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Turn-over in pulsar spectra around 1 GHz

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ABSTRACT

Aims. The main aim is to investigate the possibility of a high frequency turn-over in the radio spectrum of pulsars.
Methods. Using the GMRT, multi-frequency flux density measurements of several candidate pulsars have been carried out and their spectra have been extended to lower frequencies.
Results. We present the first direct evidence for turn-over in pulsar radio spectra at high frequencies. A total of 3 pulsars (including 2 new ones from this study) are now shown to have a turn-over frequency $\gtrsim$1 GHz, and one is shown to have a turn-over at ∼600 MHz.

Key words. pulsars: general

1. Introduction

A typical pulsar spectrum is steep compared to spectra of other non-thermal radio sources and can be described by a simple power law, with a mean spectral index of −1.8 (Maron et al. 2000). Whereas several pulsars exhibit such a power law spectrum down to the lowest observable frequencies, some pulsars show a low-frequency turn-over in the spectrum (Malofeev et al. 1994; hereafter M94). The frequency at which such a spectrum shows the *maximum flux* density is called the *peak frequency*, $\nu_{\rm peak}$, and is known to occur at ∼100 MHz (with the maximum known about 600 MHz). It is still an open question 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; hereafter S73).

In a recent paper (Kijak & Maron 2004; hereafter K04), the authors analysed the collected pulsar spectra and presented several pulsars as possible candidates for a high frequency turn-over ($\nu_{\rm peak} \sim 1$ GHz) in the spectrum (see Fig. 1 for an example). In this paper, we present recent observations of some of these candidates using the GMRT, and report the evidence for $\nu_{\rm peak}$ to be around or greater than 1 GHz for a few of them.

2. Observations and results

The observations were made at several epochs between November 2004 and February 2005, and some additional epochs in December 2005, using the GMRT at one of the following three frequencies at each epoch: 325 MHz, 610 MHz or 1060 MHz, with a 16 MHz bandwidth. We used the phased array mode with 0.512 msec sampling and 256 spectral channels across the band (Gupta et al. 2000). We observed a total of 11 pulsars in total intensity mode at several different epochs (see Table 1 for details). Some pulsars were not observed at the lower frequencies as the expected pulse broadening due to interstellar scattering was found to be comparable or larger than the pulse period. To estimate the mean flux density S_ν of the pulsars (which represents the total on-pulse energy, E, averaged over the entire pulse period, P, i.e. $S_\nu = E/P$), we carried out regular calibration measurements of known continuum sources (e.g. 1311−22, 1822−096, 2350+646 and 3C48) from which an appropriate flux density calibration scale for the pulsar data was established.

We obtained good quality pulse profiles for most of the observed pulsars. Some of these are presented in Figs. 2 and 3. Pulse broadening at the lower frequencies was clearly visible in four pulsars: B1557−50, B1641−45, B1740−31 and B1822−14 (see for example Fig. 2). The calculated average flux densities (from all epochs of measurements) are given in Table 1. For each measurement, we estimated the error in S_ν due to uncertainties in the calibration procedure and pulse energy estimation. Errors due to calibration uncertainties were about 30%. For multiple measurements, the error in the average S_ν estimate was calculated as the mean standard deviation of the set of measurements. There are some cases in Table 1 where we have only lower limits on the S_ν estimate. This happened for cases where the scatter broadened pulse profile was almost as broad as (or slightly broader than) the pulsar period, making it difficult to estimate the true off-pulse power level and hence leading to an underestimate of the total on-pulse energy.

Using our results, in combination with data from the literature, we have constructed spectra for these pulsars and find three pulsars with clear indication of a spectral turn-over (Figs. 4, 5 and 6), wheras for the others we find a steadily rising spectrum at the lower frequencies (pulsars in Table 1 which are *not* in bold face font). Below, we examine in detail the results for these 3 turn-over pulsars (along with PSR B1054-62):

Psr B1054−62. The spectrum is constructed from data published during last 15 years (see Fig. 1). This pulsar is the brightest amongst those with turn-over presented here. The slope in the spectrum has a positive value below 1 GHz and at high frequency the flux density drops again, showing clear evidence for $\nu_{\rm peak}$ being around 1 GHz. The profile has a single component with a somewhat asymmetric shape at low frequencies which is due to scatter broadening.

