The radio pulsars spectra with turnovers around 1 GHz

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In this short overview we summarize our knowledge of the pulsars showing gigahertz-peaked spectra characteristics. Especially, we focus on two objects: PSR J1740+1000 and PSR B1800−21.

1 Introduction

Most of the pulsar spectra can be described by a simple power law function, with the population average spectral index close to −1.6 (Lorimer et al., 1995; Jankowski et al., 2017). However, spectra of some pulsars show a different behaviour. Among them are the spectra with turnovers around 1 GHz. The first direct evidence of the turnover in the pulsar spectrum at high frequency was published by Kijak et al. (2007). Kijak et al. (2011a) named them gigahertz-peaked spectra (GPS) and proposed to explain their nature using the free-free thermal absorption model. Later, Lewandowski et al. (2015) and Rajwade et al. (2016) applied this model to study the GPS behaviour in more details.

Recently, Jankowski et al. (2017) classified the 349 spectra of radio pulsars. They showed that 79.1% of pulsar spectra are best described by the simple power law model, 10% by log-parabolic spectrum and 7% by broken power law (i.e. two power law functions with different spectral indexes). In their data set 11 pulsars spectra were classified as GPS (with 3 newly discovered). Taking that into account we know around 30 GPS pulsars up to date. 18 of them are associated with either a supernova remnant (SNR), a pulsar wind nebula (PWN), an H II region or an unidentified source from the HESS gamma-ray catalogue. This fact strengthens the hypothesis that the apparent low frequency flux density deficit is caused by some external mechanism (see Kijak et al., 2011a). One of the possible external mechanisms is the free-free thermal absorption.

In this short overview we summarize our knowledge of the known GPS pulsars. In section 2 we describe the free-free thermal absorption model. In section 3 we discuss the GPS phenomemon in general. In section 4 we focus on two peculiar objects. The first is the PSR B1800−21 - a Vela-like GPS pulsar with a variable radio spectrum. The second is the PSR J1740+1000 - a pulsar that shows high frequency turnover based on our most recent observations using the Giant Meterwave Radio Telescope (GMRT) and the Green Bank Telescope (GBT).

2 The free-free thermal absorption model

The free-free thermal absorption was proposed by Sieber (1973) to explain the low frequency turnover around 100 MHz seen in some selected pulsars known at the time.

The amount of free-free absorption depends on the electron temperature, density and the physical thickness of the absorber, and on the observed frequency (see Rybicki & Lightman, 1979; Wilson et al., 2009, for details). Hence the strongest absorption will be caused by the dense, cold but ionized regions. In our approach we assumed that the intrinsic pulsar spectrum can be expressed by a single power law function: $I_\nu = A(\nu/\nu_0)^\alpha$. Using an approximate formula for thermal free-free absorption we get the estimated flux S_ν at any frequency ν as (Rybicki & Lightman, 1979; Wilson et al., 2009):

$$S_\nu = A\left(\frac{\nu}{10\ \mathrm{GHz}}\right)^\alpha e^{-B\nu^{-2.1}}, \tag{1}$$

where A is the pulsar intrinsic flux at 10 GHz, α is the pulsar intrinsic spectral index and $B = 0.08235 \times T_\mathrm{e}^{-1.35}$ EM (emission measure); T_e is the electron temperature.

3 GPS pulsars

The PSR B1259−63 spectrum evolution was a key factor to define physical mechanisms which potentially are responsible for the GPS phenomenon (see Kijak et al., 2011b, 2014; Dembska et al., 2015, for details). PSR B1259−63 formed a binary system with the Be star. In this system the pulsar spectra were observed at different epochs with the pulsar at different locations with respect to the Be star. When the pulsar is far away from the star its spectrum looks like a typical *power-law*, while closer to the periastron passage it shows a turnover. In this case the absorption can happen either in the stellar wind or in the disc around the Be star. The only type of absorption that could work in such environment is the free-free thermal absorption on the electrons of the stellar wind or disc.

In case of isolated pulsars, one of the possible absorbers is the bow-shock pulsar wind nebula. Lewandowski et al. (2015) studied this case in detail. They showed that the appearance of the GPS depends on the geometry of the line-of-sight. If we are observing PWN from its front then its physical thickness is very small and we should expect to see a typical spectrum of the power-law type. But if we are observing pulsar from behind, then the physical thickness is much larger and thus the absorption may be big enough to cause a turnover. Therefore, not all pulsars with the bow-shock PWNe will exhibit turnovers. However, this model will not work in case of the young spherical symmetric PWNe, because such nebulae are too small and too hot to fulfill the physical conditions necessary for free-free thermal absorption.

