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Timing of the Binary Pulsar PSR B1259−63

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Abstract. Timing of PSR B1259−63, the first radio pulsar discovered to have a massive main-sequence companion, has been carried out since 1990. The timing is complicated because the orbital period is very long, the pulsar is eclipsed for 40 days around periastron, the pulsar has significant timing noise and also has been seen to glitch. A model for the timing data based on spin-orbit coupling no longer provides a good fit to the data. We have proposed an alternative model which involves jumps in the inclination angle of the system at each periastron, however, the physical basis for this model is far from clear.

1. Introduction

PSR B1259−63 was discovered in a high frequency survey of the Galactic plane (Johnston et al. 1992a). It is unique because it is the only known radio pulsar in orbit about a massive, main-sequence, B2e star (Johnston et al. 1992b). The companion, SS 2883, is a 10th magnitude star with a mass of about $10\,M_\odot$ and a radius of $6\,R_\odot$. Typical of Be stars as a class, it has a hot, tenuous polar wind and a cooler, high density, equatorial disk. Assuming the B2e star is rotating at ∼70% of its break up velocity, it then has an equatorial velocity $\sim 280\,\mathrm{km\,s^{-1}}$. The spin-induced oblateness of the star implies an additional $1/r^3$ gravitational potential term in the interaction with the pulsar, known as the quadrupole gravitational moment. This effect introduces an apsidal motion and precession of the orbital plane if the spin of the companion is not aligned with the orbit angular momentum, characterised by $\dot{\omega}$ and $\dot{x}$ respectively, where ω is the longitude of periastron passage and x is the projected pulsar semi-major axis (Lai et al. 1995). In an eccentric binary system, the passage of the pulsar through periastron excites tidal motions on the companion star which then interact with the orbital motion. In the case of PSR J0045−7319, tidal effects may account for the observed evolution in binary parameters (e.g., Lai 1997). The tidal interactions may be enhanced by large factors if there is a resonance with oscillation modes of the star (Witte & Savonije 1999). For PSR J0045−7319, at periastron the pulsar is only $\sim 4\,R_*$ from the companion compared to $24\,R_*$ for PSR B1259−63. Tidal effects are strongly dependent on the separation of the two stars, and so may be insignificant in PSR B1259−63. Interactions between the pulsar and the disk of the Be star may also be important. If there is accretion from the disk on to the neutron star, the pulsar may be spun up or slowed down. For accretion to occur, the bow shock, where there is pressure balance between the pulsar wind and the Be-star disk gas, must lie inside the accretion radius, which depends on the relative velocity of the pulsar and the accreting gas. For PSR B1259−63, accretion is unlikely (Manchester et al. 1995; Tavani & Arons 1997), with X-ray observations (Hirayama et al. 1999) most easily interpreted as originating from a bow shock well outside the pulsar magnetosphere. Disk interactions may also affect pulsar orbit directly through frictional drag. Estimates of variations in the Keplerian parameters P_b, ω and e suggest the effect is negligible (Manchester et al. 1995; Wex et al. 1998).

2. Observations

Observations have been made of PSR B1259−63 using the Parkes radio telescope over a time interval of nearly 5000 days between 1990 January and 2003 June. A total of 1031 times of arrival, spanning four orbital periods, were obtained for the pulsar. The majority of the observations were made at frequencies around 1.4 GHz with additional observations at 0.66, 2.4, 4.8, 8.4 and 13.6 GHz.

The eclipses of the pulsar, which last for ∼40 days around periastron make the timing difficult. The problem is exacerbated by the fact that DM changes are observed over a few tens of days leading up to and immediately following the eclipse due to the changing line of sight intersecting the Be star wind. These DM variations need to be removed to obtain a good timing solution, and this involves making observations at several different frequencies as near to simultaneously as possible. Multi-frequency observations were therefore made before and after the 1994, 1997 and 2000 periastron passages and have been described in detail in Johnston et al. (1996) and Johnston et al. (2001).

The timing properties were analysed using TEMPO, which provides least-squares fitting to the pulsar rotation and orbital parameters and the dispersion measure. The MSS binary model of Wex (1998) was used for most of the fitting. To fit for steps in the orbital parameters, a new binary model (BTJ) based on the Blandford & Teukolsky (1976) model was implemented. This allows cumulative steps in longitude of periastron (ω), projected semi-major axis (x), eccentricity (e) and binary period (P_b) to be inserted at specified times and also allowed setting or solving for jumps in pulsar phase at the specified times.

3. Results and Discussion

There is strong evidence for a glitch in the pulsar period near MJD 50691 (1997 August 30), 94 days after the 1997 periastron. The total frequency change at the time of the glitch was 67×10^{-9} Hz of which 22×10^{-9} Hz decayed exponentially with an assumed timescale of 100 days.

We attempted to obtain a timing solution including the effects of spin-orbit coupling in a similar fashion to Wex et al. (1998). The post-fit residuals after including the glitch are shown in Figure 1a. Clearly, systematic variations are still unmodelled, and this model no longer fits the data.

