THE ASTROPHYSICAL JOURNAL, 387:L37–L41, 1992 March 1

PSR 1259−63: A BINARY RADIO PULSAR WITH A Be STAR COMPANION

SIMON JOHNSTON AND R. N. MANCHESTER
Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia
A. G. LYNE AND M. BAILES
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, SK11 9DL, UK
V. M. KASPI
Joseph Henry Laboratories and Physics Department, Princeton University, Princeton, NJ 08544
QIAO GUOJUN
Center of Astronomy and Astrophysics, CAAST, and Department of Geophysics, Peking University, Beijing 100871, China
AND
N. D'AMICO
Istituto di Fisica dell'Università di Palermo and Istituto di Radioastronomia del CNR, Bologna, Italy
Received 1991 November 19; accepted 1991 December 12

ABSTRACT

We report the discovery of the first known radio pulsar with a massive, nondegenerate companion. PSR 1259−63, found during a large-scale high-frequency survey of the southern Galactic plane, has a period of 47 ms and a pulse profile similar to that of the Crab pulsar. Observations using the Parkes radio telescope at frequencies around 660 and 1520 MHz over the period 1989 November to 1991 September show that the pulsar is in a highly eccentric orbit around a massive companion. Near periastron, the pulsar is eclipsed, presumably by a wind from the companion star. On the basis of astrometric measurements, we have optically identified the companion as a 10th magnitude Be star, SS 2883. This unique system forms a link between Be X-ray binary systems and recycled pulsars.

Subject headings: binaries: eclipsing — pulsars: individual: PSR 1259−63 — stars: emission-line, Be

1. INTRODUCTION

Although the vast majority of radio pulsars possess no companion, the small subset which do (∼2%) have provided a great deal of information about the formation and evolution of radio pulsars and binary X-ray systems (van den Heuvel 1989). About half of pulsar-progenitor stars are thought to be members of binary systems, so the small fraction of pulsars in binaries is probably due to the disrupting effect of the supernova explosion which produces the pulsar. It has been demonstrated that most binary systems disrupt when the second supernova explosion takes place in a massive binary (Dewey & Cordes 1987). At the time of the first explosion, the mass of the secondary is too great to allow the pulsar to escape, unless the system has a large orbital period and the pulsar receives a kick velocity which assists ejection. Massive X-ray binary systems provide evidence that neutron stars do orbit post–main-sequence stars, suggesting that they must orbit main-sequence stars as well. However, no such systems have been detected as radio pulsars (Manchester, D'Amico, & Tuohy 1985). The strong stellar winds of OB stars are usually invoked to explain the deficit of pulsar-OB binary systems, with either multipath scattering or absorption making the radio pulsations invisible.

A recent high-frequency survey of the southern Galactic plane using the Parkes radio telescope resulted in the discovery of 46 pulsars (Johnston et al. 1991), complementing the similar Jodrell Bank survey (Clifton et al. 1991) which discovered 40 pulsars along the northern Galactic plane. These surveys exploited the benefits of higher radio frequencies to reduce both pulse broadening due to multipath scattering in the interstellar medium and the sky background temperature of the Galactic plane. A timing program was started in 1989 November to obtain improved parameters for these pulsars. Of particular interest was PSR 1259−63, which has the shortest period (47 ms) of the new discoveries and a double pulse profile similar to that of the Crab pulsar.

Sections 2 and 3 describe the radio observations of this pulsar, which show it to be a member of a highly eccentric binary system, and the identification of the optical companion, respectively. In § 4 we discuss the implications of this discovery for the models of binary pulsar evolution.

2. RADIO TIMING AND SPECTRAL OBSERVATIONS

Timing observations of PSR 1259−63 were carried out using the 64 m Parkes radio telescope in frequency bands centered at 1520, 660, and 430 MHz in the period 1989 November to 1991 September. A total of 93 independent observations of the pulsar were made in 23 separate observing sessions.

Each of the three receivers consisted of cyrogenically cooled dual-channel systems receiving orthogonal linear polarizations. The signals were downconverted to an intermediate frequency, filtered in a multichannel filter bank and low-pass filtered. After summing of the polarizations, the signals were sampled at 1.2 ms intervals using one-bit digitization and recorded on magnetic tape. At 1520 MHz the filter bank consists of 2 × 64 × 5 MHz filters; at 660 MHz it consists of 2 × 128 × 250 kHz filters; and at 430 MHz the filter bank contains 2 × 256 × 125 kHz filters. At 1520 MHz, typical observation times were 500 s except during the eclipsing phase when several 60 minute observations were obtained. At 660 and 430 MHz observation times were generally about 60 minutes.

