

Pulsars with gigahertz-peaked spectra (Research Note)

J. Kijak¹, W. Lewandowski¹, O. Maron¹, Y. Gupta², and A. Jessner³

¹ Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265 Zielona Góra, Poland
e-mail: jki.jak@astro.ia.uz.zgora.pl

² National Centre for Radio Astrophysics, TIFR, Pune University Campus, Pune, India

³ Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

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ABSTRACT

Aims. We investigate a high frequency turn-over effect in radio spectra for pulsars with positive or flat spectral index.

Methods. Using GMRT and Effelsberg observatory, we estimated the flux density to reconstruct pulsar spectra.

Results. We find objects that have a maximum flux in their spectrum above 1 GHz, whose emitted energy decreases below 1 GHz and whose spectral indices are positive at lower frequencies. Some pulsars with a turn-over in their spectrum at high frequencies are found to exist in very interesting environments. We call these objects gigahertz-peaked spectra pulsars.

Key words. pulsars: general – ISM: general

1. Introduction

Flux density measurements and the shapes of pulsar spectra are very important in understanding pulsar emission mechanism. The difficulties in obtaining a true pulsar spectrum are mainly due to the influence of interstellar scintillation, which causes variations in the measured flux. As stated by Stinebring et al. (2000), pulsars are nearly constant luminosity radio sources over time spans of between several days and 5 years, hence interstellar scintillations must always be taken into account when measuring the flux.

A typical pulsar spectrum has been modelled using either a simple power law with mean spectral index of -1.8 ± 0.2 or two power laws with spectral indices of -0.9 and -2.2 and a break frequency on average of 1.5 GHz (Maron et al. 2000, M00). For several pulsars a low frequency turn-over has been observed (Sieber 1973; Malofeev et al. 1994). The frequency at which this spectrum displays a *maximum flux* is called the *peak frequency* ν_{peak} , and occurs in the range ~ 100 to 600 MHz for most pulsars with turn-over spectra.

The shape of pulsar spectrum is independent of the pulsar profile evolution. The changes in pulsar profile over the observing frequency do not affect the shape of the spectrum and vice versa – the observed low frequency turn-over is not caused by any significant profile change at the particular frequency. There is no correlation between the profile type and the pulsar spectrum (M00). However, Löhmer et al. (2008) show that the spectrum of PSR B0144+59 has a “turn up” at 5 GHz to 10 GHz, which may be caused by its peculiar high-frequency profile evolution.

Lorimer et al. (1995, hereafter L95) show a positive spectral index for some pulsars between 400 MHz and 1600 MHz. By combining flux density measurements taken at frequencies above 1.4 GHz with published data, Kijak & Maron (2004) were able to identify several pulsars who possibly had a high frequency turn-over in the spectrum. In Kijak et al. (2007), the authors presented the first direct evidence of a turn-over in pulsar

radio spectra at high frequencies using the multifrequency flux density measurements of these candidate pulsars.

The spectra of the majority of known pulsars have yet to be acquired. If the pulsars with positive spectral index in the spectra below 1 GHz turn out to be a significant sub-group of the pulsar population, then we may need to re-evaluate (at least to some degree) the future low-frequency search strategies (for instruments such as LOFAR or SKA), otherwise we may overestimate the flux densities of these sources, hence overestimate the expected number of sources to be found in the future surveys.

In this paper, we present our observations and the information that we can derive from our pulsar radio spectra. These objects reach a *maximum flux* in their spectrum above 1 GHz and their energy decreases below 1 GHz, producing a positive spectral index at lower frequencies. We call these objects gigahertz-peaked spectra (GPS) pulsars. For ten new pulsars, we also estimated the spectral index and for an additional ten objects, we recalculated the spectral index after considering values in the ATNF Catalogue.

2. Observations and results

Knowing that pulsars with a turn-over around 1 GHz are relatively young (Kijak et al. 2007, hereafter KGK), we planned to search for the high frequency turn-over effect in some recently discovered young pulsars and selected candidates from previous work (Kijak & Maron 2004). Observations of these pulsars, using the GMRT and Effelsberg observatory helped us to study this effect.

The observations with Giant Metrewave Radio Telescope (GMRT) were conducted in January and February 2008 at two frequencies, 610 MHz and 1170 MHz, using 16 MHz bandwidth. We used the phased array mode with 0.512 ms sampling and 256 spectral channels across the band (Gupta et al. 2000). To estimate the mean flux density of the pulsars, we carried out regular calibration measurements of known continuum sources (e.g.

Table 1. Flux density measurements in GMRT and Effelsberg.

PSR	F_{610} (mJy)	F_{1170} (mJy)	F_{2640} (mJy)	F_{4850} (mJy)
J1740+1000	$6.1 \pm 2.7(4)$	$0.9 \pm 0.3(3)$	<0.5	<0.05
B1800-21			$7.60 \pm 0.50(2)$	
J1806-2125		$1.5 \pm 0.5(1)$	<0.6	<0.08
J1809-1917		$1.1 \pm 0.3(2)$	$2.30 \pm 0.30(2)$	$0.91 \pm 0.10(2)$
B1820-14			$0.26 \pm 0.09(1)$	
B1822-14	$2.0 \pm 0.3(4)^a$			
B1823-13			$3.60 \pm 0.10(2)$	
J1828-1101			$1.20 \pm 0.20(1)$	$0.09 \pm 0.05(2)$
B1828-11	$1.6 \pm 0.2(2)^a$		$0.40 \pm 0.10(2)$	$0.06 \pm 0.01(1)$
B1832-06		$3.5 \pm 0.6(1)^b$	$0.55 \pm 0.10(2)$	$0.09 \pm 0.05(2)$
J1835-1020	$5.8 \pm 1.7(1)$	$2.7 \pm 0.4(2)$	$0.88 \pm 0.09(2)$	$0.14 \pm 0.08(2)$
B1849+00		$5.5 \pm 1.5(1)^b$	$1.30 \pm 0.15(1)$	
J1857+0143	<0.8	$0.5 \pm 0.2(2)$	$0.19 \pm 0.06(3)$	$0.03 \pm 0.02(1)$
J1905+0616	$2.1 \pm 0.6(1)$	$0.4 \pm 0.1(2)$		
J1907+0918	$1.0 \pm 0.2(2)$	$0.2 \pm 0.06(3)$	$0.04 \pm 0.02(2)$	

Notes. The number of measurements at each frequency are given in parentheses. “<” denotes an upper limit. ^(a) GMRT 2005 and 2008; ^(b) GMRT 2005 (KGK).

