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PSR B1259–63: Periastron Puzzles

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1. Introduction

I was fortunate enough to have been involved with unravelling the secrets of PSR B1259–63 right from the start. The major part of my PhD thesis was a large survey of the southern galactic plane at an observing wavelength of 20 cm. Confirmation of a further batch of good-looking pulsar candidates from the data processing took place in November 1989 at the Parkes radio telescope in central New South Wales, Australia. My fellow student Jeremy Lim and I were in the control room when the 47.7 ms periodicity of PSR B1259–63 was confirmed. At first, the slight increase in period from the original detection led us to believe we had discovered a 'Crab-like' pulsar. However by the end of the following year we realised we had something much more exciting on our hands.

I have recently published a review paper on PSR B1259–63 (Johnston 1995) which I hope gives a good flavour of work to date. In this article I will review the work which has gone into this pulsar over the last 6 years, drawing heavily on already published papers. I will then discuss some observations which are not yet published and finally a add a few thoughts on what we are looking for on the next periastron passage. First, however, I will describe searches for other radio pulsar / OB star pairings.

2. Searches for similar systems

There are only 2 radio pulsars known with companions which are high mass main sequence stars. Both were found in untargetted surveys. PSR B1259–63 was found in a large scale survey of the southern galactic plane, and PSR J0045–7319 was discovered in a survey of both Magellanic Clouds and remains the only pulsar known in the Small Magellanic Cloud (McConnell et al. 1991). Both these systems are fascinating for several reasons and this has encouraged searches for similar systems.

To date, none have been successful. Two independent searches have been carried out with the Parkes radio telescope, and a survey of northern OB stars was carried out at Green Bank by Sayer et al. (1996). A total of some 500 OB stars have thus been searched for radio pulsations without success although it is interesting to note that neither of the two known pulsars fit the search criteria for any of the surveys! Possible reasons for the lack of success are (i) they are rare objects (ii) the beaming fraction and/or luminosity is small (iii) the radio pulses are eclipsed for a substantial fraction of the orbit (iv) bad luck.

The fraction of neutron stars around OB runaways is probably quite high - 100% is an oft-quoted figure - but perhaps the majority of these systems have short-period orbits which masks their radio emission (like the LSI +61°303 system described below). However, the lack of X-ray emission from the OB runaways seems to imply that short-period orbits are not the norm. Recent ROSAT results on OB stars in the galactic disk which appear so show excess X-ray emission over that expected from the OB stars themselves need to be followed up in this regard. The beaming fraction is an unknown, although a value somewhere around 30% for 'middle-aged' pulsars is a generally used figure. This would then rule out any hope of detecting the pulses in 70% of cases. The pulsar luminosity function continues to be argued over, but, simple-mindedly, the fact that untargetted searches have been more successful than targetted ones leads me to believe that luminosity must be the reason for their lack of success.

3. Previous Work on PSR B1259–63

PSR B1259–63 is a unique binary pulsar. It was discovered in a galactic plane survey at 20 cm (Johnston et al. 1992a) and was found be to in a highly eccentric ($e \sim 0.9$), 3.5-yr orbit around a 10th magnitude Be star, SS 2883 (Johnston et al. 1992b). Optical observations (Johnston et al. 1994) show that SS 2883 is of spectral type B1e, and thus has a mass of ~10 $M_\odot$ and a radius ~6 $R_\odot$. This implies that the inclination angle of the binary orbit is ~36 degrees. The Hα emission line shows that the Be star disc extends to at least 20 R_*, just inside the pulsar's orbital radius at periastron. Figure 1, taken from Johnston et al. (1996), shows a schematic of the orbital motion of the pulsar near periastron.