Pulse profiles at 1520 and 660 MHz, obtained by averaging

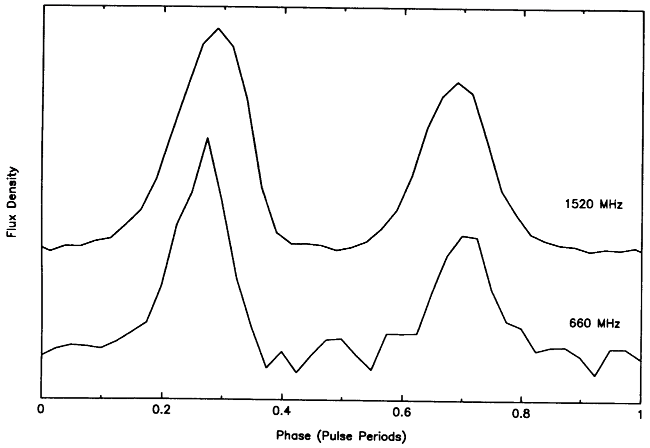

FIG. 1.—Mean pulse profile for PSR 1259−63 at two radio frequencies, 1520 and 660 MHz.

all available data, are shown in Figure 1. In spite of good sensitivity, the pulsar remains undetected at 430 MHz. There is a strong interpulse which is separated from the main pulse by 145° at 1520 MHz, giving a pulse profile similar to that of the Crab pulsar. At 660 MHz the separation of the main pulse and interpulse is significantly greater, approximately 160°. This suggests that we may be observing a wide double from a single magnetic pole rather than radiation from two poles (Lyne & Manchester 1988). On average, the interpulse contains about 40% of the total power, but the ratio appears to be time variable with the interpulse power exceeding that of the main pulse in some observations.

In the upper section of Figure 2 we show the observed time dependence of the pulsar period. The period was determined independently for each observation with an uncertainty which is smaller than the size of the plotted points. After an initial gradual increase, with an apparent period derivative of about 4×10^{-14}, the period decreased dramatically at about MJD 48100 and subsequently recovered toward its initial value. As shown in the lower section of Figure 2, the pulsed flux density is also time variable. In particular, the observed flux density decreased significantly around MJD 48100 when the period variations were most rapid. We believe that these variations result from the orbital motion of the pulsar around a massive companion star. A fit of a binary model to the observed periods accurately accounts for the observed variations and also allows precise predictions of the period.

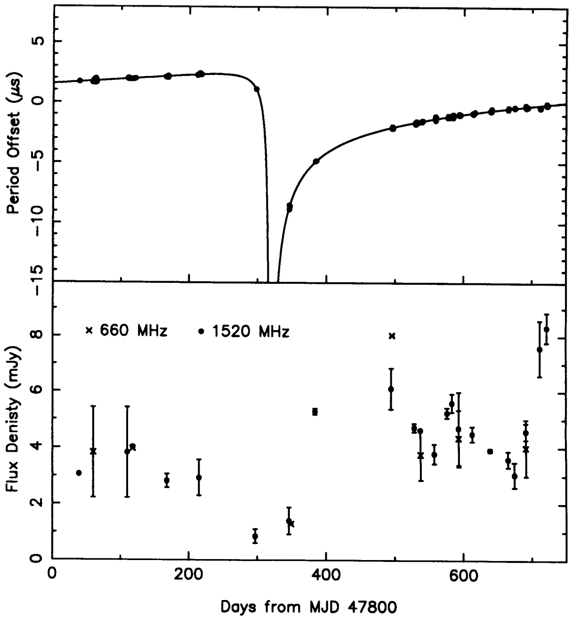

FIG. 2.—Offset in the observed pulse period from 47.762 ms (*upper*) and mean flux density at two radio frequencies, 660 and 1520 MHz (*lower*) for PSR 1259−63 as a function of time in days from MJD 47800 (1989 October 1). The curved lines in the upper part represent a fit of a binary model to the data with the pulsar period derivative fixed at 2×10^{-14}. In the lower part, the vertical bars indicate the rms scatter in pulsed flux density over a session when there were two or more observations of the pulsar in that session.