1822-096). We observed nine pulsars in total intensity mode for most sources at several epochs (see Table 1). Some pulsars were not observed at the lower frequency as the expected scatter broadening was found to be comparable to or greater than the pulse period (see in details KGK). Integration times of the pulsars were between 20 and 30 min per source, depending on the expected flux density.

All observations at higher frequencies (2.6 GHz and 4.85 GHz, with 100 MHz and 500 MHz bandwidth, respectively) were made with the 100-m radio telescope of the Max-Planck Institute for Radioastronomy at Effelsberg. We used secondary focus receivers (with cooled HEMT amplifiers) providing LHC and RHC signals that were digitised and independently sampled every $P/1024$ s and synchronously folded with the topocentric pulse period P (Jessner 1996). We carried out our observation in June 2009. The typical integration time was about 30 min. To measure flux density, we carried out regular calibration measurements using an injected signal of a noise diode, which was compared to the flux density of known continuum sources (NGC 7027, 3C 273, 3C 286). We did not observe the sources at 8.35 GHz because of poor weather conditions.

None of the pulsars in our sample displays any signs of a profile evolution at low frequencies (see Figs. 1 and 2, discussion and KGK), that may have caused the flux densities to be underestimated. Interstellar scattering for all the pulsars at the lowest observing frequencies was found to be much less than pulse period so it shouldn’t affect our results either.

The flux measurements derived from the above observations are presented in Table 1, i.e. the flux density F_ν , the error in F_ν , and the number of measurements. The estimated uncertainties include contributions from both the calibration procedure and the pulse energy estimation.

3. Spectral index and gigahertz-peaked spectra

Using our results with data taken from literature (e.g. L95; M00; McLaughlin et al. 2002; Hobbs et al. 2004; KGK), we constructed spectra for the pulsars and investigated them by searching for those objects with *peak frequency* above 1 GHz. The results of our work are summarized in Table 2, and a graphical representation of the pulsar spectra can be found in Figs. 3–5.

Table 2 presents the derived spectral indices and additional basic parameters for the 20 pulsars that were investigated. The second column of the table, denoted α_{ATNF} , contains the

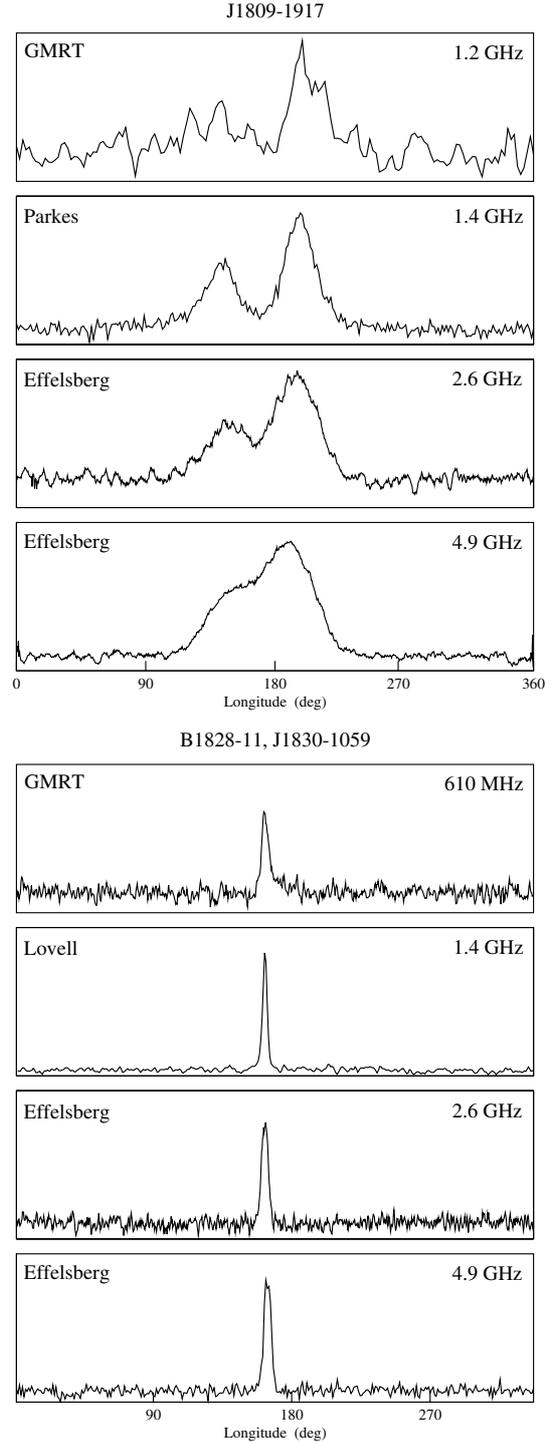


Fig. 1. Pulse profiles for PSR J1809-1917 and PSR B1828-11 showing no significant profile evolution with frequency (see discussion for details). Profiles were taken from our observations (610 MHz, 2.6, and 4.85 GHz), from EPN data base (1.4 GHz, see Lorimer et al. 1998 and Gould & Lyne 1998) and from the CSIRO Data Access Portal (<http://datanet.csiro.au/dap/>).

spectral indices of these sources taken from the ATNF¹ database (Manchester et al. 2005). We note that a majority of these cited spectral indices correspond to spectra much flatter than the usual pulsar spectra, one of the main reasons why these sources were

¹ <http://www.atnf.csiro.au/research/pulsar/psrcat/>

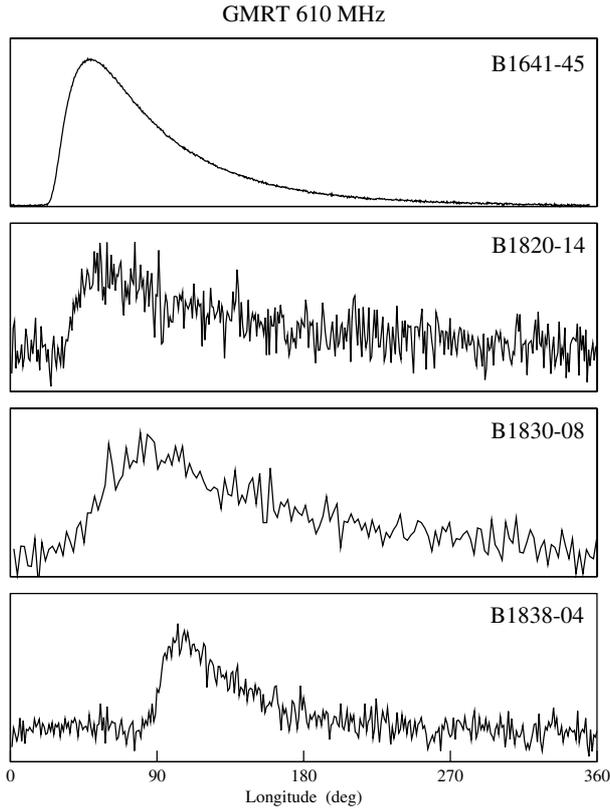


Fig. 2. Example profiles, from our observations at 610 MHz, showing significant pulse broadening. Three bottom panels show pulsars for which our flux measurements do not agree with previously published data. For details, see discussion in the text.