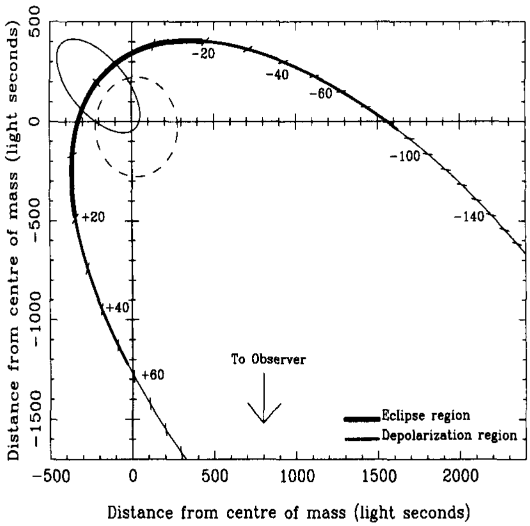

Figure 1. The orbital motion of PSR B1259–63 near periastron

PSR B1259–63, which has a pulse period of 47.7 ms, has a mean pulse profile with two components of almost equal amplitude separated by 140 degrees of longitude. Both components are more than 80% linearly polarized and there is an approximately constant gradient of position angle across them. The observed position angles are well represented by the rotating vector model, with the implication that the minimum angle between the rotating vector and the line of sight occurs in the wider gap between the components (Manchester & Johnston 1995).

Timing observations of this pulsar, made over a 4.8 yr interval using the Parkes radio telescope, cover two periastron passages, in 1990 August, and 1994 January. The timing data cannot be fitted by the normal pulsar and Keplerian binary parameters but are well fitted by a model which includes pulsar spin-down episodes at each periastron. The most likely explanation is that the pulsar is interacting with the circumstellar disk of SS2883 via the propellor mechanism (Manchester et al. 1995).

The last periastron passage of PSR B1259–63 occurred on 1994 Jan 9 (which I shall denote as $\mathcal{T}$). Pulsed radio observations were made of the system for several months before and after periastron (Johnston et al. 1996). In brief, these results showed (i) depolarization of the pulses at $\mathcal{T}-100$, (ii) a dispersion measure increase of more than 10 cm^{-3}pc by $\mathcal{T}-25$, (iii) scatter broadening of the pulses by more than 10 ms at 5 GHz around $\mathcal{T}-25$, (iv) an eclipse of the pulsed emission at frequencies up to 8.4 GHz from $\mathcal{T}-18$ to $\mathcal{T}+17$ and (v) extremely large (negative) rotation measures varying on short timescales near $\mathcal{T}+30$. All these observations are unprecedented in any other radio pulsar.

Non-pulsed but variable X-ray emission was detected from the system during two pointed ROSAT observations, taken five months apart near apastron. According to Cominsky et al. (1994), the X-ray flux is significantly greater than expected from the Be star's corona and seems likely to originate either from low-level stellar wind accretion onto the neutron star or from the shock between the stellar wind and the relativistic pulsar wind.

High energy observations of the binary system were also made close to periastron. The OSSE instrument on board CGRO made a 3 week observation of this pulsar from $\mathcal{T}-6$ until $\mathcal{T}+14$ (Grove et al. 1995). The ASCA satellite also observed towards PSR B1259–63 on days $\mathcal{T}-12$, +1 and +17 (Kaspi et al. 1995). In summary, these results show no evidence for pulsed emission, a power law spectrum with photon index ~1.8 between 10 and 200 keV, evidence for flux variability by a factor ~2. Grove et al. (1995) conclude high energy emission arises from synchrotron radiation developed in the shock between the Be star and the pulsar wind and that this contact discontinuity is located close to the pulsar.

Both Johnston et al. (1996) and Melatos et al. (1995) have proposed a model of the disc and wind of the Be star to explain the pulsed radio observations. In the Johnston et al. (1996) model, the disc has an opening angle of 15 degrees and a power law dependence on the electron density (n_e). They find that n_e is $\sim 4 \times 10^{12}$ cm^{-3} close to the star and has a steep drop-off (power law index −4.2) as a function of radius. The models are strongly constrained by the dispersion measure increase prior to periastron and the rotation measure increase after periastron. In both models, free-free absorption plays an important role in the eclipse of the pulses. Note that Ghosh (1995) has proposed a thin-disc model of the Be star's wind to explain the spin-down of the pulsar observed by Manchester et al. (1995).