Pulsar and orbital parameters for the system are given in Table 1. The pulsar period is given for the epoch of the ascending node, and the error is in the last quoted place. Position measurements are described in § 3. As discussed below, the observed flux density depends on orbital phase; the values quoted in the table are for MJD 48495. Between 660 and 1520 MHz, the spectral index, α (where $S \propto \nu^{\alpha}$), is close to zero, and the nondetection of the pulsar at 430 MHz implies that α must be greater than about 3.5 between 430 and 660 MHz.

TABLE 1

PARAMETERS OF THE PSR 1259−63 SYSTEM

Parameter (1)	(2)	(3)
Pulsar radio position (J2000)	$13^{h}02^{m}47\overset{s}{.}72 \pm 0\overset{s}{.}03$	$-63^\circ 50' 08\overset{''}{.}5 \pm 0\overset{''}{.}2$
Pulsar radio position (B1950)	$12^{h}59^{m}38\overset{s}{.}25$	$-63^\circ 34' 01\overset{''}{.}8$
SS 2883 optical position (J2000)	$13^{h}02^{m}47\overset{s}{.}65 \pm 0\overset{s}{.}10$	$-63^\circ 50' 09\overset{''}{.}5 \pm 0\overset{''}{.}7$
Dispersion measure (cm^{-3} pc)	146.7 ± 0.2	...
Pulsar distance (kpc)	2.3	...
Flux density at 430 MHz (mJy)	< 1.0	...
Flux density at 660 MHz (mJy)	4 ± 1	...
Flux density at 1520 MHz (mJy)	4.6 ± 0.3	...
Pulsar period, P (ms)	47.76164 ± 7	47.76219 ± 5
Period derivative, $\dot{P}$	0.0	2×10^{-14}
Orbital period (days)	1133 ± 24	2150 ± 100
Epoch of ascending node (MJD)	48043 ± 2	48027 ± 3
Epoch of periastron (MJD)	48120 ± 2	48117 ± 3
$a \sin i$ (lt-sec)	3480 ± 1900	3450 ± 1000
Longitude of periastron	164° ± 9°	158° ± 6°
Eccentricity	0.976 ± 0.025	0.967 ± 0.017
Mass function, M_f ($M_\odot$)	35	10

1992ApJ...387L..37J

We discuss later the possibility that this unusual spectral index is due to absorption in the companion's stellar wind.

Because of the large covariance between the various parameters, especially the pulsar period derivative and the orbital period, we cannot at this stage solve for the period derivative. Also, the formal errors in the fitted parameters are quite large. In column (3) of the lower part of Table 1 we give parameters fitted with the period derivative ($\dot{P}$) held at 2×10^{-14} which is close to the value giving minimum residuals. This fit is also shown in Figure 2. A period derivative of zero cannot be excluded with the present data, and fitted parameters for this value are given in column (2).

The orbit is highly eccentric with a lower limit on the eccentricity of 0.95. At periastron, which last occurred around MJD 48120, the pulsar approaches to within $\sim 50\ R_\odot/\sin i$ of its companion. A hyperbolic orbit is not excluded by the fit, but the probability of a chance encounter this close between a pulsar and a star in the Galactic disk is extremely low. From the mass function

$$M_f = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_B^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}, \tag{1}$$

where P_B is the orbital period and $a \sin i$ is the projected semimajor axis length, and assuming that the mass of the pulsar, m_p, is 1.4 $M_\odot$, the lower limit on the mass of the companion m_c is 12 $M_\odot$ for the best-fit solution or 35 $M_\odot$ for the $\dot{P} = 0$ solution.

We attribute the drop in pulsed flux density at both 660 and 1520 MHz near periastron to the eclipse of the pulsar by the extended atmosphere of the companion star. The coincidence of this eclipse with periastron is strong supporting evidence for the binary nature of this system. Explanations for the drop in flux density based on scintillation are untenable. Diffractive scintillation has a time scale which is too short and, in any case, is averaged out by the wide observing bandwidth. Refractive scintillation, on the other hand, has a time scale which is too long and does not normally produce such deep modulation (Kaspi & Stinebring 1991).