chosen. However, the next column of the table (α) indicates the spectral index of the investigated pulsars, which was derived using our observations, along with the previously published flux density data. For nine pulsars, this is the first estimate of their spectral index. For the remaining eleven sources, our values differ significantly from those published in the ATNF database, i.e., they are much closer to the average pulsar spectral index of -1.8 . The main reason for this difference is the much wider frequency range we used (see Col. 4 of the table).

For pulsars with a break in the spectrum – whether a turn-over, or a change from flat or nearly-flat to steep spectrum (classic broken-type spectra) – the spectral index α given in Col. 3 of the table denotes the slope of the spectrum in the high frequency part, i.e. after the break.

For the above-mentioned cases, we decided to use a simple double-power-law model to describe the pulsar spectrum, and find the value of the frequency of the spectral break where applicable. Column 5 of the table, denoted α_p , presents the value of the spectral index of the low-frequency part of the spectrum, while the subsequent two columns describe the frequency range that was used to find the slope, and the approximate value of the frequency at which the turn-over (or break) in the spectrum appears.

Two of the pulsars – B1054–62 and B1740–31 – were included in Table 2 only for completion reasons. Despite no new data have been gathered for them (all values were taken from KGK), we wished that the table include all the pulsars that, in our opinion, show a genuine turn-over above 600 MHz in their spectra.

The spectra of the remaining 18 sources can be found in Figs. 3 to 5. In these plots, full squares represent our Effelsberg

observations, full circles our GMRT data, empty circles are measurements from L95 and M00, diamonds indicate ATNF data (see references therein), and the star symbols are the measurements of Hobbs et al. (2004).

For clarity we distinguished four groups of pulsars in Table 2:

Group one consists of three sources that are regular steep spectra pulsars (see Fig. 3), which were included in our program because they were young and moderate- to high-DM objects that previously only had flux measured at single frequency (1.4 GHz).

The second and largest group in Table. 2 consists of sources that were believed to have either flat spectra or a positive spectral index based on previously available data (L95 and M00). The majority of the spectra for this group can be found in Fig. 3. In most cases, adding our observations, especially at the higher frequencies, changed the appearance of spectra to regular steep spectra, such that a negative spectral index occurred close to the canonical -1.8 ; we believe that this occurred because the spectra of these pulsars were previously known only over relatively narrow frequency ranges.

In a few cases (the pulsars that have the values of ν_{peak} cited), the shape of the pulsar spectrum, especially at lower frequencies, remains unclear, while at frequencies higher than ν_{peak} the spectra behave like those of regular pulsars. Some of these objects were previously believed to have flat spectra because the only flux measurements available were at frequencies close to the spectral break frequency. For these sources, the existence of the turn-over (or break) in the spectrum may be – at the moment – is at best doubtful.

In three cases, B1820–14, B1830–08, and B1838–04, our measurements at 610 MHz differ significantly from those previously published in the literature, i.e., Lorimer et al. (2005). We compared the profiles of these pulsars, which can be found in the EPN Database² (Lorimer et al. 1998), with our profiles acquired at GMRT (that can be found on Fig. 2)³. Our belief is that the flux density measurements published earlier are doubtful, and probably underestimated because of problems finding the proper baseline of the profile. The same applies to the L95 flux measurement of B1838–04 at 410 MHz. We note that the authors of that paper were aware of the problem, and note their measurements as heavily affected by scattering.

Similar results are found for PSR B1832–06, and the observation at 610 MHz – measurement marked as a cross in the appropriate panel of Fig. 3. The value of the flux density at this frequency was published by L95, but the corresponding profile is in neither the paper nor the EPN Database. Judging by the relatively broad profiles acquired at 1.4 GHz and 1.6 GHz, and taking into consideration this pulsar’s DM value of 463 pc cm^{-3} , we doubt whether the published measurement is a reliable value, as it probably suffers from the effects described above.

In our fits of the spectral slopes for the purposes of Table 2, we decided to omit these values, and use our measurements instead where applicable.

Three special cases that we wish to highlight in this group are J1740+100, B1800–21, and B1828–11.

Pulsar J1740+1000 was first observed by McLaughlin et al. (2002) and reported to have an unusually high positive spectral

² <http://www.mpifr-bonn.mpg.de/div/pulsar/data/browser.html>

³ full sample of the acquired profiles will be published in a forthcoming paper considering the scattering phenomenon itself; Lewandowski et al. (in prep.)

Table 2. Spectral indices and other parameters of pulsars from a search for turn-over at high frequency (KGK and Table 1 in this paper).

PSR	α ATNF	α	Freq. range (GHz)	α_p	Freq. range (GHz)	ν_{peak} (GHz)	DM (pc cm ⁻³)	Age (kyr)	\dot{E} (erg/s)	Assoc. & Remarks
<i>Normal spectra</i>										
B1557–50		-1.4	0.3–1.4				260	603	2.8e+34	
J1828–1101		-2.5	1.4–4.9				607	77	1.6e+36	
J1835–1020		-1.6	0.6–4.9				113	810	8.4e+33	
<i>Flat-normal or unclear spectra</i>										
B1641–45		-0.9	0.6–1.4				478	359	8.4e+33	
J1740+1000	0.9	-2.9	0.4–1.4				24	114	2.3e+35	see Fig. 4
B1800–21	-0.1	-1.1	1.4–11	0.0	0.6–1.4	(1.6)	234	15.8	2.2e+36	HESS, X:PWN, SNR
B1828–11	-0.5	-2.4	1.4–4.9	0.5	0.6–1.0	1.2	161	107	3.6e+34	
B1820–14	-0.8	-2.5	0.6–2.6				651	3750	3.6e+33	corrected L95(610 MHz)
B1830–08	-0.4	-1.8	0.6–4.9				411	147	5.8e+35	corrected L95(610 MHz)
B1832–06	-0.4	-1.9	1.0–4.9				473	120	5.6e+34	
B1838–04	-0.4	-1.7	0.6–8.4				325	461	3.9e+34	corrected L95(610 MHz)
B1849+00		-2.4	1.4–4.9			1.3?	787	356	3.7e+32	
J1857+0143		-1.5	1.0–2.6			(1.2)	249	71	4.5e+35	3EG, HESS
J1905+0616		-1.9	0.6–1.4			0.6?	256	116	5.5e+33	
J1907+0918	-0.3	-2.2	0.6–2.6			0.6?	358	38	3.2e+35	
<i>Turn-over and GPS from KGK</i>										
B1054–62		-3.2	0.9–1.4	1.0	0.3–1.0	0.95	320	1870	1.9e+33	HII
B1740–31	-0.9	-2.0	0.6–1.4	0.6	0.3–0.6	0.6	193	317	3.4e+32	
B1822–14	-1.4	-0.7	1.4–4.9	0.6	0.6–1.4	1.4	357	195	4.1e+34	3EG, HESS
B1823–13		-0.9	1.6–11	1.1	1.0–1.6	1.6	231	21	2.8e+36	3EG, HESS, X:PWN
<i>New GPS</i>										
J1809–1917		-1.9	2.6–4.9	4.3	1.1–1.4	1.7	197	51.3	1.8e+36	X:PWN, HESS

