Spectrum evolution in binary pulsar B1259−63/LS 2883 Be star and gigahertz-peaked spectra

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ABSTRACT
We study the radio spectrum of PSR B1259−63 orbiting around the Be star LS 2883 and show that the shape of the spectrum depends on the orbital phase. At frequencies below 3 GHz, PSR B1259−63 flux densities are lower when measured near the periastron passage than those measured far from periastron. We suggest that an interaction of the radio waves with the Be star environment accounts for this effect. While it is quite natural to explain the pulsar eclipse by the presence of an equatorial disc around LS 2883, this disc alone cannot be responsible for the observed spectral evolution of PSR B1259−63 and we, therefore, propose a qualitative model which explains this evolution. We consider two mechanisms that might influence the observed radio emission: free–free absorption and cyclotron resonance. We believe that this binary system can hold the clue to the understanding of gigahertz-peaked spectra of pulsars.

Key words: radiation mechanisms: non-thermal – pulsars: general – pulsars: individual: B1259−63 – stars: winds, outflows.

1 INTRODUCTION
Generally, the observed radio spectra of most pulsars can be modelled as a power law with negative spectral indices of about −1.8 (Maron et al. 2000). If a pulsar can be observed at frequencies low enough (i.e. 100–600 MHz), it may also show a low-frequency turnover in its spectrum (Sieber 1973; Malofeev et al. 1994).

On the other hand, Lorimer et al. (1995) mentioned three pulsars which have positive spectral indices in the frequency range 300–1600 MHz. Later, Maron et al. (2000) re-examined spectra of these pulsars taking into account the data obtained at higher frequencies (above 1.6 GHz) and consequently were the first to demonstrate a possible existence of spectra with turnover at high frequencies, about 1 GHz. Motivated by this unusual spectral feature, Kijak & Maron (2004) selected several pulsars which showed a decreasing flux density at frequencies below 1 GHz. Kijak, Gupta & Krzeszowski (2007) used multifrequency flux measurements for these candidate pulsars and presented the first direct evidence of a high-frequency turnover. A frequency at which such a spectrum shows the maximum flux was called the peak frequency.

Based on their observations of these pulsars, Kijak et al. (2011) provided a definite evidence for a new type of pulsar radio spectra. These spectra show the maximum flux above 1 GHz, while at higher frequencies the spectra look like a typical pulsar spectrum. At lower frequencies (below 1 GHz), the observed flux decreases, showing a positive spectral index. They called these objects the gigahertz-peaked spectra (GPS) pulsars.

Kijak et al. (2011) also indicated that the GPS pulsars are relatively young objects, and they usually adjoin such interesting environments as H II regions or compact pulsar wind nebulae. Additionally, they seem to be coincident with the known but sometimes unidentified X-ray sources from third EGRET Catalogue or HESS observations. We can assume that the GPS appearance owes to the environmental conditions around the neutron stars rather than to the radio emission mechanism. The issue of our interest PSR B1259−63 was also inscribed by Lorimer et al. (1995) in the list of pulsars with positive spectral indices. Therefore, B1259−63 seems a natural candidate to be classified as the GPS pulsar. This pulsar was discovered by Johnston et al. (1992) in 1990 during a large-scale high-frequency (1.5 GHz) survey of the Galactic plane. It is important to mention that PSR B1259−63 is the only known radio pulsar orbiting a main-sequence Be star.

PSR B1259−63 has a short period of 48 ms and a characteristic age of 330 kyr. Its average dispersion measure (DM) is about 147 pc cm$^{-3}$ and the corresponding distance is about 2.75 kpc. The companion star LS 2883 is a 10-mag massive Be star with a mass of about 10 $M_{\odot}$ and a radius of 6 $R_{\odot}$. Let us note that Be stars are generally believed to have a hot tenuous polar wind and a cooler high-density equatorial disc. Johnston et al. (1994) and Melatos, Johnston & Melrose (1995) suggested the presence of the disc around LS 2883. Its density is quite high near the star and falls...
analysed the spectra using a function, using the data of flux measurements with errors for several GPS pulsars (Kuzmin & Losovsky 2001) for pulsar spectra with turnover at low frequencies. The same fitting method. This method was previously used by Kuzmin & Losovsky (1997, 2001 and 2004) and present detailed study of the pulsar B1259−63 radio flux measured during three periastron passages (1997, 2000 and 2004). Three black dots represent the spectral evolution in PSR B1259−63 obtained for three different orbital epochs (see Fig. 2). The obtained values of spectral indices differ significantly from the typical value of about −1.8 (Maron et al. 2000). However, Fig. 2 shows that this approximation is apparently inaccurate as the spectra clearly show the peaked frequency for the corresponding periastron passages (see Fig. 1 for comparison). Therefore, we have decided to study variation of the observed radio flux with orbital phases.