The observed period variations have some resemblance to those which occur in giant glitches (Manchester & Taylor 1977). However, we rule out this explanation on several grounds. First, the "glitch" is about two orders of magnitude greater than the largest glitch observed so far (Lyne 1987). Secondly, there was a significant change in the apparent period derivative of the pulsar before the "glitch." For the session around MJD 47910 the period derivative was $(4.44 \pm 0.06) \times 10^{-14}$, whereas for that around MJD 48015, it was $(3.82 \pm 0.07) \times 10^{-14}$. Real glitches give no warning (Cordes, Downs, & Krause-Polstorff 1988). Third, the observed drop in flux density at the time of the "glitch" is unprecedented and has no ready explanation. Finally, as discussed above, the observed period variations can be precisely represented by a binary Keplerian model. We therefore conclude that PSR 1259−63 is the first known example of a pulsar in a binary system with a massive nondegenerate stellar companion.

3. OPTICAL IDENTIFICATION

To obtain a more accurate position for the pulsar, two 12 hr synthesis observations were carried out using the Australia Telescope Compact Array (ATCA) on MJDs 48351 and 48507. In each case, the observations were at a frequency of 1472 MHz and had a maximum baseline of 6 km, giving a synthesized half-power beamwidth of 6″ and an rms noise level in the image of about 250 μJy per beam. For the first observation, a single position calibrator was observed, whereas there were four calibrators for the second observation.

Both images show a point source close to the pulsar position quoted by Johnston et al. (1991). The flux density of this source was about 6 mJy in the first observation and 9 mJy in the second; both are comparable to the pulsed flux density observed in the timing measurements at the corrsponding epochs (Fig. 2). These flux density variations confirm the identification of this source with the pulsar. Table 1 gives the J2000 and B1950 positions for the pulsar, derived from the second synthesis.

A search of the relevant SERC(J) Schmidt plate for the optical companion revealed a 10th magnitude star at the pulsar position. This star was cataloged by Stephenson & Sanduleak (1971) as a Be star, SS 2883. Astrometric measurements based on nine Perth 70 stars within 3° of SS 2883 gave the J2000 position for SS 2883 listed in Table 1, which is in excellent agreement with the ATCA position for the pulsar. We therefore identify this star as the binary companion. The stellar mass derived from the pulsar timing is consistent with a Be star, and such stars are often observed in high-mass X-ray binary systems (Rappaport & van den Heuvel 1982).

Photometry of early-type stars in this region was carried out by Westerlund & Garnier (1989) and Velghe, Denoyelle, & De Kersgieter (1970). From the values of color magnitudes and visual extinction, these authors derive distances of 1.9 and 2.3 kpc, respectively, for SS 2883. These are in excellent agreement with the distance to the pulsar (Table 1) based on the dispersion measure and a model for the Galactic distribution of interstellar electrons derived by Taylor, Lyne, & Manchester (1991). Using the relations of Westerlund & Garnier (1989), we find the luminosity of the star to be $5.8 \times 10^4\ L_\odot$ and the radius of the star, R_*, to be 11 $R_\odot$.

An optical spectrum of SS 2883 was obtained under the service spectroscopy program of the Anglo-Australia Telescope on 1991 May 18. As expected for Be stars, Hα and Hβ were seen strongly in emission with half-power line widths of 440 ± 40 and 480 ± 50 km s^{-1}, respectively. If we assume that this emission originates from a circumstellar disk of material and further assume Keplerian rotation of the disk around a 15 $M_\odot$ star, then the emitting region is about 54 $R_\odot/\sin i$ or $\sim 5R_*/\sin i$ from the star's center.

4. DISCUSSION

The evidence that PSR 1259−63 is in a highly eccentric orbit around the Be star SS 2883 is compelling. The coincidence of the radio and optical positions and binary model fit to the data are both excellent. Glitch activity is ruled out on a number of counts, but especially by the observed eclipse of the pulsar at the time of periastron. Therefore PSR 1259−63 is unique: it is the only known radio pulsar with a massive, nondegenerate companion. It is also the most highly eccentric binary system known to contain a neutron star.

How does this system fit in with the standard model for the evolution of pulsars, massive binary systems and Be stars? In the model of Rappaport & van den Heuvel (1982), Be stars are formed in binary systems by the transfer of large amounts of mass and angular momentum during the giant phase of the primary (initially more massive) star to the secondary star. This spins up the secondary to near breakup velocities resulting in a disk of circumstellar material orbiting the star at velocities of several hundred km s^{-1}. The material in this disk is the source of the characteristic emission lines in the spectrum. Eventually the primary explodes and produces a neutron star, which, should it remain bound, orbits the Be star in a wide and eccentric orbit. The probability of the system remaining bound depends upon the amount of mass lost and the degree of asymmetry in the explosion.