Notes. In column containing ν_{peak} , the break frequency is given in parentheses (see details in text). α and α_p were estimated using our data.

index of +0.9. During our observations, we were however able to successfully observe this source at GMRT at two frequencies, 610 and 1100 MHz, and found that our values sharply contradict the published findings (see Fig. 4), i.e. our value measured at 1100 MHz is lower than the previously reported value at 1.4 GHz by a factor of ten. We tried to follow this using the Effelsberg radiotelescope at high frequencies (2.6 GHz and 5 GHz), but we were unable to detect the pulsar. Triangles on the plot denote upper limits derived from the gathered data.

The only explanation we have for this discrepancy is that McLaughlin et al. (2002) reported during their observations that the pulsar was undergoing strong scintillations, which we did not see in our data. These scintillations apparently amplified the pulsar’s signal during their 1.4 GHz by a huge factor, which in turn changed the appearance of the spectra of this – based on our data – otherwise average pulsar. Nevertheless, this case requires further study, as we do not have an explanation of why these strong scintillations were present during the initial observations, and there was no evidence whatsoever during our project.

PSR B1800–21, whose spectrum can also be found in Fig. 4, is believed to be a young, Vela-like pulsar, associated with a supernova remnant, because it displays clear indications of a pulsar wind nebula in X-ray observations (Kargaltsev et al. 2007). The radio spectrum of this source displays a clear break around 1.6 GHz. The spectrum appears to be flat at low frequencies, especially when one excludes the flux measurement at 408 MHz (denoted by a cross on the plot) which we consider at best doubtful. The inspection of the profile for this observation in the EPN Database clearly shows that at such a low frequency this pulsar undergoes a significant scatter-broadening, and we doubt that a proper profile baseline could be found in these data, hence the flux measurement may be scrambled.

The spectral index above the break for B1800–21 is -1.1, which is lower than average but not alarmingly so.

B1828–11 is a pulsar that could be considered to display a high frequency turn-over in the spectrum, where the *peak frequency* is around 1.2 GHz (as suggested in Fig. 4), but the spread of measurements around this frequency causes that this interpretation is questionable. One would need a reliable measurement at frequencies lower than 600 MHz to decide between a broken type spectrum and a turn-over spectrum. This measurement should be possible, as our profile at 610 MHz suggests that the pulsar is not undergoing significant scattering – DM is only 161 pc/cm³, one of the smallest in our sample, and the measured scattering at 610 MHz is $\tau_{\text{sc}} \sim 5$ ms for our GMRT data (we used the method from Löhmer et al. 2004 with their PBF_1 function to estimate this value), slightly above 1% for a pulsar with 405 ms period (see also Fig. 1). Despite this, except for an upper limit from L95 there is no measurement as of yet, a situation that we plan to change in the near future.

Until then, we decided to classify this pulsar as an unclear case, probably a broken-spectra type similar to B1800–21.

The third group in Table 2 are previously known pulsars with a high frequency turn-over in the spectrum (from KGK). On the basis of these new observations, we corrected the values of ν_{peak} and both spectral indices (for the positive and negative part of the spectrum) for pulsars B1822–14 and B1823–13 (see Fig. 5).

We note that our fit for the positive spectral index of B1823–13 did not include the L95 measurement at 610 MHz, since no profile has been published (marked by a cross; see above-mentioned cases of B1832–06 and B1800–21). Its agreement with the fit is purely coincidental.

The last pulsar in the table is found to display gigahertz-peaked spectra for the first time. Flux had previously been measured for PSR J1809–1917 at only one frequency; new data (see Fig. 5) clearly indicate a peak in the spectrum around 1.7 GHz. The profile of this pulsar shows evidence of neither significant scattering nor dispersion smearing. Dispersion at 1170 MHz for