Our next attempt at a timing solution involved fitting for frequency and frequency derivative jumps at each of the four periastron epochs (in a similar fashion to that done by Manchester et al. 1995). The residuals are significantly better than that obtained with the spin-orbit coupling model, albeit at the expense of having extra free parameters. Even this fit, however, does not remove the systematic deviations seen between the periastron passages. The most probable cause of frequency jumps at periastron is accretion of mass and angular momentum from the Be-star disk. While the amount of accreted mass is not unreasonable, there are several problems with this idea. First, the bow shock between the pulsar wind and the circumstellar wind must lie inside the accretion radius for accretion to occur. Secondly, the observed jumps are of different magnitudes and signs at the different periastrons and it would be surprising if the accretion torque were able to change sign. Finally, frequency jumps alone do not account for the observed variations; jumps in frequency derivative are also required. The implied changes in braking torque or moment of inertia are large and physically improbable.

The best timing solution (see Fig. 1b) was obtained by fitting for the pulsar frequency, its first two derivatives, the orbital parameters, the glitch and jumps in x at each periastron. The size of the jumps ranged from −26 ms to 60 ms. If the jumps in x are interpreted as changes in semi-major axis a, Kepler's Third Law implies changes in P_b of thousands of seconds, orders of magnitude larger than permitted by the timing so-

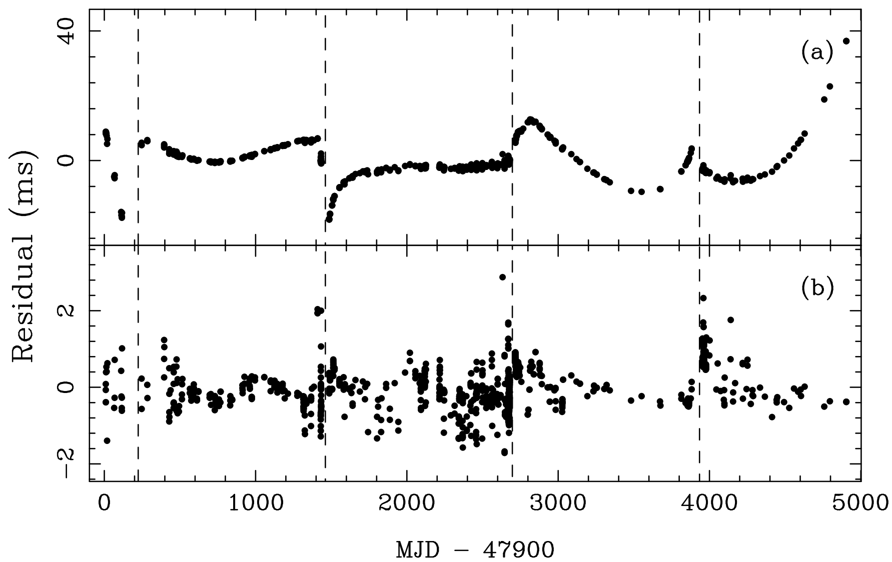

Figure 1. Residuals as a function of time for the entire 13-year data set on PSR B1259−63. The top panel shows the residuals after fitting for spin-orbit coupling terms. The bottom panel shows the best fit we obtained, which includes jumps in x at each periastron.

lutions. The observed changes in x must then be interpreted as changes in inclination angle i of the orbit of order a few arcsec. The question then is: what can cause changes in inclination angle without making significant perturbations to the other orbital parameters? Furthermore, the mechanism must be able to produce changes of different sign and magnitude at different periastrons. Two possibilities are frictional drag and tidal interactions. Frictional drag could tilt the orbit if the velocity of the outflowing disk material has a significant component perpendicular to the orbit. However, the change in sign of the tilt cannot be easily explained and the magnitude of the changes appears to be too large. Tidal interactions at periastron can be greatly enhanced by resonances with modes of stellar oscillations. Since there is evidently a large angle between the spin axis and the orbit normal, it is possible that the dominant effect could be on the orbit inclination. Different relative phases of the tides and stellar oscillations could alter the effect on the orbit from one periastron to the next. Again though, the magnitude of the changes appears to be much larger than expected from the relatively large ratio of periastron distance to companion-star radius.

4. Conclusions

We have been timing PSR B1259−63 for 13 years, a time span which encompasses four periastron passages. It is clear that secular changes in orbit parameters due to spin-orbit coupling does not give a good description of the data. The effect of timing noise is difficult to quantify because of coupling with the orbital parameters, a problem exacerbated by the long-duration eclipses which occur at each periastron. Consequently, we cannot rule out the possibility that our measured parameters are affected by timing noise. However, excepting the glitch which occurred near MJD 50691, the fact that within each orbit the observed residuals show variations with characteristic timescale of the same order as the orbital period and significant shorter-term variations only near periastron strongly suggests that changes in orbital parameters at periastron are the dominant effect. This is reinforced by the excellent fit to the data by a model containing the MJD 50691 glitch and steps in projected semi-major axis at each periastron. It is clear that these steps must result from step changes in the orbit inclination. However, we are unable to offer any plausible mechanism to account for the observed changes. Readers interested in a complete description of the data and the analysis should consult Wang et al. (2004).

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