For a symmetric explosion in which the system remains bound, the mass of the presupernova star $m_{\rm pre}$ can be derived from the masses of the companion star m_c, the resulting neutron star mass m_p, and the orbital eccentricity e as follows:

$$m_{\rm pre} = (1 + e)(m_c + m_p) - m_c \tag{2}$$

(Gott 1972). Therefore, in this system, if we assume a pulsar mass of 1.4 $M_\odot$ and a companion mass greater than 12 $M_\odot$, $m_{\rm pre} > 14\ M_\odot$. This is a large presupernova mass, indicating that the progenitor was greater than 20 $M_\odot$ at birth (Vanbeveren et al. 1979).

In the case of an asymmetric explosion, the presupernova orbit and masses cannot be uniquely determined. However, it has been shown by Hills (1983) that in systems where half the mass is lost in the explosion and the velocity kick is of the same order as the presupernova orbital velocity, the mean orbital eccentricity of surviving systems is very high. Therefore the orbital parameters of PSR 1259−63 are consistent with either a large pre-explosion progenitor, or a large, suitably directed kick velocity being imparted to the pulsar. In the presupernova system, the Be star would have possessed an orbital velocity of about 100 km s^{-1}. Therefore the system should now have a runaway velocity of this order, making it an OB runaway star (Blaauw 1961). The large orbital period and eccentricity would make a spectroscopic determination of the binary orbit almost impossible. Thus, the nondetection of binary companions to OB runaway stars (Gies & Bolton 1986) is only weak evidence against the binary supernova hypothesis of Blaauw (1961) to explain the origin of these stars. The existence of the PSR 1259−63 system is striking confirmation of the violence of the events which produce pulsars and consistent with the observed very low proportion of radio pulsars which are members of binary systems.

The long duration of the eclipse in PSR 1259−63 shows that it is caused by the stellar wind and not the circumstellar disk of the companion star. It demonstrates that stellar winds of massive stars can render invisible otherwise bright radio pulsars. The long orbital period and large orbital eccentricity of PSR 1259−63 provide it with a trajectory which removes it far from the companion where the stellar wind density is greatly reduced, and allow the radio pulsations to penetrate the stellar wind. There are many neutron stars in closer orbits to massive stars, and, in these, any pulsed radio emission will be permanently "eclipsed." PSR 1259−63 would be extremely difficult to detect in any pulsar survey at frequencies less than 1 GHz.

It seems likely that the unusual spectrum of the pulsar is also due to absorption effects in the stellar wind. However, there are some difficulties with this interpretation. There has been no detectable systematic change in the ratio of flux densities at 1520 and 660 MHz as a function of orbital phase. Also, dispersion measures determined from relative pulse arrival times at 1520 and 660 MHz at three epochs, MJD 47910, 48330, and 48491, are equal within the uncertainty of 0.2 cm^{-3} pc. These observations imply that the dimensions of the absorbing medium are large compared to those of the orbit. Also, if the eclipse mechanism is free-free absorption, the limit on variations in dispersion measure imply that the medium must be very clumpy, with a volume filling factor of less than 1%.

Magnetic field strengths of radio pulsars are inferred from their period derivatives, as are their ages. As discussed above, we cannot yet obtain a reliable measure of the period derivative for PSR 1259−63. If the pulsar penetrates the circumstellar disk of the Be star, the radio pulsar will almost certainly be subject to accretion torques which may make a determination of the "intrinsic" period derivative impossible. Around periastron the source may be visible as an X-ray transient, like many other Be X-ray binary systems (Rappaport & van den Heuvel 1982).

If we take our best-fit period derivative value of about 2×10^{-14}, the implied surface magnetic flux density is $\sim 10^{12}$ G and the pulsar characteristic age is about 40,000 yr. However, there is no evidence for a radio supernova remnant at the pulsar position in the Molonglo Observatory 843 MHz Galactic plane survey (J. B. Z. Whiteoak, 1991 private communication). If the magnetic field is as strong as 10^{12} G, there would be no accretion on to the neutron star, and stellar wind torques would be expected to slow the pulsar down on an even shorter time scale than that due to magnetic braking. Perhaps the pulsar is much older and the field strength is much smaller, say, 10^{10} G or less, and the pulsar has achieved its current short period via mass accretion. We note that a negative period derivative is not completely ruled out from the present measurements. The lifetime of the Be star and the time scale for orbit circularization place upper limits on the age of the pulsar, but it could be as much as several million years.

