-3} along that line of sight (Taylor & Cordes 1993). PSR ,10045–7319 is the only known radio pulsar in the SMC, and is the most distant pulsar known.

Radio timing observations of the pulsar by Kaspi et al. (1 994) have shown that it is in a 5] day binary orbit with a companion having a minimum mass of 4 $M_{\odot}$. Although the pulsar is a faint source (its flux density

Figure 1.   Relative sizes of the PSRs }11259−63 and J0045−7319 *orbits,* assuming 10 M$_\odot$ companions in both cases. The orbits of both binary components are shown. Crosses mark locations of the binary centers of mass.

at *430* MHz is only ∼1 mJy), its large distance makes it easily the most luminous binary radio pulsar known. Optical observations in the direction of the pulsar have revealed a V=16 mag B1 star at the timing position. The probability of chance alignment being small, we conclude that the PSR J0045−7319 binary system is the second in a new class of binary pulsars having massive, non-degenerate companions. The first example of such a system was PSR B1 259−63, reported by Johnston *et al.* (1 992) and also discussed in this volume by Johnston. A schematic drawing of the relative sizes of the two orbits is given in Figure 1, where we have assumed 10 M$_\odot$ companions in both systems, consistent with estimates from optical photometry and spect rose.opy.

2. Timing Properties

We have made timing observations of PSR J0045−7319 for 3.3 yr at the 64-m Parks radio telescope. We obtained a total of 155 pulse arrival times from February 1991 through June 1994. Most, observations were made at 430 MHz however a few were made at 660 and 1520 MHz. The standard pulse timing analysis was done using the TEMPO software package (Taylor & Weisberg 1989). The best-fit timing model including astrometric, spin, and Keplerian orbital parameters is given in Table 1; the postfit residuals after subtraction of this model are shown in Figure 2 versus date and in Figure 3 versus orbital phase.

TABLE 1. Astrometric, Spin, and Orbital Parameters for PSR J0045-7319 assuming a Keplerian orbit.

Right Ascension, α (J2000)	00^h 45^m 35^s .09 $\pm$ 0^s .08
Declination, δ (J2000)	$-73°19'$ $03''$.1 $\pm$ $0''$,3
1 'cried, P	0.926275835356(15) s
l'cried Derivative, $\dot{P}$	4.486(1) x 10^{-15}
Epoch of Period	MJD 48964.2000
Orbital 'cried, P_b	51. 169226(3) days
Projected semi-major axis, $a_p\sin i$	174.2540(8) lt s
Longitude of periastron, ω	$115''$.2537(7)
Eccentricity, e	0.807995(5)
Epoch of Periastron	MJD 49578.56742(3)
R.M.S. timing residual	15 ıns

Figure 2. Residuals versus time using the model given in Table 1.

3. Discussion

The residuals in Figures 2 and 3 clearly show significant, deviations from the straightforward spin-down and Keplerian orbit model. We consider here possible origins of the deviations. We note, however, that the deviations, though significant, are low-level, with maximum excursions under 5% of the pulse period. Thus, we are effectively probing the details of the dynamics of this main sequence star binsry system with unprecedented precision.

3.1. TIMING NOISE?

Deviations from simple spin down models amounting to significant fractions of the pulsar period are frequently seen in timing data from isolated pulsars

Figure *3.* Residuals versus orbital phase using the model given in Table 1.

(e.g. A rzoumanian *et* al. 1994, Kaspi 1 994), and are usually ascribed to rotational instabilities inherent to the pulsar itself. The timing residuals for PSR J0045–7319, however, do not share the salient characteristics of standard "timing noise." Timing noise typically has a "red" spectrum, that is, has more power at long time scales, with spectral indexes ranging from -2 to -6 (Groth 1975). By contrast, the residuals for PSR J0045–7319 as shown in Figure 2 show no sign of long-term modulation. Further, timing noise is a phenomenon most common to young pulsars having characteristic ages $\simeq$ 105 yr, and has been shown to be correlated with $\dot{P}$ (Cordes & Downs 1 9/35). Here, however, the pulsar's characteristic age is 3 x 10^6 yr; its $\dot{P}$ is correspondingly small. Thus, standard pulsar timing noise seems an unlikely source of the residuals.

3.2. ADDITIONAL ORBITAL COMPANION?

Unexplained deviations of pulse arrival times from simple spin-down models have also been used as evidence for an unseen orbital companion (Backer, Foster & Sallmen 1993; Thorsett, Arzoumanian & Taylor 1993). Prom Figures 2 and 3, it is clear that any additional orbital companion must have an orbital period much shorter than the length of the data span. However, a Fourier transform of the resid uals reveals no obvious period icities.