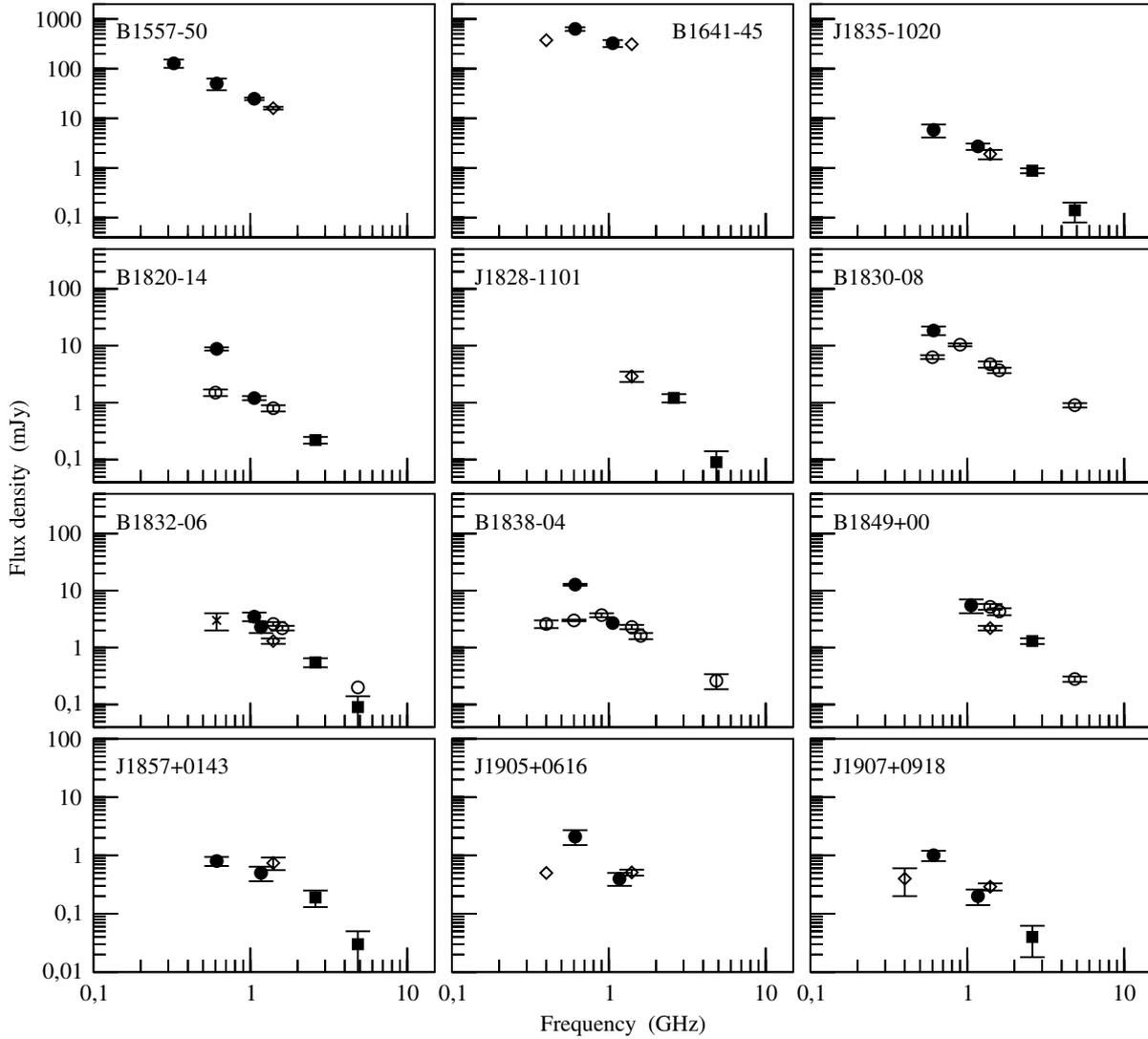


Fig. 3. The spectra of pulsars from Table 2. Empty circles – L95, M00 and K98, full circles – KGK and this paper, diamonds – ATNF, and cross is the result for B1832–06 from L95, which we consider to be doubtful because no profile for this measurement was published (see text for details)

a $DM=197 \text{ pc/cm}^3$ pulsar is 1 ms per MHz. For our GMRT data at 1.17 GHz, the scattering comes out as $\tau_{sc} \sim 3$ ms, similar to what can be measured for a profile from the ATNF database at 1.4 GHz (2 ms, conf. Fig. 1).

Another source of measurement error may be the interstellar scintillation (ISS). For PSR J1809–1917, we estimated the diffractive timescale at 1170 MHz (Lorimer & Kramer, 2005; see also Sect. 4.2 for details) to be of the order of 100 s, which means that any flux density variations caused by DISS will be averaged-out in a 30-min integration. At the same time, the refractive timescale is found to be ~ 2.5 day, and the expected refractive modulation index is relatively small, $m_{RISS} \approx 0.28$ (all these are of course crude estimations). Since our flux density measurement is an average of two observations separated by a few days, the flux density at 1170 MHz that we obtained should be reliable.

As for our higher frequency observations at 2.6 and 4.8 GHz, the DISS timescale can be estimated to be 260 and 1300 s, respectively, while for a refractive ISS we obtained 0.5 and 0.25 days. In this case, both RISS and DISS may influence the measured values. We observed the pulsar at each frequency for a total of 1 hour, which we hope is long enough to alleviate the effects of diffractive scintillations, as the observation

time is several times longer (in the case of 2.6 GHz observations) down to at least three times longer (4.8 GHz) than the DISS timescale. On the other hand, RISS may be more significant at these frequencies, especially since the expected modulation index is larger than at 1170 MHz (0.43 at 2.6 GHz to 0.62 at 4.8 GHz), although we hope that even if ISS would cause errors in our measurements it would not be to a degree large enough to change the appearance of the spectrum in any significant way.

For our entire sample, the average spectral index of the pulsars with typical spectrum shown in Table 2 is -1.8 , i.e. exactly equal to the global average value for all the pulsars with known spectra. For the pulsars with a turn-over in their spectrum the spectral index at lower frequencies varies from $+0.5$ to $+4.3$ (with exclusion of PSR B1800–21), and the value of ν_{peak} ranges from 600 MHz to 1.7 GHz.

4. Discussion

It remains unclear whether the cause of the turn-over is some kind of absorption in the magnetosphere, efficiency loss of the emission mechanism, or an interstellar effect (Sieber 1973).