The PSR 1259−63–SS 2883 system appears to provide a link between Be X-ray binaries and recycled pulsars. If tidal circularization of the orbit occurs, then the system is likely to evolve into an X-ray source very similar to the recurrent X-ray transient in the Large Magellanic Cloud, A0538, which contains a 69 ms X-ray pulsar in an eccentric orbit (Skinner et al. 1982). This system, in turn, makes an ideal progenitor for the binary pulsars PSR 1913+16 and PSR 1534+12, which contain pulsars with periods of 59 and 37 ms, respectively, and weak magnetic fields $\sim 10^{10}$ G (Hulse & Taylor 1974; Wolszczan 1991). Should circularization be avoided, then the system will disrupt when the Be star explodes, and two single pulsars will be produced. One will be a normal high-velocity, high-field pulsar and the other a low-field, low-velocity object, thus contributing to the observed velocity–magnetic moment correlation (Bailes 1989).

Further study of PSR 1259−63 and SS 2883 should elucidate the relationships between radio and X-ray pulsars, Be stars and X-ray binary systems. In particular, radio, optical, and X-ray observations about the time of the next periastron approach will be of great interest. Spectroscopic studies around periastron may provide radial velocity measurements which would give the mass ratio and hence (if we assume we know the pulsar mass) the inclination angle of the system and the Be star mass.

V. M. K. received support for this project through a Natural Sciences and Engineering Research Council of Canada 1967 Fellowship, N. D'A. acknowledges support from CNR-GIFCO and CNR Bilateral Projects, and Q. G. acknowledges support from the NSF of China and the ATNF. M. B. is an

Endeavour Fellow of the Royal Society and the Australian Academy of Science. We thank the Anglo-Australian Observatory for assistance with the optical astronometry and spectroscopy of SS 2883. The Australia Telescope National Facility is operated in association with the Division of Radiophysics by CSIRO.

REFERENCES

Bailes, M. 1989, ApJ, 342, 917

Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265

Clifton, T. R., Lyne, A. G., Jones, A. W., & McKenna, J. 1991, MNRAS, in press

Cordes, J. M., Downs, G. S., & Krause-Polstorff, J. 1988, ApJ, 330, 847

Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780

Gies, D. R., & Bolton, C. T. 1986, ApJS, 61, 419

Gott, J. R. 1972, ApJ, 173, 227

Hills, J. G. 1983, ApJ, 267, 322

Hulse, R. A., & Taylor, J. H. 1974, ApJ, 191, L59

Johnston, S., Lyne, A. G., Manchester, R. N., Kniffen, D. A., D'Amico, N., Lim, J., & Ashworth, M. 1991, MNRAS, in press

Kaspi, V. M., & Stinebring, D. R. 1991, ApJ, submitted

Lyne, A. G. 1987, Nature, 326, 569

Lyne, A. G., & Manchester, R. N. 1988, MNRAS, 234, 477

Manchester, R. N., D'Amico, N., & Tuohy, I. R. 1985, MNRAS, 212, 975

Manchester, R. N., & Taylor, J. H. 1977, Pulsars (San Francisco: Freeman)

Rappaport, S., & van den Heuvel, E. P. J. 1982, in Be Stars, ed. M. Jaschek & H. G. Groth (Dordrecht: Reidel), 327

Skinner, G. K., Bedford, D. K., Elsner, R. F., Leahy, D., Weisskopf, M. C., & Grindlay, J. 1982, Nature, 297, 568

Stephenson, C. B., & Sanduleak, N. 1971, Publ. Warner & Swasey Obs., 1, 1

Taylor, J. H., Lyne, A. G., & Manchester, R. N. 1991, in preparation

Vanbeveren, D., De Greve, J. P., van Dessel, E. L., & De Loore, C. 1979, A&A, 73, 19

van den Heuvel, E. P. J. 1989, in Timing Neutron Stars (NATO ASI Series), ed. H. Ögelman & E. P. J. van den Heuvel (Dordrecht: Kluwer), 523

Velghe, A. G., Denoyelle, J., & De Kersgieter, A. 1970, A&A, 8, 123

Westerlund, B. E., & Garnier, R. 1989, A&AS, 78, 203

Wolszczan, A. 1991, Nature, 350, 688