3.3. APSIDAL ADVANCE?

inspection of the residuals as a function of orbital phase (Fig. 3) reveals no obvious trends such as might, be expected for a secular variation of a single Keplerian parameter, such as the longitude of periastron. Apsidal advance at the level of a few hundredths of a degree per year is expected in this system beta.use of the tidal deformation of the companion near

Figure 4. Residuals versus time at two periastron epochs. The upper panel is around periastron on MJD 48964, while the lower panel is around periastron of MJD 49527, 11 orbits later. Periastron is at orbital phase 0.0/1.0, and the timing model used is given in Table 1. The duration of the orbital phase interval shown in these figures is 10 days.

periastron, as well as from rotational deformation of the companion and general relativistic effects (Kaspi *et al.* 1994), Such an effect would be at a similar level to the observed deviations from the Keplerian orbit, but would have an obvious signature.

3.4. DISPERSION MEASURE VARIATIONS?

in Figure 4 we show two well-sampled residual time series, both taken around periastron. The upper panel shows the residuals as a function of orbital phase (which is also time since we are looking at a single orbit) at periastron on MJD 48964. All data at this epoch were taken at 430 MHz. The obvious systematic trend could be due to an orbital-phase-dependent variation in the line-of-sight integrated electron density, the dispersion measure, due to an ionized wind from the B star. A variation in the integrated electron density will result in time delays or advances of the pulsar signal because radio waves are dispersed by free electrons according to the standard $1/f^2$ plasma, law, where f is the observing frequency.

To test this hypothesis, we repeated the detailed periastron observation 11 orbits later, this time, observing at three different radio frequencies, 430, 660, and 1520 MHz. The results of these June 1994 observations are shown in the lower panel of Figure 4. It is clear that arrival Limes at all frequencies are consistent within the measurement uncertainties, which argues strongly against the stellar wind as an origin of the timing residuals. These results can be used to set an interesting and uniquely direct limit on the B star mass loss; the implied upper limit on $\dot{M}$ is $\sim 10^{-11} M_\odot yr^{-1}$ for a wind velocity of 1000 km s-].

3.5. TIDAL INTERACTION?

In the absence of alternatives, a remaining possibility **for** the origin of **the** PSR J0045–7319 residuals lies in a gravitational interaction between the components that results in a deformation of the companion's field. However such possibilities have been considered in detail in recent work by Ku mar, Ao & Quataert (1994), who conclude that apart from apsidal **advance**, no deviations from a Keplerian orbit should be detectable.
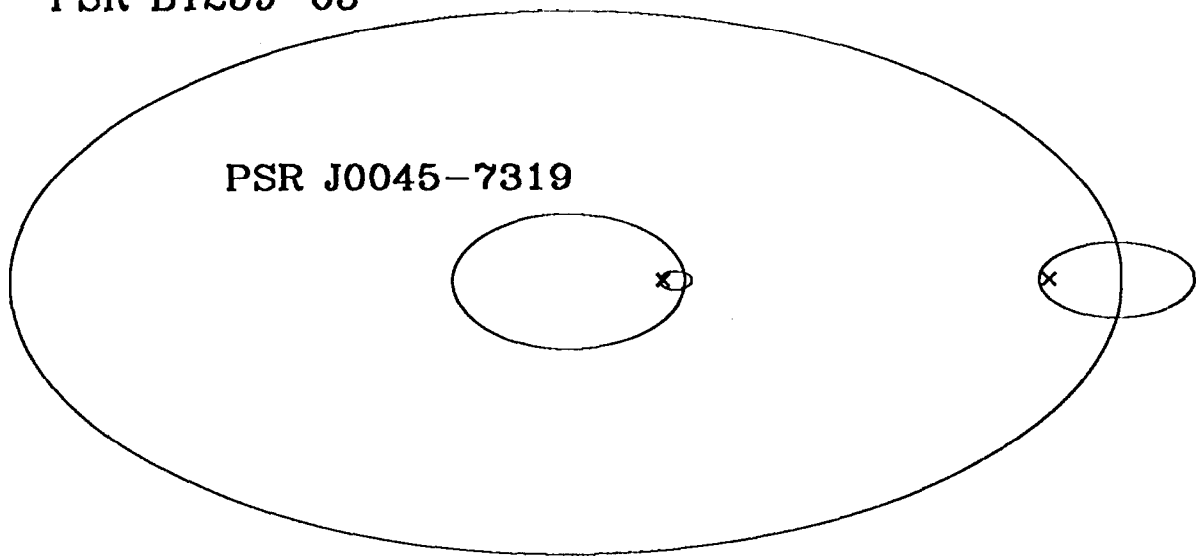
4. Conclusions