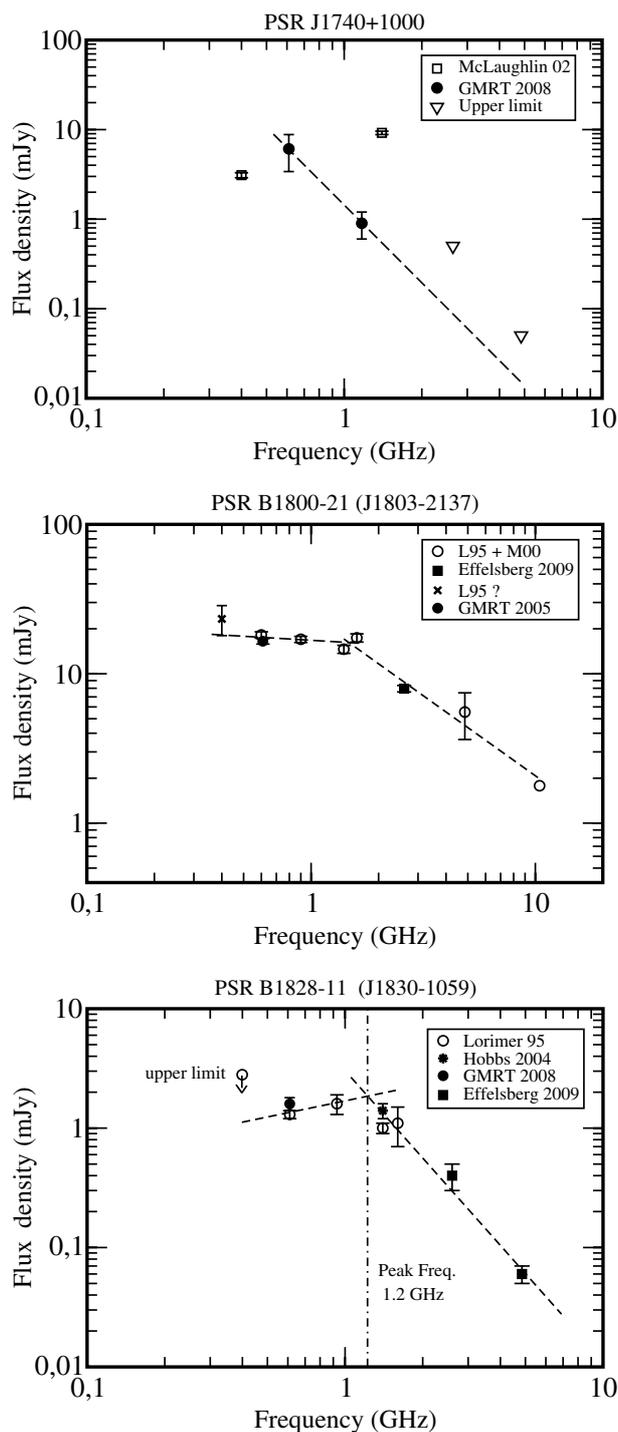


Fig. 4. Spectra of PSR J1740+1000, PSR B1800–21 and PSR B1828–11. Cross on the spectrum of B1800–21 represents a flux measurement from L95, for which no profile has been published, and we consider it doubtful (see discussion and similar case in Fig. 3).

To confirm or disregard one of the above possibilities, we need to construct the spectra for a large number of pulsars, especially at frequencies below 1 GHz where positive spectral index may correspond to a possible turn-over at high frequency. This and some connection with high frequency flux measurements will allow us to estimate the *peak frequency* and the shape of the spectrum, which may be helpful when we attempt to identify the origins of the spectral turn-overs.

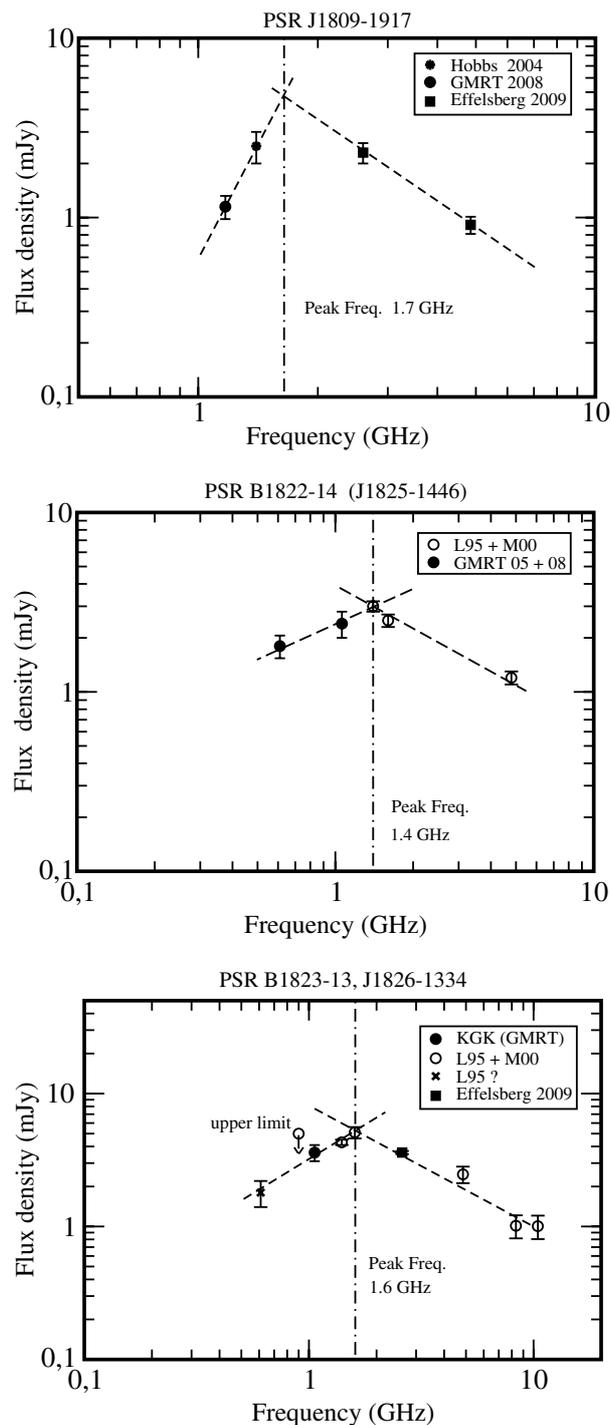


Fig. 5. Pulsars with the gigahertz-peaked spectra. Spectra of B1822–14 and B1823–13 are updated with respect to those published in KGK. For J1809–1917, this is the first presentation of its GPS-like spectrum.

There are also many other reasons that for an apparent decrease in the flux density at lower frequencies.

4.1. Interstellar scattering and corrected spectra

The scattering phenomenon causes pulse profiles to become broader, i.e. pulses to attain roughly exponentially decaying scattering tail. It has been shown that the characteristic broadening of the pulse, τ_{sc} , depends on both the observing frequency, as well as the dispersion measure, the empirical relation given by

Bhat et al. (2004) being $\log \tau_{\text{sc}} = -6.46 + 1.054 \log(DM) + 1.07 \log^2(DM) - 3.86 \log \nu$. For high DM pulsars at low frequencies, τ_{sc} may become so long that one will not see any pulsed emission, when the scattering time is greater than the pulsar period by a significant factor.

The most difficult analyses of pulsar spectra occur when the scattering time is close to the pulsar period. The classical method of flux density measurement requires that the baseline of the profile is found to subtract the background flux. One has to remember that τ_{sc} is the characteristic timescale of the exponential scattering tail decay, the timescale across which the tail flux density decreases by a factor of $1/e$. If P is a pulsar period and we assume that $\tau_{\text{sc}} = 0.5P$, the tail will still contribute $1/e^2$ (~ 0.135) of the peak flux after a full pulsar period, i.e. to the next pulse, or to the main pulse in the integrated profile case. This means there can be no proper baseline of the profile found.