Using the same data base (1997, 2000 and 2004), we have calculated an average flux density for four given frequencies and for each chosen interval of orbital phases. Fig. 3 shows the spectra for various orbital phase ranges, determined by the chosen days prior to or past the periastron passage. It is clear that the flux at the given frequency apparently changes with orbital phases. When the pulsar is close to periastron, the flux generally decreases at all observed frequencies, but its drastic decrease is observed at the lowest frequency. The spectrum for the furthest orbital epoch during which the pulsar was observed so far (i.e. from 113 to 186 d past periastron; see the green thickened segment in Fig. 4, bottom panel) is consistent with a typical pulsar spectrum described by a power-law function (see Fig. 3c and Fig. 4 left-hand panel). On the other hand, the spectral index for this orbital epoch is of about −0.8 which is

Table 1. The results of our spectral fits to the known GPS pulsars. The values of peak frequencies $\nu_p$ are taken from Kijak et al. (2011). $\nu_p$ is estimated using different spectral fit methods (see text for details). In the first column (PSR), numbers correspond to the following pulsars B1054−62, J1809−1917, B1822−14, B1823−13 and B1828−11 consequently.

| PSR    | $a$    | $b$    | $c$    | $\chi^2$ | $\nu_p$ | $\nu^K_p$ |
|--------|--------|--------|--------|----------|--------|----------|
| 1      | −7.28 ± 1.98 | −1.95 ± 0.50 | 1.94 ± 0.07 | 4.40 | 1.0 | 0.73 |
| 2      | −3.96 ± 1.14 | 2.80 ± 0.84 | −0.10 ± 0.09 | 2.91 | 1.7 | 2.25 |
| 3      | −1.30 ± 0.29 | 0.40 ± 0.20 | 0.41 ± 0.03 | 1.59 | 1.4 | 1.43 |
| 4      | −1.18 ± 0.22 | 0.52 ± 0.17 | 0.56 ± 0.04 | 2.35 | 1.6 | 1.66 |
| 5      | −2.09 ± 0.24 | −0.55 ± 0.11 | 0.12 ± 0.03 | 1.69 | 1.2 | 0.74 |

The spectra of five known GPS pulsars. The flux measurements are taken from Kijak et al. (2007, 2011), and the curves represent our fits to the data points (see Table 1).

Figure 1. The average spectra of PSR B1259−63 obtained for three different periastron passages (1997, 2000 and 2004). Three black dots represent the flux measurements obtained in 1993 by Manchester & Johnston (1995).
at 2.6 GHz based on a power-law fitting of two data points at higher frequencies (Fig. 3, panel a).

The small (much less than unity) values of the reduced $\chi^2$ in Table 2 are caused by rather large uncertainties in the flux measurements for four orbital epochs (see Fig. 3 for comparison). Let us note that $\chi^2$ is especially small (of about 0.01) for $+16:20$ and $+21:24$ epochs when the relative uncertainties of the measured flux are quite large (see Fig. 3b). On the other hand, in the case of epochs when the uncertainties (for all frequencies) are relatively small (see the blue filled dots in Fig. 3a and the blue empty diamonds in Fig. 3c), the value of $\chi^2$ is close to unity. We hope to reduce the uncertainties significantly by gathering more flux measurements during these orbital epochs.

To clarify the spectrum evolution, we have presented the corresponding orbital epochs in the bottom panel of Fig. 4. Our analysis shows that the shape of the PSR B1259—63 spectrum depends on the orbital phase and therefore it definitely undergoes evolution. It should be underlined that the peak frequency also depends on the pulsar orbital phase. Comparing Figs 1 and 4 (left- and right-hand panels), we can conclude that the spectra of B1259—63 resemble those of the GPS pulsars. Moreover, we can see that the shapes of the B1259—63 spectrum at different orbital phase intervals mimic those of various GPS.

