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# THE PROPER MOTION AND WIND NEBULA OF THE NEARBY MILLISECOND PULSAR J0437−4715

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## ABSTRACT

Pulse arrival time measurements have been obtained over a 2 year interval for PSR J0437−4715 using the Parkes radio telescope. These data show that the proper motion of the pulsar is $135 \pm 4$ mas $yr^{-1}$ at a position angle of $122° \pm 2°$. This agrees well with the proper motion of the optical companion, putting the association beyond doubt. An H$\alpha$ image confirms that the nebulosity first detected by Bell, Bailes, & Bessell is a bow shock associated with the pulsar and shows that its orientation is close to that expected from the proper motion.

*Subject headings:* ISM: H II regions — pulsars: individual (PSR J0437−4715)

## 1. INTRODUCTION

The millisecond pulsar PSR J0437−4715 was discovered during a survey of the southern sky for millisecond and low-luminosity pulsars (Johnston et al. 1993). It is the closest and brightest millisecond pulsar known, with an estimated distance of 140 pc and a flux density of about 90 mJy at 1500 MHz. The pulsar, which has a rotation period of 5.75 ms, is in a 5.74 day circular orbit with a low-mass white dwarf companion (Bell, Bailes, & Bessell 1993). Its proximity to Earth makes it an excellent candidate for proper-motion and parallax measurements.

Proper-motion measurements have shown that pulsars are high-velocity objects with typical birth velocities of 450 km $s^{-1}$ (Lyne & Lorimer 1994). Most of these proper motions have been determined interferometrically (Harrison, Lyne, & Anderson 1993; Fomalont et al. 1992), but a few, particularly of millisecond pulsars, have been measured using high-precision timing (Ryba & Taylor 1991a, b). A transverse velocity contributes to the observed period derivative (Shklovskii 1970; Camilo, Thorsett, & Kulkarni 1994) and hence affects the derived characteristic age and surface magnetic field of a pulsar. For PSR J0437−4715, this effect is very significant.

For systems where the companion is optically identified as a white dwarf, the true age of the associated neutron star can be estimated from the white dwarf's color and luminosity. Observations of this type have shown that the neutron stars have ages of several Gyr (Kulkarni, Djorgovski, & Klemola 1991; Bell et al. 1993), implying that their magnetic fields do not decay below about $10^8$ G. These studies have also shown the companions to be among the coolest and faintest white dwarfs known.

Pulsar wind nebulae (PWNs) are H$\alpha$ nebulae generated by the interaction of the pulsar's relativistic wind with the interstellar medium. The rapid motion of pulsars often results in the PWNs having the form of a bow shock. Studies of other PWNs (Kulkarni & Hester 1988; Aldcroft, Romani, & Cordes 1992; Cordes, Romani, & Lundgrem 1993) suggest that H$\alpha$ photons are produced by collisional excitation. Broadband optical imaging by Bell et al. (1993) revealed an apparent bow-shock nebula close to PSR J0437−4715. The proper-motion measurements reported here, along with an H$\alpha$ image, confirm the existence of this nebula and show that it is associated with the pulsar.

## 2. PULSAR ARRIVAL TIME MEASUREMENTS

Between 1992 July and 1994 June, 1416 pulse arrival times were obtained using the Parkes radio telescope at a central frequency of 1520 MHz. Orthogonal linear polarizations were observed using a 2 × 64 × 5 MHz filter bank. After detection, signals for the two polarizations were added, filtered, one-bit digitized at 0.08 ms intervals, and written to magnetic tape. Offline, the data were folded at the topocentric pulsar period to produce mean pulse profiles for each frequency channel, typically with integration times of 100 s. These were then transformed to the Fourier domain, phase-shifted to compensate for dispersive delays, and retransformed and summed to form a final mean profile. A standard pulse template was fitted to the observed profiles to determine the pulse times of arrival (TOAs). Formal uncertainties in the TOAs, based on the observed pulse width and signal-to-noise ratio, were about 0.3 $\mu$s. The data were analyzed using the program TEMPO (Taylor & Weisberg), together with the DE200 ephemeris of

