The Astrophysical Journal, 459:717–720, 1996 March 10

ON THE WIND FROM THE SMALL MAGELLANIC CLOUD B1 V COMPANION TO PSR J0045−7319

V. M. Kaspi[1]
IPAC/California Institute of Technology/Jet Propulsion Laboratory, Pasadena, CA 91125
T. M. Tauris[2]
Institute of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
and
R. N. Manchester[3]
Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 2121, Australia
Received 1995 August 1; accepted 1995 September 19

ABSTRACT

We report on multifrequency radio timing observations of the unique binary pulsar PSR J0045−7319, the only known radio pulsar in the Small Magellanic Cloud. Observations made at epochs near periastron and apastron, when the pulsar was at distances of ~ 4 and ~ 34 stellar radii from its B1 V star companion, respectively, reveal no significant frequency dependence of the observed pulse-arrival times, implying a 3 σ upper limit to variations of the integrated electron density along the line of sight of $\Delta\mathrm{DM} < 0.9$ pc cm^{-3}. Using simple geometric arguments we infer a 3 σ upper limit to the ionized component of the B-star mass outflow of $\dot{M} < 3.4 \times 10^{-11}(v_\infty/v_{\mathrm{esc}})\ M_\odot\ \mathrm{yr}^{-1}$. This is the first constraint on a main-sequence B-star wind in the SMC and provides evidence in favor of the predicted metallicity dependence of models of radiation-driven winds in luminous stars.

Subject headings: binaries: general — Magellanic Clouds — pulsars: individual (PSR J0045−7319) — stars: atmospheres — stars: early-type — stars: mass loss

1. INTRODUCTION

Observational constraints on wind velocities and mass-loss rates of luminous, massive stars are important for testing models of radiation-driven winds. In such winds, the mass outflow is a result of the absorption of photospheric radiation by UV metal lines in the outer atmosphere. Mass loss from hot, luminous stars is relevant to their evolution, interaction with the interstellar medium, and hence galactic evolution. However, measurements of wind parameters, especially mass-loss rates, are made difficult by large uncertainties, both random and systematic, as well as by the necessity for relying on models of the winds to interpret the observations (see Kudritzki & Hummer 1990 for a review). Observational tests of radiation-driven wind theory include modeling spectra of individual stars and comparing trends in the wind properties of a large sample of stars with parameters such as effective temperature, luminosity, and metallicity.

PSR J0045−7319 (PSR B0042−73) is a 0.926 s radio pulsar in a highly eccentric 51 day binary orbit with a B1 V star (Kaspi et al. 1994, hereafter Paper I). It is the only known pulsar in the Small Magellanic Cloud (SMC). This association is assured both by the observed line-of-sight integrated electron density or dispersion measure DM ≈ 105 pc cm^{-3}, since models of the Galactic electron distribution account for no more than ~ 25 pc cm^{-3} along the line of sight (Taylor & Cordes 1993), and by the apparent luminosity (16 mag in V) of the B1 V star that lies within the $\sim 1''$ positional error box determined via pulsar timing. The spectral type of the companion was determined in Paper I from the Balmer jump, which implied an effective temperature of $T_{\mathrm{eff}} = 24000 \pm 1000$ K, and weak helium lines observed in a low-resolution spectrum obtained using the Australian National University's 2.3 m telescope. The companion shows no evidence of optical emission lines.

Recently, Bell et al. (1995) detected Doppler shifts of the B1 V star's optical absorption lines, making this the first dual-line binary pulsar and confirming the nature of the pulsar's companion. Those observations determined the mass ratio in the system, 6.3 ± 1.2, which, for a pulsar mass of $M_p = 1.4\ M_\odot$, implies a B-star mass of $M_c = 8.8 \pm 1.8\ M_\odot$ and an orbital inclination angle of $i = 44° \pm 3°$. From the effective temperature of 24000 ± 1000 K and the luminosity of $1.2 \times 10^4\ L_\odot$, Bell et al. (1995) deduced a radius for the companion B star of $R_c = 6.4 \pm 0.7\ R_\odot$.