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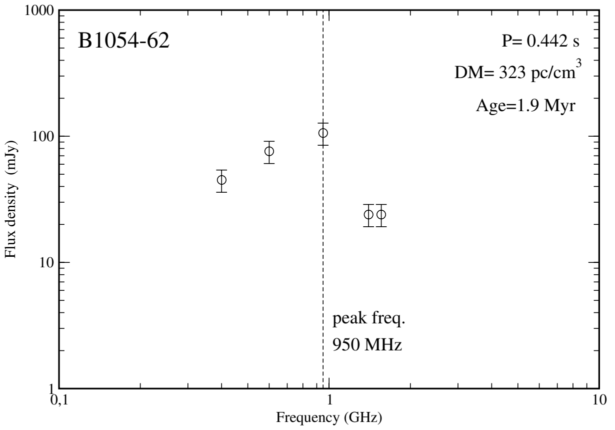

Fig. 1. Example of a spectrum with high-frequency turn-over. Data were taken from C91, T93, vO97, K95 and W93 (see references).

Psr B1740−31. This pulsar was observed at three frequencies with the GMRT, and the profile shows a single emission component that gets significantly scatter broadened with decreasing frequency (Fig. 2). The frequency of 610 MHz is common with published results from Lorimer et al. 1995 (hereafter L95), and the flux density estimates at this frequency agree quite well within the error bars. Our S_ν measurement at 1060 MHz confirms the negative slope of the spectrum above 600 MHz, whereas that at 325 MHz is in agreement with the upper limit from L95. Taken in conjunction with the small error bar on the 610 MHz flux density estimate of L95, our results show that the spectrum has a turn-over near 600 MHz.

Psr B1822−14. The profile of this pulsar is a single component at 1400 and 1600 MHz (Gould & Lyne 1998), and our observations at 1060 MHz (Fig. 3a) confirm the same. However, there is significant scatter broadening of the pulse even at 1060 MHz, which gets worse at 610 MHz. This, coupled with somewhat low signal to noise, makes it difficult to discern the full extent of the profile at 610 MHz. Using the profile from the epoch with the best signal to noise, we estimate the longitude extent of the profile and use the same width for each of the other epochs, to estimate the S_ν at 610 MHz. From the spectrum shown in Fig. 5, it is clear that the flux density falls at frequencies above 1.4 GHz. Below this frequency also, the flux density appears to be decreasing. Though the error bars on our flux density estimates are somewhat large, it is clear that the data points are *not* consistent with a rising spectrum below 1.4 GHz. Hence, we propose a ν_{peak} at 1.4 GHz.

Psr B1823−13. The profile for this pulsar shows two emission components (Fig. 3b) which do not evolve much at the higher frequencies studied by L95 and Gould & Lyne 1998. From the spectrum in Fig. 6, we conclude that the turn-over is close to 1.6 GHz. This is based on the very accurate flux density estimates at 1.4 and 1.6 GHz by L95 and our own measurement at 1060 MHz which, though it has a relatively larger error bar, has a mean value that is consistent with the L95 measurements, for a turn-over at 1.6 GHz.

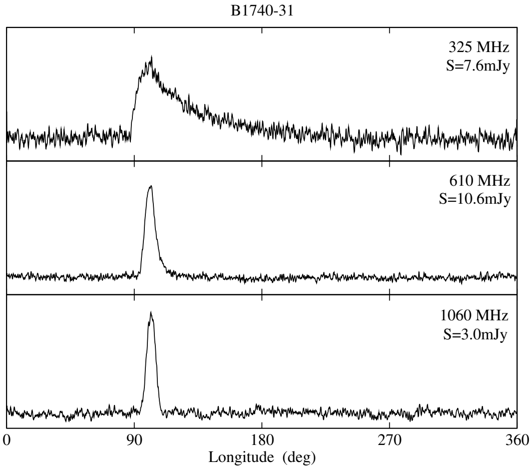

Fig. 2. Profiles for PSR B1740−31 with the GMRT, each from one observing session.

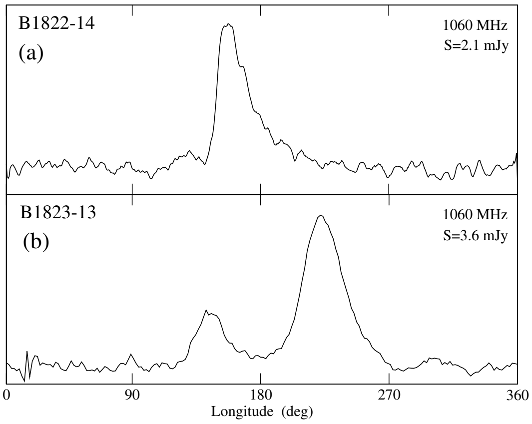

Fig. 3. Profiles for PSRs B1822−14 **a)** and B1823−13 **b)** with the GMRT, each from one observing session.