TABLE 1

Timing Parameters for PSR J0437−4715

| | |
|---|---|
| R.A. (J2000) | $04^h37^m15^s.7102(2)$ |
| Decl. (J2000) | $-47°15'07''.998(6)$ |
| Proper motion in R.A. | 114(2) mas $yr^{-1}$ |
| Proper motion in decl. | −72(4) mas $yr^{-1}$ |
| Period | 5.757451819356(4) ms |
| Period derivative | $5.709(10) \times 10^{-20}$ |
| Period epoch (MJD) | 48,825.00 |
| Dispersion measure | 2.6484 $cm^{-3}$ pc |
| Orbital period | 496,026.0468(16) s |
| Semimajor axis | 3.3666787(14) s |
| Eccentricity | 0.0000187(10) |
| Epoch of periastron (MJ) | 48,817.82(4)[a] |
| Longitude of periastron | 1°(2)[a] |
| Mass function | 0.0012431 $M_{\odot}$ |

[a] The epoch and longitude of periastron are highly covariant because of the small eccentricity. Observers should use 48.817.8258288 and 0°.788747, respectively.

the Jet Propulsion Laboratory (Standish 1982) and the Blandford & Teukolsky (1976) model for the timing of a pulsar in a binary system.

A satisfactory 11 parameter fit to the data was obtained giving an rms timing residual (difference between the measured TOAs and model predictions) of 2.7 $\mu$s. Derived parameters from this fit are given in Table 1, and the postfit residuals are shown in Figure 1. Deviations of the postfit residuals are an order of magnitude larger than would be expected from the independently estimated uncertainties in the TOAs, as can be clearly seen in Figure 1. The systematic errors may arise from imperfect calibration of the orthogonal polarizations leading to changes in observed pulse shape, but other contributions are possible. Because of the non-Gaussian nature of these errors, the estimated parameter uncertainties quoted in Table 1 (in parentheses) have been increased to 10 times the rms values given by TEMPO. Despite these increased errors, the derived proper motion is highly significant. However, we are not yet able to detect the effect of annual parallax in the timing residuals. Since the pulsar is at a high ecliptic latitude, the expected residuals due to parallax are small, $\sim 1$ $\mu$s in amplitude.

## 3. PROPER MOTION

The derived proper motion, $135 \pm 4$ mas $yr^{-1}$ at a position angle (measured from north toward east) of $122° \pm 2°$, compares well with the optical proper motion (Danziger, Baade, & Della Valle 1993) of $110 \pm 40$ mas $yr^{-1}$ at a position angle of $116° \pm 10°$. This puts the association of the optical companion and the pulsar beyond doubt. For a distance of 140 pc (Taylor, Manchester, & Lyne 1993), the transverse velocity implied by the timing proper motion is $91 \pm 3$ km $s^{-1}$. However, the distance estimate, based on the pulsar dispersion measure, is uncertain by about 30%, so the real uncertainty in the velocity is of the order of 25 km $s^{-1}$. The proper-motion estimate is therefore in reasonable agreement with the value of $63 \pm 30$ km $s^{-1}$ estimated from interstellar scintillation observations (Johnston & Nicastro 1994).

The kinematic contribution to the pulsar period derivative, first identified by Shklovskii (1970), is very significant in the