The periastron separation, given by $s_{\min} = a_p(1 - e)(1 + M_p/M_c) = 3.7 \pm 0.5\ R_c$ (where $a_p = 251 \pm 14$ lt-s is the pulsar's semimajor axis and $e = 0.80798 \pm 0.00001$ is the eccentricity), and the apastron separation, $s_{\max} = a_p(1 + e)(1 + M_p/M_c) = 35.2 \pm 5.1\ R_c$, are determined by observations under the assumption that $M_p = 1.4\ M_\odot$. The uncertainty in a_p is dominated by that for the inclination angle i while the uncertainty in $s_{\max}$ is dominated by both the uncertainty in i and that in R_c. Despite the close approach of the pulsar to the companion at periastron, no eclipse, anomalous scattering, nor any DM increase has been observed at any orbital phase (Paper I). Indeed, the 3 σ upper limit on DM variations obtained in Paper I, 3.2 pc cm^{-3}, implied a mass-loss rate significantly below that predicted on the basis of standard empirical mass-loss rate formulae (de Jager, Nieuwenhuijzen, & van der Hucht 1988; Lipunov, Postnov, & Prokhorov 1995). Nevertheless, low-

---

[1] Hubble Fellow; vicky@ipac.caltech.edu.
[2] tauris@obs.aau.dk.
[3] rmanches@atnf.csiro.au.

level yet significant deviations from a simple Keplerian orbit, as evidenced by the high rms timing residual reported in Paper I (see also Kaspi et al. 1995a), suggested the presence of DM variations just below the level measurable using only the spectral baseline available from observations at a single radio frequency with a finite bandpass.

To search more sensitively for the effects of dispersion due to orbital-phase–dependent DM variations from the B1 V star's wind, we have conducted multifrequency radio observations of PSR J0045−7319 at several epochs near and away from periastron.

2. OBSERVATIONS AND RESULTS

All observations were made using the 64 m radio telescope at Parkes, Australia. A total of 44 arrival times were obtained at center radio frequencies 436, 660, and 1520 MHz from 1994 June 22 through July 25. Cryogenically cooled systems receiving orthogonal linear polarizations were used at all three observing frequencies, with coaxial feeds allowing simultaneous observations at 436 and 1520 MHz. The signals were downconverted to an intermediate frequency, filtered in multichannel filter banks, detected, and band-limited. The filter banks consist of 2 × 64 × 5 MHz filters at 1520 MHz, 2 × 128 × 250 kHz filters at 660 MHz, and, at 436 MHz, 2 × 256 × 125 kHz filters. After summing the polarizations, the signals were sampled at 4.8 ms intervals using 1 bit digitization and recorded on magnetic tape. Off-line, the data were folded with the predicted topocentric pulse period, and average profiles were cross-correlated with high signal-to-noise ratio templates. Arrival times were recorded and analyzed with the standard pulsar-timing software package TEMPO (Taylor & Weisberg 1989) using the JPL DE200 solar system ephemeris. Arrival-time uncertainties are in the range 0.5–3 ms for these observations and are limited in precision by the average profile signal-to-noise ratios, typically 10–20.

The epochs of the observations, the number of observations at each frequency, the corresponding orbital phases ϕ, the pulsar/B star separation s, and the observed DM values with 1 σ uncertainties are listed in Table 1. Periastron is defined to be at $\phi = 0.0$. The uncertainty in the mass ratio and in the companion radius result in 15% uncertainties in the separations s. The DM values are plotted as a function of time in Figure 1, where the finite duration of the measurement interval is indicated with a horizontal error bar, smaller than the size of the point for all but one epoch. The vertical dashed lines indicate periastron and apastron. The solid horizontal line is the mean value of DM, 105.08 ± 0.30 pc cm^{-3}, in agreement within uncertainties with the value measured in Paper I using only the 436 MHz bandpass. The reduced χ^2 of the DMs is 1.76; with 7 degrees of freedom, the probability of exceeding this value is 10%. We note that a large contribution to the observed χ^2 comes from the epoch right before periastron, at which the DM is *lower* than the mean by 1.7 σ. Furthermore, the mean value of the DM measurements near periastron is slightly lower than that near apastron, though consistent within measurement uncertainties. Thus, we see no statistically significant evidence for any variation in DM as a function of orbital phase and place a 3 σ upper limit on DM variations of $\Delta \mathrm{DM} < 0.9$ pc cm^{-3}.