4 DISCUSSION

Multiwavelength observations showed that some pulsars with turnover in the spectra at high frequencies have very interesting environments. For example, PSR B1054—62 lies behind or within a dense H II region (Koribalski et al. 1995), while PSR B1823—13 surroundings appear to show some peculiar properties in radio (Gaensler et al. 2003), as well as in X-ray observations (Pavlov, Kargaltsev & Brisken 2008), which may indicate the existence of a compact pulsar wind nebula. The same holds for the GPS pulsar J1809—1917 (Kargaltsev & Pavlov 2007). This could suggest that the phenomenon of the turnover at high frequencies is associated with environmental conditions around the neutron stars rather than with the radio emission mechanism. Because of more or less stable environmental conditions around the GPS pulsars, the shapes of their spectra do not vary on observable time-scales. However, in the case of B1259—63, the pulsar environment considerably changes due to high orbital eccentricity while it goes through various orbital phases. The distance of the pulsar from the Be star varies from 4.8 au in apastron to 0.34 au in periastron (by a factor of 14). Be stars have a strong stellar wind and possibly a strong magnetic field, and both the disc density and the magnetic field decrease as the distance from the star increases. Thus, it is natural to expect that the inhomogeneous environment alters the spectrum of B1259—63 in different ways.

At present, it is difficult to construct a detailed theory of the spectrum evolution as we lack observational data especially near apastron (see Fig. 4). These data must be important because the pulsar spectrum is the least affected by the environment near apastron, and this spectrum could be used as a reference spectrum. However, from the available limited observations, we can still deduce general conclusions about the main factors that influence variations of the observed spectra.

Generally, both the hot stellar wind (by means of thermal absorption) and the magnetic field may provide absorption at low frequencies (Sieber 1973; Khechinashvili & Melikidze 1997; Khechinashvili, Melikidze & Gil 2000). While the eclipse itself can be naturally explained by free–free absorption in the stellar disc...
The sign of the GPS feature first appears as early as about 60 days prior to periastron, and it is still observed during at least 90 days after periastron. It is clear that the polar disc cannot extend that far. It seems that the polar wind is the only factor that can affect the spectrum of the pulsar. Preliminary estimations show that free-free absorption due to the stellar wind can be responsible for this effect before the eclipse as well as after it (see Fig. 4). The optical depth of free-free absorption can be expressed as (Rybicki & Lightman 1979)

\[ \tau_{ff} = 0.4 \times T_3^{3/2} \nu_{GHz} \int n_e^2 dl_{au}, \]

where \( n_e \) is the electron density in \( \text{cm}^{-3} \), \( T_3 \) is the temperature in \( 10^3 \text{K} \), \( \nu_{GHz} \) is the frequency in GHz and \( l_{au} \) is the distance in au.

Table 2. The results of our spectral fits to the PSR B1259–63 flux densities, averaged over the given orbital epochs, determined by the chosen days prior to or past the periastron passage (see also Figs 3 and 4). There are no errors in the fit for the orbital phase corresponding to day \(-18\), because in this degenerate case, all errors are zero by definition (numbers of data points and parameters are the same, see Fig. 2a).

| Days | \( a \) | \( b \) | \( c \) | \( \chi^2 \) | \( \nu_p \) (GHz) |
|------|-------|-------|-------|----------|----------------|
| \(-60: -40\) | \(-1.70 \pm 0.46\) | \(1.38 \pm 0.54\) | \(0.27 \pm 0.16\) | \(0.74\) | \(2.54\) |
| \(-24: -21\) | \(-2.10 \pm 0.22\) | \(1.76 \pm 0.23\) | \(0.10 \pm 0.05\) | \(0.10\) | \(2.62\) |
| \(-18\) | \(-2.77\) | \(2.84\) | \(-0.89\) | \(3.26\) |
| \(16: 20\) | \(-4.59 \pm 0.03\) | \(4.84 \pm 0.02\) | \(-0.71 \pm 0.01\) | \(0.01\) | \(3.37\) |
| \(21: 24\) | \(-1.72 \pm 0.05\) | \(1.51 \pm 0.06\) | \(0.31 \pm 0.01\) | \(0.01\) | \(2.75\) |
| \(27: 55\) | \(-0.88 \pm 0.35\) | \(0.34 \pm 0.38\) | \(0.55 \pm 0.09\) | \(1.49\) | \(1.57\) |
| \(63: 94\) | \(-1.48 \pm 0.10\) | \(0.55 \pm 0.11\) | \(0.56 \pm 0.03\) | \(0.04\) | \(1.53\) |