4. New Results

Radio continuum observations of the system were made using the Molonglo Observatory Synthesis Telescope (MOST) and the Australia Telescope Compact Array at five frequencies between 0.84 and 8.4 GHz. The results are shown in Figure 2. Note that although the figure is truncated at $\mathcal{T}$+65, data from the MOST showed that the radio continuum emission persisted until at least $\mathcal{T}$+400. This radio continuum source is *not* the pulsar itself. Simultaneous flux measurements with the Parkes telescope show that the pulsar never exceeds 10 mJy at these frequencies and is often only 2-5 mJy.

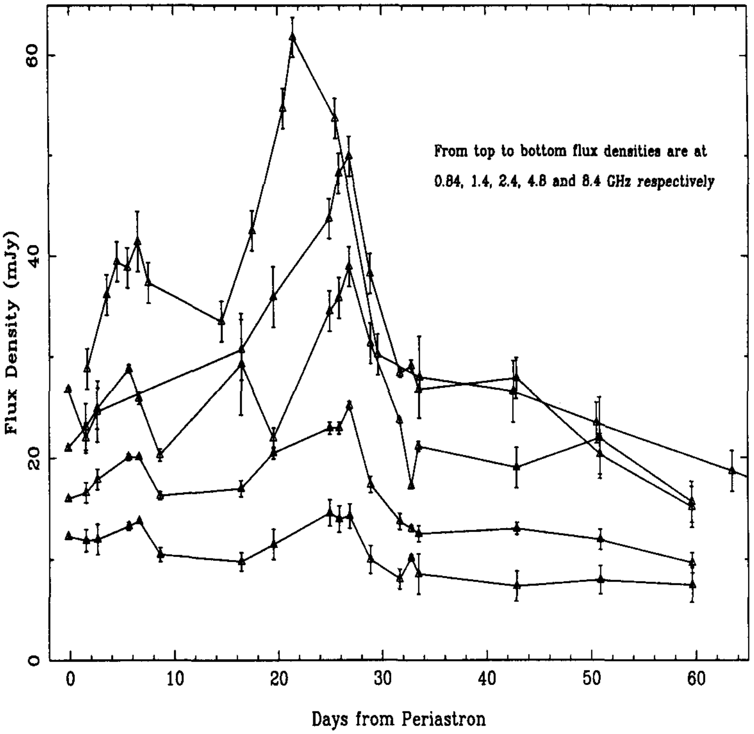

Figure 2. Radio continuum emission from the PSR B1259–63 system

As expected, the source was unresolved at all epochs, putting an upper limit of ~1" on the source size. At a distance of 1.5 kpc the entire orbit has an angular diameter of only ~ 4 mas. The radio emission is probably synchrotron emission from the shock formed between the relativistic pulsar wind and the Be star wind. From pressure balance arguments and a knowledge of the Be star wind, the bow shock stand-off distance is roughly at 1.5×10^{12} cm at periastron and 2×10^{13} cm at $\mathcal{T}$+60. The contribution of the pulsar's magnetic field at the shock front, assuming a dipolar field to the light cylinder surface and a toroidal field thereafter is 3.4 G at periastron dropping to 0.3 G at $\mathcal{T}$+60 for the stand-off distances quoted above. The synchrotron half-lifes for these magnetic fields are long enough to keep the radio emission going for a few hundred days. Using simple synchrotron arguments, the energy density in the particles is roughly 5×10^{-2} Jm^{-3} and is about two orders of magnitude greater than the magnetic energy density. A more complete description of this work is currently in preparation and will be submitted to MNRAS.