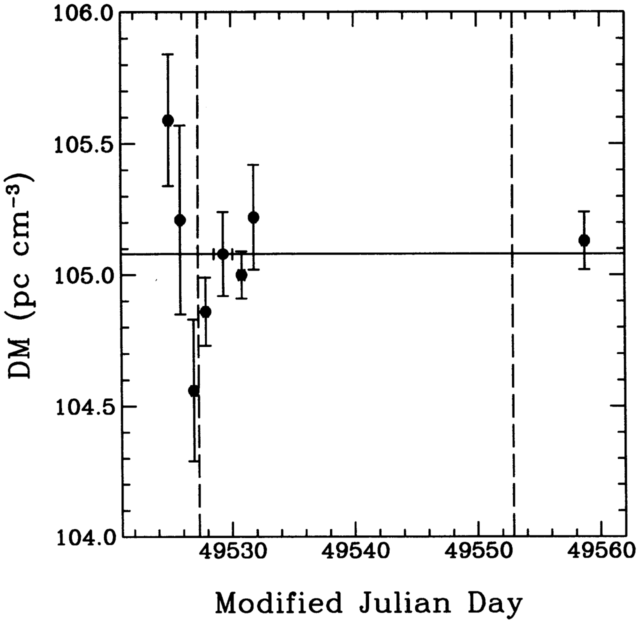

FIG. 1.—Observed dispersion measure vs. time. The solid horizontal line represents the mean DM, 105.08 ± 0.30 pc cm^{-3}, and error bars are $\pm 1\ \sigma$. The vertical dashed lines indicate the epochs of periastron ($\phi = 0$) and apastron ($\phi = 0.5$). Horizontal error bars represent the interval over which the DM measurements were made but are smaller than the size of the points for all but one observation.

3. DISCUSSION

The translation of the above upper limit on orbital-phase–dependent DM variations to a limit on the amount

TABLE 1

DISPERSION MEASURE DETERMINATIONS FOR PSR J0045−7319

MJD	Number of Observations: 1520 MHz	660 MHz	436 MHz	ϕ	s (R_c)	DM (pc cm^{-3})	σ_{DM} (pc cm^{-3})
49,524.7–49,525.1	1	0	5	0.947–0.955	10.3–9.1	105.59	0.25
49,525.7–49,526.0	0	1	2	0.967–0.973	7.1–6.1	105.21	0.36
49,526.7–49,527.1	0	2	3	0.986–0.995	4.1–3.8	104.56	0.27
49,527.7–49,528.1	0	4	4	0.005–0.014	4.8–6.1	104.86	0.13
49,528.6–49,530.1	1	1	5	0.025–0.053	7.7–12.2	105.08	0.16
49,530.7–49,531.1	2	1	3	0.064–0.072	13.8–14.8	105.00	0.09
49,531.7–49,532.0	1	0	2	0.083–0.089	16.2–16.9	105.22	0.20
49,558.6–49,559.0	3	1	3	0.609–0.618	34.0–33.9	105.13	0.11

of ionized mass loss from the B star is straightforward. The definition of DM is

$$\mathrm{DM} \equiv \int_0^d n_e(l)\, dl \,, \qquad (1)$$

where d is the distance to the source from Earth, n_e is the electron density, and l is the line-of-sight distance measured from the pulsar to Earth. Conservation of mass can be expressed via

$$\dot{M} = 4\pi r^2 n_e(r) m_p v(r) \,, \qquad (2)$$

where r is the radial distance from the B star's center, m_p is the proton mass, and $v(r)$ is the wind speed. Here we assume that hydrogen is the dominant element in the wind, that it is fully ionized, and that $\dot{M}$ is constant. We adopt the standard velocity law for radiatively driven winds,

$$v(r) = v_\infty (1 - R_c/r)^\beta \,, \qquad (3)$$

where v_∞ is the terminal velocity and $\beta = 0.5$ (Castor, Abbott, & Klein 1976; Pauldrach, Puls, & Kudritzki 1986).

Using equations (2) and (3) to determine $n_e(r)$, we integrate through the atmosphere of the companion star from the pulsar to Earth along l according to equation (1). Using the expression

$$r^2 = s_{\min}^2 + l^2 - 2 s_{\min} l \sin i \sin \omega \qquad (4)$$

at periastron, where $\omega = 115\overset{\circ}{.}236 \pm 0\overset{\circ}{.}002$ is the longitude of periastron, and an analogous expression at apastron, we evaluate the line-of-sight integrals numerically and find their difference I. We obtain

$$\dot{M} = \frac{4\pi v_\infty m_p}{I} \Delta\mathrm{DM} \,, \qquad (5)$$

and using the observed 3 σ upper limit $\Delta\mathrm{DM} < 0.9$ pc cm^{-3}, we have