The exact value of \( \tau_{ff} \) depends on the geometry of the binary system as well as on the density and temperature of the stellar wind. One can note that the shapes of spectra are not fully symmetric with respect to the periastron point. To some extent, the spectrum plotted by the green curve in the left-hand panel of Fig. 4 can be used as a reference spectrum. This spectrum is obtained while the pulsar is in the orbital epoch designated by the thickened green segment in the bottom panel of Fig. 4. It is the furthest orbital phase at which the pulsar is observed so far, but the spectrum still does not look exactly like a typical pulsar spectrum. Indeed, the waves emitted before the eclipse travel longer distance through the stellar wind; thus, they are stronger attenuated by free-free absorption, than the waves emitted after the eclipse (see Fig. 4). This is in agreement with DM and RM variations presented by Melatos et al. (1995). The most significant change of the spectrum shape occurs during a couple of days just before the eclipse as well as immediately afterwards (the thickened black segments in the bottom panel, Fig. 4). One can see that the difference between the red and black curves on the left-hand panel as well as on the right-hand panel of Fig. 4 is much more noticeable than the difference between the red and blue curves in the same panels.

In addition, we have shown (see Table 2) that the peak frequency (as it follows from the fitting procedure) also depends on the orbital phase. This effect suggests that the peak frequency varies with the changes of the pulsar environment. We argue that such behaviour can be explained by the radio-wave absorption in the magnetic field associated with the disc. In this case, the radio waves should pass through the “magnetosphere” of the disc. Magnetic field lines just above the stellar disc are populated by the electrons and positrons of the pulsar wind. Such kind of environment affects the pulsar spectra in the same way as it does in the case of those eclipsing pulsars whose eclipse duration depends on the observed frequency.
The frequency of waves which are affected by the cyclotron dumping can be expressed in the following way:

$$v_{\text{GHz}} \approx 2.8 \times 10^{-3} \frac{B_0}{\gamma(1 - \cos \theta)},$$

where $B_0$ is the value of the magnetic field associated with the disc, $\gamma$ is the Lorentz factor of the secondary electron–positron pairs of the pulsar wind and $\theta$ is the angle between the wave vector and magnetic field direction.

Finally, let us underline that the PSR B1259–63/LS 2883 binary system can hold the clue to the understanding of the GPS pulsars. As we mentioned in Section 3, the spectrum of B1259–63 at the various orbital phases mimics that of the pulsars with GPS. Thus, we can conclude that the GPS feature should be caused by some external factors rather than by the emission mechanism. On the other hand, the GPS pulsars are isolated radio pulsars and therefore, we cannot draw a direct analogy between the PSR B1259–63/LS 2883 system and the GPS pulsars, as the latter have no companion stars and/or discs. But the GPS pulsars apparently are surrounded by some kind of environment that can affect the spectra of those pulsars in the same way as the stellar wind affects the B1259–63 spectrum. As an example, we can take the cases of B1823–13, which is surrounded by a compact pulsar wind nebula (Pavlov et al. 2011), or PSR B1054–62, which lies behind or within a dense H II region (Koribalski et al. 1995). All GPS pulsars have relatively high DMs that, in some cases, are too large to be accounted for by the Galactic electron density, and thus, we can speculate that there is a quite high particle density in the vicinity of these pulsars (see also Kijak et al. 2011). As soon as all the necessary observational data are available, we will model the physical conditions which cause the evolution of the B1259–63 spectrum. Consequently, we will be able to estimate the particle density, temperature and magnetic field that are necessary to form the spectra shown in Fig. 4. We believe that the same physical processes (i.e. free–free and/or cyclotron absorption) are responsible for both B1259–63 and the GPS pulsars spectra; therefore, we will be able to estimate characteristic values for the GPS pulsar surroundings in a similar way. The only difference could be an invariable shape of the GPS, in contrast to the B1259–63 spectrum, which undergoes evolution due to orbital motion.

5 SUMMARY

Finally, we can conclude that the B1259–63 spectrum undergoes evolution while the pulsar orbits around the Be star LS 2883. The most significant change of the spectrum shape occurs during a couple of days just before the eclipse as well as immediately afterwards (the thickened black segments in the bottom panel of Fig. 4). We argue that the observed variation of the spectra is caused by a combination of two effects: the free–free absorption in the stellar wind and the cyclotron resonance in the magnetic field. This field is associated with the disc and is infused by the relativistic particles of the pulsar wind. Having noted the apparent resemblance between the B1259–63 spectrum and the GPS, we suggest that the same mechanisms should be responsible for both cases. Thus, the case of B1259–63 can be treated as a key factor to explain the GPS phenomenon observed for the solitary pulsars with interesting environments. Therefore, the binary system B1259–63/LS 2883 seems to be an important astrophysical laboratory to study the interaction between pulsar and their environments, such as bow shocks and pulsar wind nebulae (Pavlov et al. 2011).

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