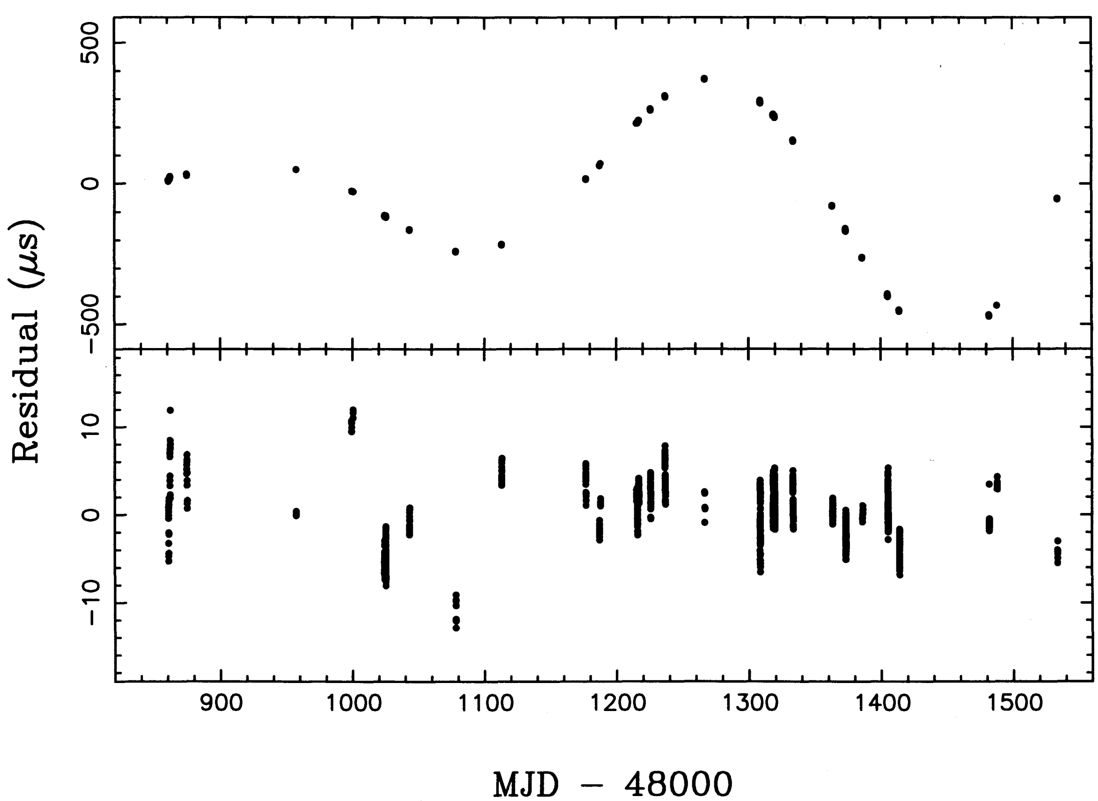


Fig. 1.—Timing residuals for PSR J0437−4715 after fitting for pulsar and orbital parameters. The upper part of the figure shows the residuals with the proper motion set to zero, and the lower part gives the final residuals.

case of PSR J0437−4715. This term is given by

$$\Delta\dot{P} = \frac{v^2 P}{cd} = (3.8 \pm 1.1) \times 10^{-20} , \tag{1}$$

where $v$ is the transverse velocity, $d$ is the distance, and $P$ is the pulsar period. For J0437−4715 the kinematic term accounts for about two-thirds of the measured period derivative. The intrinsic period derivative is therefore about $2 \times 10^{-20}$. This implies a dipolar field strength of about $3 \times 10^8$ G and a characteristic age of about 5 Gyr. The characteristic age is an upper limit to the true age of the pulsar, since it assumes that the rotation period of the pulsar at birth is much less than its present rotation period. Hence, this age is consistent with estimates of cooling ages of the white dwarf companion (Bell et al. 1993; Danziger et al. 1993; Bailyn 1993) which range between 1 and 4 Gyr. The uncertainty in these estimates is again about 30%, corresponding to the uncertainty in the distance.

Correction for the motion of the Sun with respect to the local standard of rest gives a pulsar velocity through the local interstellar medium of 96 km s$^{-1}$ at a position angle of 119°. The corresponding Galactic position angle (measured anticlockwise from Galactic north) is 26°. Since the Galactic latitude of the pulsar is −42°, this may indicate that it is moving toward the plane. However, at this Galactic latitude, the $z$-motion of the pulsar could be easily dominated by the unmeasured radial velocity component. Since the pulsar is very old, it may have executed many oscillations in the Galactic $z$-direction, so that either direction of motion is reasonable.