$$\dot{M} < 3.4 \times 10^{-11} (v_\infty / v_{\rm esc})\, M_\odot\ \mathrm{yr}^{-1} \,, \qquad (6)$$

where $v_{\rm esc} = (2 M_c G / R_c)^{1/2} = 724$ km s^{-1} is the companion's escape velocity, with $v_\infty / v_{\rm esc}$ probably in the range 1–3 (Abbott 1982; Bjorkman & Cassinelli 1993). For a velocity law with $\beta = 1.0$, we have $\dot{M} < 2.9 \times 10^{-11} (v_\infty / v_{\rm esc})\, M_\odot$ yr^{-1}. Note that if the simplifying assumption of a hydrogen-dominated wind is relaxed, in equation (5), m_p should be replaced by the atomic mass unit multiplied by the mean atomic mass per free electron, which could increase the upper limit on $\dot{M}$ by as much as 20%.

The upper limit on the mass-loss rate from the B1 V companion to PSR J0045−7319 is considerably smaller than that expected from empirical mass-loss rate–luminosity relations (Garmany et al. 1981; Garmany & Conti 1984; Van Buren 1985; de Jager et al. 1988), which predict mass-loss rates in the range 10^{-9} to 10^{-8} $M_\odot$ yr^{-1} for a star of this luminosity and effective temperature in the Galaxy. However, empirical relations are heavily weighted by those stars (O stars and luminosity class I and II stars) for which mass loss can be observed easily via standard methods (e.g., P Cygni profiles, Hα line profiles, radio free-free emission). Hence, those relations likely overestimate mass-loss rates of less luminous main-sequence B stars, for which wind observations using standard techniques are difficult.

The low mass-loss rate measured for the companion to PSR J0045−7319 is likely a result of the low metallicity in the SMC. The metallicity dependence in the models for the mass loss of luminous stars is a prediction of the theory of radiation-line–driven winds, since the accelerative force is obtained from the radiative momentum absorbed by metal lines near the peak of the stellar continuum (Lucy & Solomon 1970; Castor et al. 1976; Abbott 1982; Pauldrach et al. 1986; Kudritzki, Pauldrach, & Puls 1987). This prediction motivated the considerable observational effort needed to compare luminous stellar winds in the Galaxy with those in the LMC and SMC, where the metallicities are known to be smaller, $Z \sim 0.3$ and 0.1 times the solar value $Z_\odot$, respectively (see, e.g., Kudritzki et al. 1987). A number of authors have noted a distinct contrast in the wind strengths of Galactic and SMC stars, with evidence for significantly smaller $\dot{M}$ and v_∞ for SMC O, B I, and B II stars, even given the large scatter and uncertainties in the measured values (Walborn 1978; Hutchings 1982; Burhweiler, Parsons, & Wray 1982; Garmany & Conti 1985; Prinja 1987; Garmany & Fitzpatrick 1988; Walborn et al. 1995). This is generally interpreted as evidence in favor of a metallicity dependence. Thus, the upper limit on the mass loss from the SMC companion to PSR J0045−7319 provides additional evidence for the metallicity dependence. Indeed, using the radiatively driven wind model outlined by Kudritzki et al. (1987), with $T = 24{,}000$ K, $R_c = 6.4\ R_\odot$, log $g = 4.0$, and adopting an SMC metallicity $Z = 0.1\ Z_\odot$, the model-predicted mass-loss rate and terminal velocity are $\dot{M} = 8 \times 10^{-11}\ M_\odot$ yr^{-1} and $v_\infty = 1536$ km s^{-1}, respectively, slightly larger than our upper limit (R. P. Kudritzki 1995, private communication). However, Puls et al. (1995) pointed out that wind theory significantly overestimates both $\dot{M}$ and v_∞ for early main-sequence B stars.

The evidence presented here in favor of a metallicity dependence of radiatively driven wind theory is admittedly based on a single SMC star. Radio timing observations of a large sample of OB pulsar binaries, both in the SMC and in the Galaxy, could provide a new, powerful, and uniquely direct method of studying the winds of luminous stars. Indeed, the mass-loss rate of the Be-star binary companion to the radio pulsar PSR B1259−63, the only other known pulsar/main-sequence star binary, has also been constrained using techniques very different from those traditionally used for studying stellar winds (Johnston et al. 1996; Kaspi et al. 1995b). Searches for more OB/pulsar binaries are currently under way (e.g., Sayer, Nice, & Kaspi 1996).

