THE ORBITAL EVOLUTION AND PROPER MOTION OF PSR J2051−0827

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Received 1998 March 12; accepted 1998 April 8; published 1998 May 14

ABSTRACT

We have carried out high-precision timing observations of the eclipsing binary PSR J2051−0827 in the 3.3 years since its discovery. The data indicate that the orbital period is decreasing at a rate of $\dot{P}_\text{orb} = (-11 \pm 1) \times 10^{-12}$. If secular, this orbital period derivative implies a decay time for the orbit of only 25 Myr, which is much shorter than the expected timescale for the ablation of the companion. We have also measured the proper motion of the pulsar to be $5 \pm 3$ mas yr$^{-1}$. Assuming the pulsar is at the dispersion-measure distance, this implies a very slow transverse velocity $v_T = (30 \pm 20)$ km s$^{-1}$. This combination of low velocity and short orbital period argues against the formation of the system in the standard manner, and we discuss the implications for its evolutionary history.

Subject headings: binaries: eclipsing — pulsars: individual (PSR J2051−0827) — stars: neutron

1. INTRODUCTION

The discovery of the millisecond pulsar PSR J2051−0827 (Stappers et al. 1996) as part of the Parkes survey of the southern sky for low-luminosity and millisecond pulsars (MSPs) (Manchester et al. 1996; Lyne et al. 1998) brought to five the number of pulsars that are eclipsed by winds from low-mass ($\leq 0.1 M_\odot$) companions. It is only the second such system that is not a member of a globular cluster and has the second-shortest orbital period of any binary-radio pulsar, $P_\text{orb} = 2.38$ hr. The duration of the eclipse, $\sim 10\%$ of the orbital period, and the delays at the eclipse egress and ingress indicate that there is material, probably originating from a wind driven from the companion, well beyond the companion’s Roche lobe. Thus, this system joins both PSR B1957+20 (Fruchter, Stonebringer, & Taylor 1988) and PSR B1744−24A (Lyne et al. 1990) as neutron stars that are in the process of ablating their companions and possibly becoming isolated MSPs (Ruderman, Shaham, & Tavani 1989a; Bhattacharya & van den Heuvel 1991).

Pulse times of arrival are extremely sensitive to changes in a pulsar’s local environment and along the propagation path. Timing measurements of PSR J2051−0827 have already shown that there is structure in the electron column density in the eclipse region (Stappers et al. 1996) and will also provide valuable information on the nature of the eclipses (Stappers et al. 1998a). The eclipsing behavior and circularity of the orbit suggest that relativistic effects are not going to have an observable effect on the timing. However, measurements of the changes in the orbital period for both PSR B1957+20 (Ryba & Taylor 1991; Arzoumanian, Fruchter, & Taylor 1994) and PSR B1744−24A (Nice & Thorsett 1996) suggest that the effects of either the tidal influence of the companion or the ablation process itself may be evident in the timing data. If the pulsar has a reasonable transverse velocity, then, given its distance, $\sim 1.3$ kpc, the proper motion would also be apparent.

2. PULSAR TIMING ANALYSIS

Since its discovery, observations of PSR J2051−0827 have been made as part of our regular high-precision timing program at Parkes (e.g., Bell et al. 1997). Timing data have been obtained approximately every 3 weeks, although there are some large gaps resulting from unavailability of the telescope. Approximately 2300 valid pulse times of arrival (TOAs), at center frequencies near 436, 660, 1520, 1940, and 2320 MHz, have been obtained using a filter-bank system and/or the Caltech Fast Pulsar Timing Machine (FPTM). The FPTM is based on an autocorrelator capable of very fast sampling (Navarro 1994). Two filter-bank systems are used: at the two lower frequencies, a $2 \times 256 \times 0.125$ MHz filter bank detects orthogonal linear polarizations, while at the higher frequencies, a $2 \times 64 \times 5$ MHz filter bank detects orthogonal circular polarizations. Details of the filter-bank–based observing systems can be found in Manchester et al. (1996), and the correlator-based system is described in Navarro (1994).

The filter-bank data were reduced off-line. A mean pulse profile for each frequency channel was produced by folding at the topocentric period of the pulsar. To compensate for the dispersive delay, these profiles were transformed to the Fourier domain, phase-shifted, transformed back to the time domain, and summed. In the FPTM, the down-converted signal is 2 bit digitized, and the autocorrelation functions (ACFs) are computed. Bandwidths were typically 128 and 32 MHz for observations above and below 1 GHz, respectively. The ACFs were hardware-integrated at the apparent pulsar period for either 60 or 90 s. After being transferred to a Sun SPARC-20 computer, the data were calibrated, dedispersed, and summed.