It is interesting to note that all of these pulsars have fairly high dispersion measure (*DM*) values: ∼200 and larger. In order to investigate such effects in the turn-over frequency in detail, we took the results for 41 pulsars with turn-over spectra from the literature (S73; M94) and combined them with the 4 pulsars discussed above: B1054−62, B1740−31, B1822−14 and B1823−13. This set of 45 pulsars was analyzed to check for correlations between ν_{peak} and other pulsar parameters (e.g. pulsar period, age, DM), using linear regression formulas. Though we did not find any strong correlations, we calculated a correlation coefficient $|r| \sim 0.6$ as well as the p-value ∼0.02 using chi-square test (a null-hypothesis) for both quantities, between ν_{peak} and DM ($\nu_{\text{peak}} \propto DM^{0.44\pm0.08}$), and pulsar age ($\nu_{\text{peak}} \propto \tau^{-0.23\pm0.05}$). The result of a null-hypothesis test is not statistically significant at the 1% level.

3. Discussion and conclusions

In their paper, K04 identified 19 pulsars as possible candidates for high frequency turn-over spectra, based on the known S_ν estimates (see their Fig. 1 and Table 1). However, a careful examination of the profiles of these pulsars (using the European Pulsar Network Data Archive[1]) shows that scatter broadening at the lower frequencies is comparable to or larger than the period for some of them (B1714−34, B1736−31 and B1820−11). As explained above, this can result in the flux density values being underestimated at the lower

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[1] `www.mpifr-bonn.mpg.de/div/pulsar/data/`

Table 1. Observed pulsars at the GMRT. PSRs with turn-over are marked in bold. The total number of epochs of flux density measurements at each frequency are given in parentheses.

Psr	DM $\left(\mathrm{pc\ cm^{-3}}\right)$	ν_{obs} (MHz)	$\langle t_{\mathrm{obs}}\rangle$ (min)	$\langle S_{\mathrm{mean}}\rangle$ (mJy)
B1557−50	261	325	16	128 ± 38 (1)
		610	9	66 ± 13 (3)
		1060	5	24.6 ± 1.4 (3)
B1641−45	480	610	10	630 ± 53 (3)
		1060	4	323 ± 52 (2)
B1740−31	192	325	25	7.6 ± 0.6 (2)
		610	12	10.6 ± 2.6 (3)
		1060	12	3.0 ± 0.3 (4)
B1815−14	625	610	16	>7.6 (4)
		1060	15	8.6 ± 0.2 (2)
B1820−14	648	610	20	8.8 ± 0.6 (2)
		1060	13	1.2 ± 0.1 (2)
B1822−14	354	610	26	1.8 ± 0.3 (3)
		1060	20	2.4 ± 0.5 (3)
B1823−13	231	1060	23	3.6 ± 0.8 (4)
B1830−08	411	610	12	18.5 ± 3.2 (2)
B1838−04	324	610	10	12.7 ± 0.5 (2)
		1060	3	2.7 ± 0.8 (1)
B2303+46	62	325	21	5.3 ± 0.6 (2)
		610	18	2.8 ± 1.3 (2)
		1060	16	1.2 ± 0.4 (2)
B2319+60	95	325	15	84.2 ± 2.5 (2)
		610	5	39 ± 12 (1)
		1060	11	23.9 ± 0.3 (2)

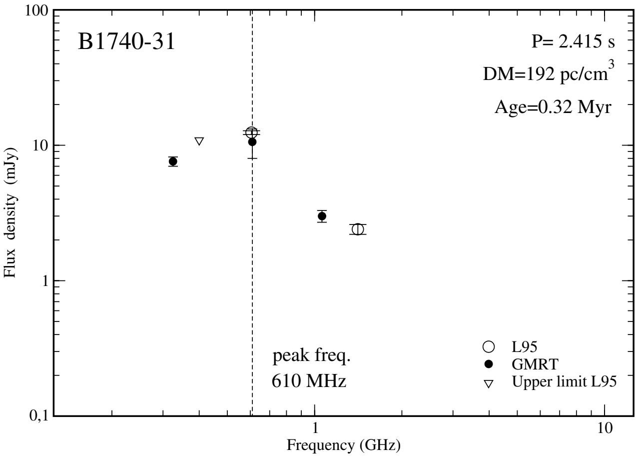

Fig. 4. The spectrum of PSR B1740−31 with turn-over.

frequencies, giving a false impression of a high-frequency turn-over. From the low frequency observations reported here, we can see that four more pulsars (B1557−50, B1641−45, B1830−08 and B1838−04) turn out *not* to show a high frequency turn-over. The two pulsars that we have confirmed to have a high-frequency ($\gtrsim$1 GHz) turn-over are B1822−14 and B1823−13, while B1740−31 is shown to have turn-over at a slightly lower frequency ($\approx$600 MHz). Of the remaining pulsars in the list of K04, there are still a few that need low frequency observations to elucidate the true nature of their spectra (e.g. B1240−64, B1815−14, B1820−14, B1828−10, B1823−11 and B1834−04) – these continue to be good candidates for high-frequency turn-over.