This system bears some resemblance to the Be/X-ray binary system LSI +61°303. There, the system contains a B0 Ve star and a neutron star in an eccentric, 26 day orbit. Periodic non-thermal radio emission is detected from the system (Taylor & Gregory 1982) and X-ray outbursts are also detected (Taylor et al. 1996). LSI +61°303 is likely to be associated with a COS B γ-ray source. Unlike other high-mass X-ray binary systems, LSI +61°303 shows only low-level X-ray emission ($L_x \sim 10^{33}$ erg/s) and little high-energy radiation both of which indicate that accretion onto the surface of the neutron star does not occur. Two competing models for the radio emission exist. Maraschi & Treves (1981) explain the radio emission as synchrotron emission from the boundary between the (young) neutron star wind and the Be star's wind. Taylor & Gregory (1984) however, prefer a model in which super-accretion from the disk of the Be star onto the pulsar occurs for a short period after which the material is blow off in expanding jets which are then the origin of the radio emission. Paredes et al. (1991) take this model one step further and show that continuous ejection of particles over a period of a few days, followed by adiabatic expansion provides the best explanation of the observed radio light curves.

A study of the scintillation properties of PSR B1259–63 is currently underway. Scintillation has the potential to tell us a great deal about the environment in which the pulsar lives. One of the many peculiarities of this pulsar is its high dispersion measure of 147 cm^{-3}pc given its (optically derived) distance of 1.5 kpc. A possible explanation is that the whole system is surrounded by a large (few parsecs) Strömgren sphere or H II region. Both the refractive and diffractive scintillation parameters may allow a verification of this. The second point is that as the pulsar approaches periastron, the scintillation parameters must necessarily change. We know already that pulse broadening occurs as early as $\mathcal{T}$–40 at low frequencies; the decorrelation bandwidth must decrease accordingly. By monitoring this bandwidth as periastron approaches, we can measure the scatter-broadening time long before it becomes visible in the pulse profile.

Observations obtained on 1994 Feb 22 proved to be highly interesting. This was a 30 minute observation at 20-cm over a bandwidth of 320 MHz. Figure 3 shows the pulse profile averaged over 3 minutes in time and 40 MHz of bandwidth. Recall that the average pulse profile shows a double peak, with approximately equal power in each component (see e.g. the figures in Manchester & Johnston 1995). In Figure 3 we see changes in the profiles on very short (minute) timescales and over narrow (100 MHz) bandwidths. As far as I am aware such effects have not been observed in any other pulsar. Mode changes which occur regularly in a number of pulsars are a possible explanation, but mode-changing is generally thought to be a wide-band phenomenon. The other possible explanation is of a strange refractive scintillation event. However this