The typical integration time required to detect the pulsar is 60–90 s, although scintillation caused by the interstellar medium means that much longer integration times are sometimes required to obtain an acceptable signal-to-noise ratio. Each integration was optimized in order to maximize the orbital phase coverage with individual TOAs, while preserving a minimum signal-to-noise ratio of $\sim 12$. The observed profiles were then cross-correlated with a standard pulse template at each frequency to determine the TOA. Separate templates were used for the higher resolution correlator data, and no offsets between the two data sets were required to the limit of the best-fitting residuals. These data were then fitted using the TEMPO timing analysis package (Taylor & Weisberg 1989) with the JPL...
DE200 ephemeris (Standish 1982). Binary parameters were fitted using the timing model of Blandford & Teukolsky (1976).

3. PARAMETERS

A binary timing model that included the pulsar position, dispersion measure, rotational period and period derivative, orbital period, projected semimajor axis of the orbit, and orbital period derivative was used to generate the best-fitting parameters shown in Table 1. Data that lie between orbital phases 0.2 and 0.35 were discarded from all fits because of the influence of the excess column density in the eclipsing region on these TOAs. This range is narrower than that rejected by Stappers et al. (1996) since the eclipse boundaries are now better defined. In all fits, both the eccentricity and the longitude of periastron were held fixed at zero to determine the remaining parameters. The eccentricity limit was determined by fitting simultaneously for the eccentricity and the remaining parameters for various input values of the longitude of periastron.

The residuals for this best fit are shown in Figure 1. There is unmodeled timing noise on timescales ranging from less than an orbit to a few orbits. The intraorbit variations can be attributed to the low signal-to-noise ratio of some profiles. The errors are from the formal fit, and we assumed that the errors were completely random. In practice, narrowband interference introduces ripples into the pulse profile that lead to underestimates of the true error. There are no trends observed in these changes, and a sufficiently large number of orbits have been observed for orbital characteristics to remain unaffected. Changes on the timescale of a few orbits may be due to changes in the electron column density. Variations on longer timescales similar to those seen for PSR B1957+20 (Ryba & Taylor 1991; Arzoumanian et al. 1994) and PSR B1744−24A (Nice & Thorsett 1996) are not present. A formal fit for a period second derivative to the timing data of PSR J2051−0827 yields \( \dot{P} = (4 \pm 2) \times 10^{-22} \text{ s}^{-1} \), suggesting that mass motions in the PSR J2051−0827 system do not greatly affect the rotation of the pulsar.

If the transverse velocity of a pulsar is sufficient, then the contribution of the apparent acceleration along the line of sight to the derivatives of the orbital and rotational period of the pulsar is significant (Shklovskii 1970). This is especially the case for MSPs that have rotational spin-down rates smaller than those of the long-period pulsars. Corruption of the rotational period derivative means that all properties of MSPs that are derived from it, such as the characteristic age, \( \tau_c = P/2\dot{P} \), and the pulsar spin-down energy, \( \dot{E}_p = 4\pi^2 IP^3 (I = 10^{45} \text{ g cm}^{-2}) \), are only provisional until the velocity, or an upper limit, can be determined. Modeling the light curve of the companion to PSR J2051−0827 has shown that at least 30% of the pulsar’s spin-down energy may be required to heat the companion star (Stappers et al. 1998b); this fraction would increase to nearly 50% for a proper motion of 16 mas yr\(^{-1} \) (\( v_\gamma \sim 100 \text{ km s}^{-1} \)). However, as shown in Table 1, our current measurement of the composite proper motion of PSR J2051−0827 is \( 5 \pm 3 \text{ mas yr}^{-1} \). Assuming the dispersion-measure distance to the system, this implies a remarkably slow transverse velocity of only \( v_\gamma = 30 \pm 20 \text{ km s}^{-1} \). Thus, the contribution to the period derivative is \( 3.4 \times 10^{-22} \), or just 3% of the measured period derivative.