## 4. PULSAR WIND NEBULA

Using the Australian National University's 2.3 m telescope at Siding Spring, NSW, Australia, we have obtained a 3000 s exposure of the PSR J0437−4715 region using a 1024 square Tektronix CCD with a filter of width 15 Å centered on Hα. The resulting image, shown in Figure 2 (Plate L7) clearly shows that the nebulosity identified by Bell et al. (1993) is an Hα bow shock PWN associated with the pulsar, thus confirming the association. The arrow in Figure 2, which indicates the direction of the timing proper motion, aligns well with the symmetry axis of the PWN, providing further evidence for the association.

The cometary shape of the nebula implies a balance between ram pressure ($\rho_0 v_p^2$) and the pressure due to a relativistic pulsar wind ($\dot{E}/4\pi R_w^2 c$), where $v_p$ is the pulsar velocity, $\rho_0$ is the density of the ambient medium, $\dot{E}$ is the spin-down energy of the pulsar, and $R_w$ is the standoff distance between the pulsar and the apex of the bow shock. Estimates derived above for the pulsar velocity and intrinsic spin-down rate imply a hydrogen density of $\sim$0.2 cm$^{-3}$ in the pulsar vicinity. A flux scale for the image in Figure 2 was established using Hα observations of the planetary nebula SMP 6 (Meatheringham & Dopita 1991). Integrating over the whole of the bright arc and assuming it dominates the flux for the PWN, $F_\alpha = 2.5 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$. Consideration of the shock excitation of the nebula shows that

$$F_\alpha = 10^{-3.6} \frac{v_7 X \dot{E}_{33}}{d^2} \text{ photons cm}^{-2}\text{ s}^{-1} , \tag{2}$$

where $v_7$ is the pulsar velocity in units of $10^7$ cm s$^{-1}$, $X$ is the fraction of neutral hydrogen, $\dot{E}_{33}$ is the pulsar spin-down luminosity in units of $10^{33}$ ergs s$^{-1}$, and $d$ is the pulsar distance in kiloparsecs (Cordes et al. 1993). The flux derived above for the J0437−4715 PWN implies that $X = 0.2$, so the local preshock gas is largely ionized.

For PSR J0437−4715 and other millisecond pulsars, reducing the uncertainty in distance is the key to gaining further insight into parameters that depend on velocity and intrinsic period derivative. For PSR J0437−4715 a good estimate of the distance will probably be obtained from improved timing observations and independently from Mk III long-baseline observations currently under way.

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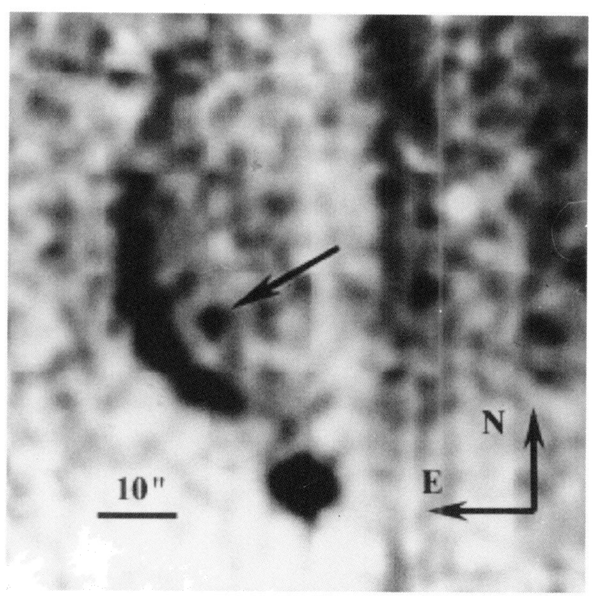


FIG. 2.—Hα image of the bow shock wind nebula around PSR J0437−4715. The arrow is oriented in the direction to the system's proper motion, and the star near its tip is the white dwarf binary companion to the pulsar.

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