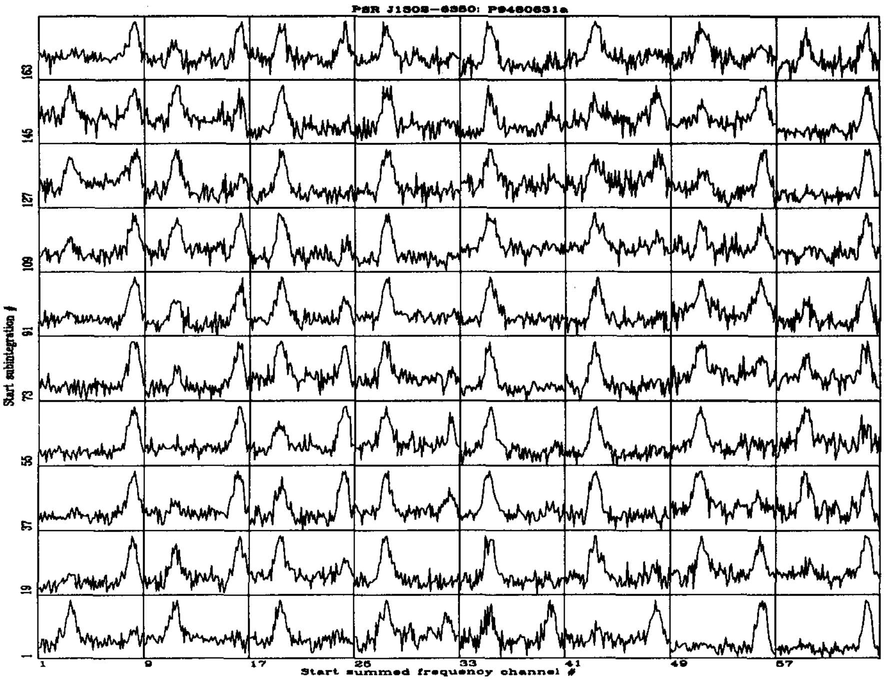

Figure 3. Structure in the pulse profile of PSR B1259–63

explanation is also not without its problems. The almost perfect anti-correlation between the power in the two pulses would imply a very special geometry. The possibilty that this is some sort of an instrumental effect is also not yet ruled out. Much of the data we have on PSR B1259–63 is currently being re-analysed to investigate which of the above possibilities is correct.

Optical observations of the Balmer emission series of the Be star were made with the Anglo-Australia Telescope over 4 nights around periastron. No changes were apparent in the emission line widths; it seems as if the optical disk of the Be star remains unaware of the passage of the pulsar! Work is still underway to look at the fine details, including the possibility of measuring the radial motion of the Be star.

Recent new radio results include the detection of the pulsar at 13 GHz in 1995 October. Although the signal-to-noise is low, enough integration time has been obtained to allow us to obtain good quality polarization data. An attempt was made to observe the pulsar at 23 GHz, but in less than optimum weather conditions we failed to detect it. However it appears as if the flat spectral index continues at least up to 13 GHz.

Timing for this pulsar continues on a roughly 3 weekly basis. It is now apparent that the ephemeris provided in Manchester et al. (1995) is no longer correctly predicting the times-of-arrival of the pulses even with the period jump (spin-down) at periastron. It seems that no combination of Keplerian and post-Keplerian parameters can solve the timing of this pulsar. In this regard, parallels with the binary pulsar in the SMC, PSR J0045–7319, can be made. That system consists of a ~1 second pulsar in a ~50 day orbit around a ~10 $M_\odot$ B star (Kaspi et al. 1994, Bell et al. 1995). This system is 'cleaner' than the PSR B1259–63 system in that there are no pulse eclipses, no dispersion measure changes and of course, the orbital period is twenty times shorter which, in principle should allow a good determination of the orbital parameters. However, in this system as in PSR B1259–63, the simple Keplerian parameters are not sufficient to determine the times-of-arrival of the pulses. Lai et al. (1995) proposed that the spin of the B star (in fact its quadrupole moment) influences the orbital parameters and this has been verified observationally by Kaspi (1996). This effect however, does not appear to be happening at a measurable level in the PSR B1259–63 system, at least not that we can determine with less than two orbits of data. Work is currently underway to try and solve the timing data.

5. The Next Periastron

Periastron comes around again in 1997 June. A campaign of radio continuum observations has already started so that good data can be obtained in the lead-up to periastron. Will we see optical depth effects in this data prior to periastron? Will we again see a peak in the radio continuum data at $\mathcal{T}$+30? In the pulsed regime, observations at 13 GHz should allow us to probe the pulsar closer to periastron than was possible previously. Both the free-free absorption effects and the scatter broadening should be greatly reduced compared to even the 8 GHz data. With clear winter weather it may be possible to track the pulsar at 23 GHz also. Again we need to see if the results are repeatable from the 1994 periastron passage, i.e. will the dispersion measure rise be the same? Will the rotation measure variations be seen post periastron? Observations during the last periastron passage missed the pulsar entering the depolarization state (sometime around $\mathcal{T}$–100) and also left the uncertainty in coming out of eclipse rather large (~ 7 days). Hopefully this time around we can determine those parameters somewhat better. Timing of the pulsar continues and as we get a few more periastron passages we should be better able to sort out the effects the close encounter with the Be star is having on the pulsar's orbital parameters. Further high energy observations of the system are also planned.

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