A significant result from these timing observations is that the orbital period of PSR J2051−0827 is decreasing at a rate \( \dot{P}_o = (−11 \pm 1) \times 10^{-12} \). This \( \dot{P}_o \) is some 2 orders of magnitude greater than the contribution expected from general relativistic effects, \( \dot{P}_o = (−3 \pm 1) \times 10^{-14} \), and the possible influence of the Shklovskii term is negligible. If the orbital period derivative were constant, then the orbital decay time would be only 25 Myr. However, observations of PSR B1957+20 indicate that its orbital period derivative varies, and even changes sign, on quite short timescales (Arzoumanian et al. 1994). The best fit obtained for a constant orbital period has an rms of \( \sim 35 \mu \text{s} \), somewhat greater than for the fit in Table 1.

If the orbital period is decreasing, the pulsar should arrive at the ascending node earlier than we would predict from the constant orbital period model. Data presented in Figure 1, except those obtained in 1997 July, were split into three, approximately equal, time-interval groups. After reassigning the epoch of ascending node to the middle of each data set, they were fitted for orbital and spin parameters. The position was held constant for all fits since none of the data sets spanned a full year, and the proper motion is small. The measured phase shifts are found to be consistent with those predicted by the orbital period derivative, thus confirming that the orbital period of the system is presently decreasing. There is insufficient data to fit for higher order variations in the orbital period.

### Table 1

| Parameter                  | Value                           |
|----------------------------|---------------------------------|
| Right ascension (J2000)     | 2051+07:5130(2)                 |
| Declination (J2000)         | −08°27′37″782(6)                |
| Proper motion in R.A. (mas yr\(^{-1}\)) | 1(2)                      |
| Proper motion in decl. (mas yr\(^{-1}\)) | −5(3)                       |
| Epoch of period (MJD)       | 49530.0                        |
| Period (s)                 | 0.0045086417433540(7)          |
| Period Derivative (\times 10^{-2}) | 1.272(2)                   |
| Dispersion measure (cm\(^{-1}\) pc) | 20.7458(2)                 |
| Orbital period (days)       | 0.0991102650(2)                |
| Orbital period derivative (\times 10^{-12}) | −10.8(10)              |
| Projected semimajor axis (lt-s) | 0.045076(1)              |
| Eccentricity               | <8 \times 10^{-4}            |
| Epoch of ascending node (MJD) | 50015.422291            |
| rms timing residual (\mu s) | 32                             |
| Distance (kpc)             | 1.3                            |
| Galactic longitude (deg)    | 39.19                          |
| Galactic latitude (deg)     | −30.41                         |
| Mass function (M\(_{\odot}\)) | 1.0108(7) \times 10^{-5}   |
| Minimum companion mass (M\(_{\odot}\)) | 0.027                      |

**Fig. 1.**—Post-fit timing residuals for \( \sim 2300 \) timing measurements of PSR J2051−0827 at a number of different frequencies (see text) for the parameters in Table 1.
4. EVOLUTION: PAST

The orbital period of PSR J2051–0827 puts it just above the upper edge of the low-mass X-ray binary (LMXB) period gap. It is one of only four binary pulsars with a period less than 4 hr. It is interesting to note that of these four binary pulsars, only J1910+0004 (Deich et al. 1993) shows no strong evidence of eclipsing behavior, and it is probably too weak to preclude the possibility that it is also an eclipsing system. Thus, at least three out of the four systems are eclipsed, more than would be expected, naively, if eclipses in these systems required inclination angles close to 90°. This is further evidence that there must be material that extends well beyond the companion’s Roche lobe. The eclipsing phenomenon is perhaps inevitable for such short-period binaries.

The proper motion and dispersion-measure–derived distance of PSR J2051–0827 indicate that its transverse velocity is very low (30 km s\(^{-1}\)). Unless there is an unusually large radial velocity component, the space velocity will also be small. There are presently 10 MSPs with estimates of their proper motions, and they indicate a mean space velocity of \(\sim 100 \text{ km s}^{-1}\). This is significantly less than the mean velocity of the long-period pulsars (e.g., Lyne & Lorimer 1994). Simulations by Cordes & Chernoff (1997) and Ramachandran & Bhattacharya (1997) show that such a low mean velocity is expected for the MSP population since progenitor systems that receive high kick velocities will be disrupted during the supernova. Thus, the low velocity of PSR J2051–0827 is consistent with its proximity to the disk (\(z = 650 \text{ pc}\)) but is problematic when considering its past evolution.

In standard evolutionary models, low-mass binary and isolated MSPs are descended from LMXBs (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). LMXBs typically have orbital periods of a few days before the supernova explosion of the primary. The simulations of Tauris & Bailes (1996) show that it is almost impossible for such initially compact systems to generate binary MSPs with orbital periods less than a day and spatial velocities less than 50 km s\(^{-1}\). This indicates that the neutron star to be spun up to a millisecond period. Thus, the companion cannot have been too massive. Our ideal progenitor system is therefore an intermediate-mass binary with a spatial velocity of less than 50 km s\(^{-1}\). This is true for the neutron star to be spun up to a millisecond period. Thus, the companion cannot have been too massive.