Timing observations of the PSR J0045–7319 binary system over a 3.3 yr period have revealed systematic deviations of pulse arrival times from a simple Keplerian orbit. We have considered several possible origins of these deviations, however their origin remains unclear. In the process, however, we have set a limit on mass loss from the B star that is low, but not **incompatible** with other highly model-dependent determinations of B star mass loss rates (Snow 1 982). The systematic variation in the residuals near periastron suggests they are due to a dynamical interaction between the neutron star and B star, rather than to the neutron star itself. 'I'bus, the above timing results provide strong evidence against a proposed black hole/pulsar model of the PSR J0045–7319 system (Lipunov, Postnov & Prokhorov 1994) (independent of the persuasive optical observations) since a neutron star/black hole binary should be an extremely clean system, similar to the well-studied neutron sta.r/neutron star binaries (e.g. Taylor & Weisberg 1989).
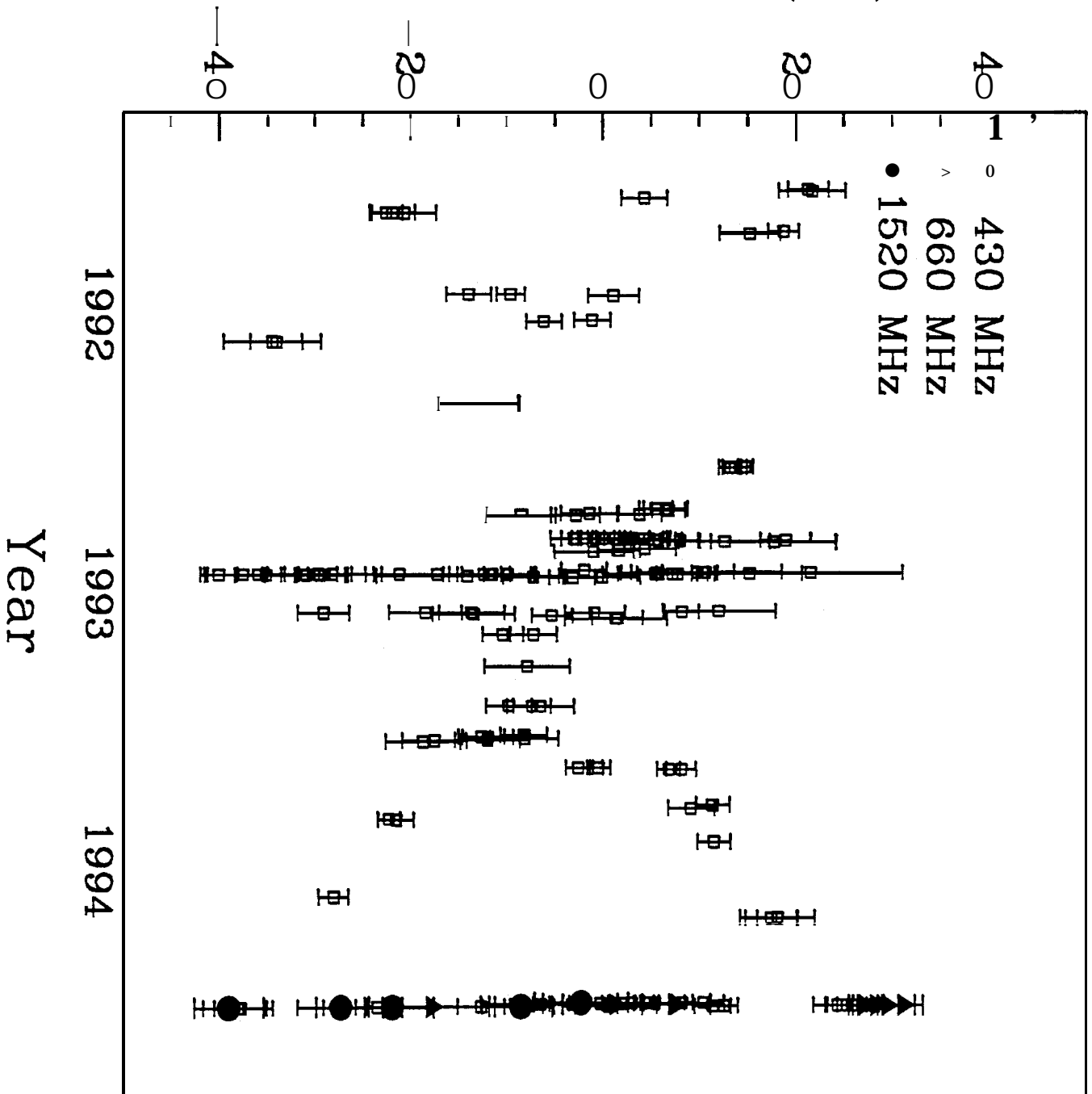
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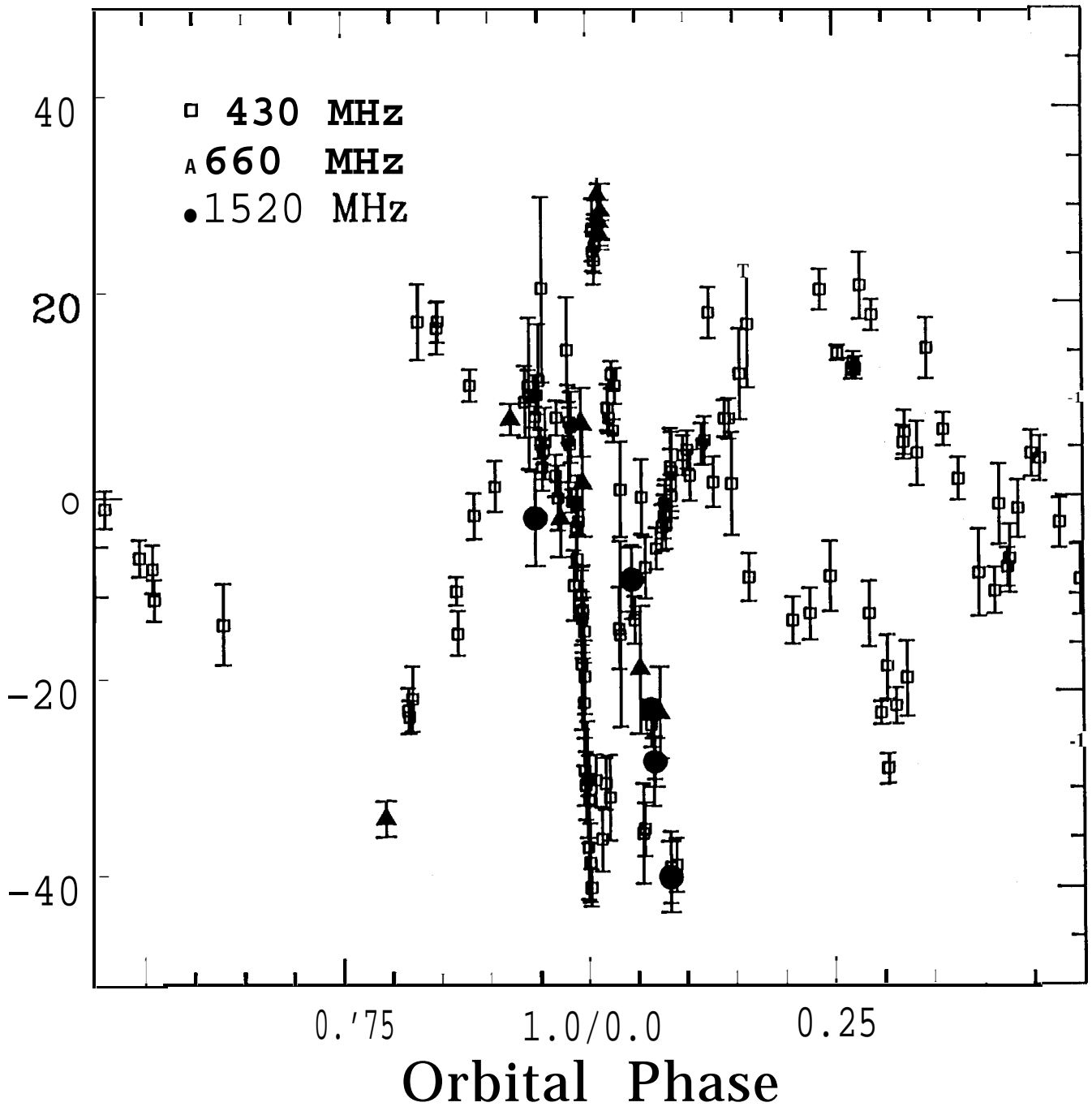Thorsett, S. II., Arzoumanian, Z. & Taylor, J. H., 1993. Astrophys. J., 412, 33.

PSR B1259−63

PSR J0045−7319

Postfit Residual (ms) vs Orbital Phase

Legend:
- □ 430 **MHz**
- ▲ 660 **MHz**
- ● 1520 **MHz**