In observations with a high noise level where it is difficult to estimate the value of τ_{sc} , one can clearly see pulsed emission, but at the same time misinterpret a noisy, low-slope scattering tail as a baseline level. This can lead to an underestimate of the pulsar flux, and hence a change in the appearance of a pulsar spectrum. The significance of this effect would increase for weaker pulsars (more noise in the profile), and the value of τ_{sc} increased. For a given pulsar, this would imply that as the frequency decreases, the flux becomes more underestimated. In cases such as this, the only way of measuring the pulsar flux is by means of continuum (interferometric) methods (see for example Kouwenhoven 2000).

For our pulsars, we are convinced that this effect if present, has a minimal impact on the flux measurements (see Figs. 1 and 2 for some examples, and the discussion of a case of J1809–1917 in a previous section), hence it would not change the appearance of the spectra in any significant way.

In the case of some old observations, such as L95 or M00 (see the discussion on pulsars B1820–14, B1830–08, B1832–06, and B1838–04 in the previous section), one has to approach the results carefully, always analyse the pulse profile before making any assumptions, and carefully study the previous analysis approaches, because in some cases authors realised the measurements may be heavily impacted by the scattering effect, and noted this accordingly.

4.2. Scintillation and decreasing/increasing energy in spectrum

Interstellar scintillations may either amplify or suppress the pulsar signal during the observation, leading to an incorrect measurement of the pulsar flux density. The only way to take this effect into account is to repeat the observations to derive an average flux value. This is especially important for pulsars that display a strong flux modulation.

The majority of our pulsars are objects with relatively high to very high dispersion measures (see Table 2), which would indicate that their transition frequency (frequency of the switch between strong and weak scintillation regimes, see Lorimer & Kramer 2005, for a review) is very high, well outside the frequency range the radio pulsars are usually observed. This implies that they are in the strong scintillation regime, and show both diffractive (DISS) and refractive scintillations (RISS). For refractive scintillations at the observed frequencies, one would expect very low modulation of the flux density as we observe at frequencies much lower than the transition frequency. To estimate the scintillation parameters, we used a few formulae from Lorimer & Kramer (2005). For a given pulsar, one has to know

its distance, which can be found in the ATNF database. To estimate scintillation parameters at a certain frequency, one can start by estimating the decorrelation bandwidth (Eq. (4.40) in Lorimer & Kramer 2005; repeated after Cordes et al. 1985), then assuming an average scintillation speed of 100 km s^{-1} one can estimate the DISS timescale (Eq. (4.49); Gupta et al. 1994). Knowing the decorrelation bandwidth, one can estimate the scintillation strength parameter u and the value of the RISS timescale (Eq. (4.46)), as well as the refractive modulation index (Eq. (4.47)). These will of course be very crude estimate. In contrast any kind of scintillation parameters derived from the analysis of the real data would be much more accurate, although usually no such information is available, for very weak sources these observations being very difficult to perform.

To illustrate the estimation process we take an hypothetical average pulsar from our sample and assume that DM equals 350 pc/cm^3 , which can be used to estimate the pulsar distance from the Taylor & Cordes (1993) galactic electron density model (value available in ATNF database). In our example, we assume that $d = 7 \text{ kpc}$, which should be a typical value. Using the method described above one can then estimate that the DISS timescale varies from 20 s at 400 MHz, to 90 s at 1.4 GHz, and 370 seconds at 4.8 GHz. At the same time, the RISS timescale drops from ~ 30 days at 400 MHz to 2.5 days at 1.4 GHz to 3.5 h at 4.8 GHz, and the RISS modulation index rises slowly with frequency, from 0.14 at 400 MHz to 0.56 at 4.8 GHz.

As one can see for this pulsar, the diffractive scintillations should cause very little trouble, even at the highest frequencies, assuming that the integration time is of the order of at least half an hour (1800 min, which is what we used for most of our observations). The RISS may cause problems at high frequency, where their timescale drops to an order of a few hours, and the modulation rises with frequency. The only way to overcome that issue is to repeat the observations and average a larger sample of measurements. Owing to telescope time limitations we decided to perform only two observations in most cases; this should give us a reliable estimate of the pulsar flux, especially since for the purposes of the spectra construction and finding the turn-overs, the high-frequency end of the spectrum rarely causes any problems.

The only pulsar in our sample with a low DM is PSR J1740+1000, which was included because of its positive spectral index (McLaughlin et al. 2002). Interstellar scintillation apparently for this source has a significant effect on the measured flux values and the appearance of its spectrum (see discussion in Sect. 3). This shows how ISS can influence the shape of the spectrum in some very unlikely – but not impossible cases.

If ISS were not taken into account and, for example, during the lower frequency observations one observed the pulsar around its scintillation minimum (i.e. maximum suppression of the pulsar signal), while, coincidentally, higher frequency observations were conducted during ISS maximum (i.e. the maximum amplification of the signal), an artificially positive spectral index might be observed.

The above example would of course be the most extreme event, but the more troublesome are the intermediate cases, where scintillations would cause a change of spectral slope in some frequency range, changing the shape of the spectrum in not so obvious, but significant ways. This can be a potential source of errors for pulsars with very few measurements, especially when the number of frequencies at which they were observed is small.

As the latter applies to the majority of c.a. 300 pulsars for which spectra have been constructed, one has to approach both

the published, as well as new (own) observational results carefully and make every effort to exclude the influence of ISS from the data.

4.3. Pulsar spectra – the shapes

Only a handful of the papers published in the past 40 years, have studied the characteristics of the pulsar radio spectra. This applies to both the observational results, as well as theoretical works. As mentioned in the Introduction, pulsar spectrum is usually described in terms of a simple power-law, with low frequency turn-over or the presumed cut-off at extremely low frequencies. There are also several known cases of broken-type spectra, which resemble the simple power-law, but the spectrum becomes steeper at higher frequencies.

The first comprehensive study of the shapes of pulsar radio spectra was performed by Sieber (1973). In addition to interpreting the very low frequency cut-off, which may be caused by a loss of coherence below a critical frequency, he proposed two mechanisms that may produce the low frequency turn-overs in the spectra. One of them is synchrotron self-absorption in the magnetosphere and the other is thermal absorption. He tried to explain the pulsar spectra (in the frequency range from roughly 80 MHz to 8 GHz) using both theoretical models, along with purely observational simple or two power-law models. In this frequency range, he found cases of pulsars with maximum energy (turn-over) at frequencies below 600 MHz, and he modelled their spectra using either synchrotron self-absorption model or thermal absorption. Nevertheless, in his sample (of 27 pulsars), the spectra of the majority of pulsars can be described by a simple power-law, which can be explained by the lack of information at low enough frequencies.