This alternative evolutionary process may explain the low velocity of PSR J2051–0827, but nominally its end product is a MSP and a massive white dwarf in a circular orbit. If the remaining core mass after the common-envelope phase were sufficiently small, then the mass transfer to the neutron star may not have become unstable. The final spiral-in phase would have been avoided, and the system may have proceeded instead to a compact LMXB-like phase. This scenario is attractive since the evolution of the system would then be similar to that discussed by Ruderman et al. (1989a, 1989b) and would naturally explain the present, very low-mass companion.

If the neutron star were formed via the accretion-induced collapse of a massive white dwarf (e.g., Bailyn & Grindlay 1990), then the velocity of the system would also be lower since less mass is lost during the formation of the neutron star. However, it would also require the explosion to be symmetric; otherwise, the system would still be expected to have a large velocity (Tauris & Bailes 1996) and would require the resultant pulsar to ablate most of the mass from the companion.

5. EVOLUTION: FUTURE

Initial ablation of the companion in eclipsing and isolated systems is thought to occur during an LMXB phase when a γ-ray flux may be generated by the interaction of the neutron star’s magnetic field and the accretion disk. This flux causes a wind to be driven from the companion star by heating its outer layers (Ruderman et al. 1989b; Kluźniak et al. 1988). Evaporation of the companion may eventually cause the accretion to cease, and the spun-up pulsar would then be able to turn on. The pulsar may then continue to ablate the companion through its relativistic wind (Ruderman et al. 1989a). Following the simple calculation of Bhattacharya & van den Heuvel (1991), we relate the rotational energy of the pulsar to the binding energy of the companion in order to determine if the pulsar can ablate its companion. Assuming the ablation process is 1% efficient, i.e., 1% of the incident pulsar spin-down energy is available to drive the wind, we find that PSR J2051–0827 will require a further 10^9 yr to evaporate its companion. This timescale is longer than the 25 Myr timescale for orbital decay, suggesting that tidal effects may be more important in completely destroying the companion. If MSPs live for 10^9 yr or more, this timescale for destruction of the companion via orbital decay is inconsistent with the observed number of eclipsing MSPs and isolated MSPs.

The value for the orbital period derivative is much larger than that predicted by gravitational radiation losses. Mechanisms whereby angular momentum is lost from the system through anisotropic mass loss from the companion’s surface (Bantel & Shaham 1992; Eichler 1992; Brookshaw & Tavani 1993) were proposed to explain the orbital period derivative of PSR B1957+20. However, they require a large mass-loss rate that is hard to reconcile with the low electron densities measured in the eclipse region of either PSR B1957+20 (e.g., Fruchter et al. 1990) or PSR J2051–0827 (Stappers et al. 1996). Moreover, they are unable to reproduce the rapid change in sign and magnitude of the orbital period derivative that has been measured for PSR B1957+20.

These variations in the period derivative have been likened to the quasi-cyclic variations seen in other close binaries where magnetic fields of the companion are important (Arzoumanian et al. 1994). Based on this idea, Appelgate & Shaham (1994) developed a model where the companion's magnetic activity
and wind generate a torque that prevents it from corotating and results in the dissipation of the tidal energy. Although we have measured only a secular change in the orbital period derivative of PSR J2051−0827 at this stage, given that its companion mass is similar to that for PSR B1957+20, and the orbital separation is less, we might expect that it too will have a variable orbital period derivative. Clearly, if such variation in the orbital period derivative were measured for PSR J2051−0827, it would indicate that it will live longer than 25 Myr and thus alleviate the birthrate problem.

The low electron column densities measured in the eclipse region for PSR J2051−0827 suggest that the current evolutionary phase is a long-lived one. However, the large orbital period derivative, if it is secular, provides a mechanism to reduce this system to an isolated MSP. The low velocity of the pulsar is a powerful constraint on the progenitor system and favors its having evolved from an initially intermediate mass binary.

We thank S. Johnston and the referee for helpful comments on the manuscript. We are grateful to S. Anderson, M. Britton, A. Hughes, V. Kaspi, A. Lyne, and the Parkes Observatory staff for assistance with observations. B. W. S. received support from an ANU Ph.D. scholarship and the ATNF student program.

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