There are three radiomagnetars among known GPS pulsars: J1550-5418, J1622-4950 and J1745-2900 (see Kijak et al., 2013; Lewandowski et al., 2015, for details). The last one, also called the Sagittarius A* radiomagnetar, is located near the supermassive black hole in the center of our Galaxy. Shannon & Johnston (2013) have published the spectra of J1745-2900 that showed the spectral change after the magnetar outburst. The PSR J1745-2900 spectrum obtained one week after the magnetar outburst (from the first of May) had turnover at high frequency. The spectrum from a month later looked almost as typical power-law. Lewandowski et al. (2015) adapted the free-free thermal absorption model to explain the spectral evolution observed in this case. They included two components in the model: first was the absorption caused by the expanding ejecta, and second was a constant external absorption, that was probably caused by the partially ionized cold molecular

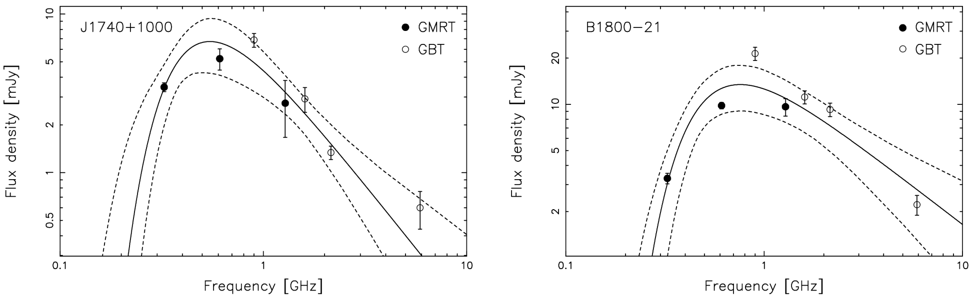

Fig. 1: The pulsars observed spectra (points) with fitted free-free thermal absorption model (solid line). The dashed lines correspond to 1σ envelope. The fitted parameters are presented in the Tab. 1.

cloud. This model explained why shortly after the outburst pulsar was not visible at radio frequencies, and why it became visible at lower frequencies only a few weeks after the outburst.

4 Two special cases

In this section we will focus on two sources: J1740+1000 – a young pulsar far from the galactic plane, and B1800−21 – a Vela-like pulsar near W30 Galactic complex. The low frequency spectra of these two sources have been studied in the past (Kijak et al., 2011a; Dembska et al., 2014; Bilous et al., 2016; Basu et al., 2016). In case of J1740+1000 there was confusion if the spectrum actually shows a turnover. On the other hand the spectral turnover of B1800−21 showed variations at multiple observing epochs. Here we present results of a multi-frequency, contemporaneous observations that characterise the spectral nature of these two sources.

The pulsars J1740+1000 and B1800−21 were observed using two radiotelescopes: the GMRT located near Pune in India and the GBT located in USA. Using the GMRT, we observed both pulsars at three frequencies: 325 MHz, 610 MHz and 1200 MHz. For each frequency we conducted three observational sessions separated by at least one week to account for the possible influence of interstellar scintillations on our flux density measurements. Observations were held between August 1, 2016 and September 3, 2016. The GBT observations covered four frequencies: 900 MHz, 1600 MHz, 2150 MHz and 5900 MHz. Observations were conducted between December 12, 2016 and January 17, 2017.

We used the free-free thermal absorption model to fit the observed spectra. The fitted parameters were: A – the scaling parameter of the intrinsic pulsar flux, B – the parameter that describes the frequency-independent part of the optical depth and α – the spectral index of the intrinsic pulsar flux (see Eq. 1). The results of our fits are presented in Fig. 1 and in Tab. 1. Following Basu et al. (2016) and Kijak et al. (2017) we used the pulsar's dispersion measure (DM) to get some constraints on the electron density and temperature of the absorber. We considered three cases: a dense supernova remnant filament (with the size equal 0.1 pc), the pulsar wind nebula (with the size equal to 1.0 pc) and a cold H II region (with the size equal 10.0 pc) as the possible absorbing media. We estimated constraints on the different physical parameters of the three potential absorbing media as showed in the Tab. 2.

Table 1: The fitting parameters for the GPS using the thermal absorption model.