The pulsar with the highest peak frequency in his sample was the Vela pulsar, which showed the maximum energy around 600 MHz, and the best fit for the spectrum was the thermal absorption model.

To our knowledge very few additional analyses have been performed since Sieber (1973), from both theoretical and observational point of views, to explain or describe the turn-over phenomenon.

Malofeev (1994) presented the spectra of 45 pulsars (some of which had been considered earlier by Sieber 1973), and found that for c.a. ten more pulsars there is maximum energy in the spectrum, which he did not however attempt to explain using any model capable of describing the turn-over effect.

From the theoretical point of view, low frequency turn-overs (and other features) in the pulsar spectra were addressed by Petrova (2002, 2008), who pointed a few phenomena in the pulsar magnetosphere that could be responsible.

As for the external effects that could be responsible for the dampening of pulsar radiation, one has to mention the work of Khechinashvili et al. (2000). These authors tried to describe the eclipses of the binary pulsar B1957+20, where the pulsar radiation is absorbed by the pulsar-wind powered magnetosphere of the companion star. While they considered only a special case of a binary pulsar, one has to note that similar effects can occur in any environment, with magnetic fields, that is close enough to the pulsar to be powered by its wind.

Finally, we note that Löhmer et al. (2008) considered a heuristic model of pulsar radiation, consisting of a superposition of a large number of short pulses of only nano-second duration. This seems to describe the majority of observed pulsar spectra quite naturally, but does not work for pulsars with turn-over effects.

4.4. GPS and X-ray or high energy observations

Some pulsars with turn-overs in their spectrum at high frequencies have been shown to reside in very interesting environments. PSR B1054-62 lies behind or within a dense HII region (Koribalski et al. 1995). The environment of PSR B1823-13 appears to have peculiar properties in both radio observations (Gaensler et al. 2003), as well as X-ray data (Pavlov et al. 2008; Kargaltsev et al. 2007), where the results may indicate the existence of a compact pulsar wind nebula (PWN). For another Vela-like pulsar PSR B1800-21, a case of a broken (flat-normal) spectrum according to our data, we also have a clear indication of a PWN surrounding it. The same is true for the new GPS pulsar J1809-1917 (Kargaltsev & Pavlov 2007; see also Smith et al. 2009 and references therein), although this source appears to be a bit older than those mentioned previously, it may still be considered a young pulsar (with characteristic age of ~500 kyr).

At this point, we note that the Vela pulsar itself has a peak frequency at a relatively high value of ~600 MHz (Sieber 1973).

For a few other pulsars included in our project (with at least one GPS pulsar amongst them), it seems that they are coincident with known but unidentified X-ray sources from the 3rd EGRET Catalogue, or HESS observations (see remarks in Table 2, associations also taken from Smith et al. 2009). This may indicate that the turn-over phenomenon is associated with the environmental conditions around the neutron stars rather than being related intrinsically to the radio emission mechanism. Whether the phenomenon is caused by the thermal absorption proposed by Sieber (1973; see the previous subsection), or the cyclotron resonance damping (Khechinashvili et al. 2000) remains to be seen. It is also possible that the Gigahertz-Peaked Spectra and pulsars that were previously assumed to have *broken spectra* (flat or close to flat low frequency part and steep high frequency spectrum), may be only different manifestations of the same phenomenon.

5. Conclusions

We have shown that pulsars with high frequency turn-overs exist, which we have referred to as gigahertz-peaked spectra (GPS) pulsars. To a few cases published earlier by KGK, we have added a new pulsar (PSR J1809-1917) which increases the number of GPS pulsars to five. During the course of our project, we have either constructed or corrected the spectra of several other pulsars; some of these had been previously assumed to have flat spectra, whereas our observations indicate that they have either a standard steep spectrum or a broken spectrum.

A significant number of GPS and broken-type spectra pulsars appear to have interesting environments that imply that the main cause of turn-overs may be absorption occurring in the close proximity of the pulsar. This would make those objects similar to other known GPS compact radio sources.

KGK suggested that the *peak frequency* of pulsars with turn-overs is correlated with both pulsar age and DM. On the basis of the available data and apparent association of the majority of these pulsars with peculiar environments, we propose that the correlation with DM is purely selection effect. Turn-overs are rare phenomena, hence (since a larger DM usually corresponds to a larger distance) we search a larger area of our Galaxy, finding more and more of these cases the larger the DM is.

The correlation of the peak frequency with the pulsar age, also proposed by KGK, may be caused by the fact that younger pulsars are more likely to reside in a dense environment that is providing some kind of absorption, leading to apparent turn-overs in the spectra. On the other hand, this does not mean that

all of the young pulsars have high frequency turn-over (GPS), since detailed studies of pulsar environments show that they usually have highly asymmetric geometry (see for example Pavlov & Kargaltsev 2008). Taking this into account, it is easy to understand that even for a single pulsar, depending on the direction of the line-of-sight, pulsar radiation will, or will not, undergo absorption effects leading to GPS-type spectrum. Consequently, when looking at the whole young pulsar population, only some of them (i.e. pulsars for which the line-of-sight crosses strongly absorbing regions of their asymmetric environments) will be found to have high frequency turn-over.

Therefore for the general pulsar population we do not expect to find any correlation between pulsar age and the *peak frequency* (or other turn-over parameters, such as the spectral index), although for pulsars with high frequency turn-overs one can expect the age to affect these parameters – this may be due to the motion of the pulsar, or the evolution of the pulsar itself, as the latter will affect the way in which the pulsar interacts with its surroundings, and hence will change its properties.

Summarizing, we believe that GPS pulsars are very interesting targets of study for a large portion of the pulsar astronomer community, both because of their peculiar environments, and the effect the existence of such sources may have on future activities (pulsar search surveys; mentioned in the Introduction).

Further investigation is clearly required and the combination of continuum (radio and X-ray) observations and pulsed flux density measurements for these objects may be the clue to understanding this phenomenon. Such a combined analysis might establish that both pulsars with GPS spectra may be interesting candidates for continuum (especially X-ray) studies, and pulsars with interesting environments may have remarkable spectrum shapes (in cases where the shapes are unknown or not well-studied over a wide range of frequencies).

Owing to the significance of the scattering phenomenon at lower frequencies and the pulse broadening that it causes, the flux densities of several of the aforementioned pulsars simply cannot be measured by the usual means with appropriate accuracy. The only way to tackle this problem would be to conduct continuum interferometric observations (in a similar way to Kouwenhoven 2000), as we intend to do so in the near future.

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