These results strongly suggest that the origin of the pulsar's timing residuals is dynamical. Although timing noise is common in pulsars, the qualitative properties of the residuals for PSR J0045−7319 are unusual (cf. Arzoumanian et al. 1994; Johnston et al. 1995), though comparable to those for PSR B1259−63 (Manchester et al. 1995). A model in which the spin-induced quadrupole moment of the B star results in classical apsidal advance and spin-orbit coupling has been proposed (Lai, Bildsten, & Kaspi 1995), but further timing observations are necessary before the model can be tested. Additional multifrequency observations will also be important for determining whether the wind strength is time variable, and reduced timing uncertainties especially near periastron may prove useful for detecting a wind below but close to the current upper limit, as is suggested by its proximity to the theoretical prediction.

We thank J. Bell, S. Johnston, R. Kudritzki, D. Van Buren, M. van Kerwijk, N. Walborn, and R. Waters for useful discussions. The filter-bank systems used in the observations were constructed at the University of Manchester, Jodrell Bank. Research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. V. M. K. received support from a Hubble Fellowship through grant HF-1061.01-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. V. M. K. also acknowledges support from a Princeton Higgins Instructorship and from an NRAO travel grant.

REFERENCES

Abbott, D. C. 1982, ApJ, 225, 893

Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, ApJ, 422, 671

Bell, J. F., Bessell, M. S., Stappers, B. W., Bailes, M., & Kaspi, V. M. 1995, ApJ, 447, L117

Bjorkman, J. E., & Cassinelli, J. P. 1993, ApJ, 409, 429

Burhweiler, F. C., Parsons, S. B., & Wray, J. D. 1982, ApJ, 256, L49

Castor, J. I., Abbott, D. C., & Klein, R. I. 1976, ApJ, 195, 157

de Jager, C., Nieuwenhuijzen, H., & van der Hucht, K. A. 1988, A&AS, 72, 259

Garmany, C. D., & Conti, P. S. 1984, ApJ, 284, 705

———. 1985, ApJ, 293, 407

Garmany, C. D., & Fitzpatrick, E. L. 1988, ApJ, 332, 711

Garmany, C. D., Olson, G. L., Conti, P. S., & Van Steenberg, M. E. 1981, ApJ, 250, 660

Hutchings, J. B. 1982, ApJ, 255, 70

Johnston, S., Manchester, R. N., Lyne, A. G., D'Amico, N., Bailes, M., Gaensler, B. M., & Nicastro, L. 1996, MNRAS, submitted

Johnston, S., Manchester, R. N., Lyne, A. G., Kaspi, V. M., & D'Amico, N. 1995, A&A, 293, 795

Kaspi, V. M., Johnston, S., Bell, J. F., Manchester, R. N., Bailes, M., Bessell, M., Lyne, A. G., & D'Amico, N. 1994, ApJ, 423, L43 (Paper I)

Kaspi, V. M., Manchester, R. N., Bailes, M., & Bell, J. F. 1995a, in IAU Symp. 165, Compact Stars in Binaries, ed. J. van Paradijs, E. van den Heuvel, & E. Kuulkers (Dordrecht: Kluwer), in press

Kaspi, V. M., Tavani, M., Nagase, F., Hirayama, M., Hoshino, M., Aoki, T., Kawai, N., & Arons, J. 1995b, ApJ, 453, 424

Kudritzki, R. P., & Hummer, D. G. 1990, ARA&A, 28, 303

Kudritzki, R. P., Pauldrach, A., & Puls, J. 1987, A&A, 173, 293

Lai, D., Bildsten, L., & Kaspi, V. M. 1995, ApJ, 452, 819

Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. 1995, ApJ, 441, 776

Lucy, L. B., & Solomon, P. 1970, ApJ, 159, 879

Manchester, R. N., Johnston, S., Lyne, A. G., D'Amico, N., Bailes, M., & Nicastro, L. 1995, ApJ, 445, L137

Pauldrach, A., Puls, J., & Kudritzki, R. P. 1986, A&A, 164, 86

Prinja, R. K. 1987, MNRAS, 228, 173

Puls, J., et al. 1995, A&A, in press

Sayer, R., Nice, D. J., & Kaspi, V. M. 1996, ApJ, in press

Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674

Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 434

Van Buren, D. 1985, ApJ, 294, 567

Walborn, N. R. 1978, ApJ, 224, L133

Walborn, N. R., Lennon, D. J., Haser, S. M., Kudritzki, R. P., & Voels, S. A. 1995, PASP, 107, 104