A	B	α	χ^2	ν_p GHz
		J1740+1000		
$0.132^{+0.275}_{-0.094}$	$0.22^{+0.11}_{-0.12}$	$-1.61^{+0.66}_{-0.63}$	4.27	0.55
		B1800−21		
$1.65^{+1.52}_{-1.05}$	$0.26^{+0.15}_{-0.10}$	$-1.00^{+0.39}_{-0.49}$	8.94	0.76

Table 2: Constraints on the physical parameters of the absorbing medium: size, electron density, emission measure and electron temperature.

Size pc	n_e cm^{-3}	EM 10^2 pc cm^{-6}	T_e K
	J1740+1000		
0.1	119.48 ± 0.13	14.277 ± 0.030	106^{+42}_{-45}
1.0	11.948 ± 0.013	1.4277 ± 0.0030	$19.3^{+7.6}_{-8.2}$
10.0	1.1948 ± 0.0013	0.14277 ± 0.00030	$3.5^{+1.4}_{-1.5}$
	B1800−21		
0.1	1169.95 ± 0.25	1368.78 ± 0.58	2680^{+1100}_{-770}
1.0	116.995 ± 0.025	136.878 ± 0.058	488^{+199}_{-140}
10.0	11.6995 ± 0.0025	13.6878 ± 0.0058	89^{+36}_{-25}

5 Discussion and conclusions

PSR J1740+1000 is a young pulsar located at a relatively large distance from the galactic plane and thus has a very low value of DM = 24 pc cm^{-3} (McLaughlin et al., 2000). It is also associated with an X-ray PWN with very extended tail (see Kargaltsev et al., 2008; Kargaltsev & Pavlov, 2010). Shortly after its discovery, McLaughlin et al. (2002) reported that the flux density measurements of the source were affected by very strong diffractive scintillations in the L-Band frequency range. That problem made the interpretation of its spectrum very difficult in the past. The ambiguity of the interpretation of the spectrum was further increased by Bilous et al. (2016), who added the 150 MHz flux density measurement from LOFAR observations, which allowed them to propose a power-law interpretation of J1740+1000 spectrum. However, they made a single 30-minutes observation and the profile upon which the measurement was based had very low signal-to-noise ratio. For these reasons, we found the reported flux density value as doubtful.

A spectral model based exclusively on our latest measurements supports the GPS interpretation (see Fig. 1). We want to point out, that almost all previous measurements from L-Band were sparsely observed with a large intervals between them. In our studies, we have used multiple, equally spaced observations and estimated their average value, which should serve as a better measurements for the flux at L-Band. The most probable absorber is a partially ionized small molecular cloud in front of the pulsar which is supported by the electron density, n_e, value derived from DM for the absorber thickness of 0.1 pc (i.e. n_e=119 cm^{-3}). The derived electron density value is consistent with the electron density in front of the shock that was estimated from optical observations of atomic emission lines to be of the order of $50-100$ cm^{-3}, in case of some of the bow-shock PWNe (Hester & Kulkarni, 1989; Li et al., 2005).

Looking at the physical constraints presented in the Tab. 2 we can rule out an H II region as a possible absorber, because the estimated temperature is unphysical for this type of structure. On the similar grounds, absorption caused by the electrons located inside the bow-shock PWN is doubtful, but not impossible. In the case of PSR J1740+1000 we are probably looking at the PWN from its side where the thermal absorption, if present, should be relatively weak (see Lewandowski et al., 2015, for explanation).

PSR B1800−21 is a Vela-like pulsar located in a very peculiar environment called W30 Galactic complex, which is a supernova remnant with a large number of H II regions around it (Kassim & Weiler, 1990). Basu et al. (2016) conducted a detailed study of the spectral changes of this object. They have shown that the turnover in the spectrum of B1800−21 was shifted from lower to higher frequency over a time scale of a few years. They explained such transition by assuming an additional absorption that happened during that time. The most probable absorber in this case is a small and dense supernova remnant filament that crossed our line of sight. Our latest observations confirmed that the turnover frequency came back to the original value (i.e prior to the 2012 change). This would suggest that the spectral change observed between 2012 and 2014 was indeed a rare event, rather than a continuous variation, which further supports the filament crossing the line of sight as the most realistic interpretation.

Today we know around 30 GPS pulsars (including B1259−63, J1740+1000 and 3 radiomagnetars) and there is considerable evidence that an external mechanism is responsible for the spectral turnovers. The most compelling possibility is the thermal free-free absorption taking place in pulsar environments (see Lewandowski et al., 2015; Rajwade et al., 2016; Basu et al., 2016; Kijak et al., 2017).

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