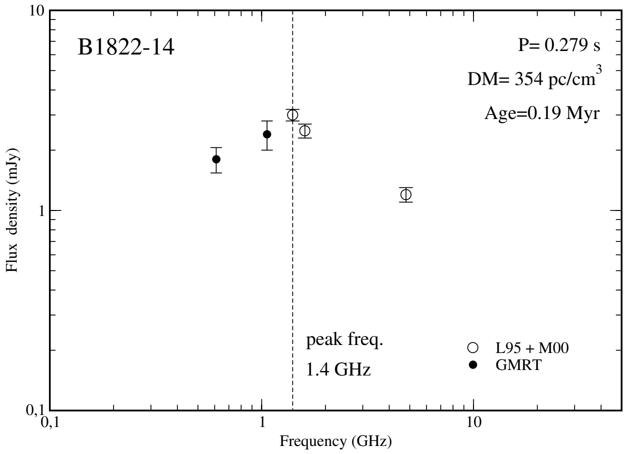

Fig. 5. The spectrum of PSR B1822−14 with turn-over.

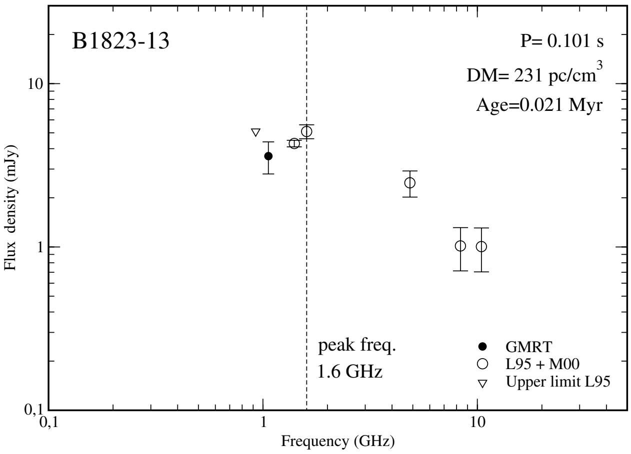

Fig. 6. The spectrum of PSR B1823−13 with turn-over.

The results thus show that there is a spread in the turn-over frequencies, with new values reported up to and more than 1 GHz. It is worth considering if other effects can bias the flux density estimates at different frequencies and hence modify the observed turn-over frequency. One possibility is the frequency evolution of a pulsar's profile which can cause new emission components to appear and become stronger (or old ones to become weaker and disappear) with frequency, thereby causing a frequency dependent variation of the total on-pulse flux density. In the case of the pulsars studied here, we believe that this is not a relevant possibility as the profiles are all relatively simple and do not show significant evolution with frequency.

Another possibility is the effect of interstellar scintillations – diffractive as well as refractive – that can bias the S_ν measured at a single epoch. For high DM pulsars, as the bandwidth and time scales of diffractive scintillations are significantly smaller than the total observing bandwidth and time, the effect of diffractive scintillations is almost completely quenched. Though the time scale of refractive scintillations is much larger than the observing time, the modulation index of these is quite small and not likely to affect the S_ν estimates significantly.

Turning now to the statistical analysis of turn-over effects, we first note that the correlations with other parameters can be more firmly tested if the error bars on the low frequency S_ν estimates (see S73 or M94) of the pulsars are reduced. The large error bars translate to large errors in the estimates of $\nu_{\rm peak}$, increasing the scatter in these correlation studies. Secondly, we note that it is possible that the tendency for higher turn-over frequencies to occur for pulsars with higher DMs could be a selection effect. The difficulties in low frequency observations (due to excessive pulse broadening) of high DM pulsars with low frequency turn-overs could account for their absence (S73 and M94). However, this would not explain why pulsars with low DMs do not show turn-overs at around 1 GHz. Hence, we think that this aspect needs a more detailed study.

The possible relation with pulsar age is also interesting. Millisecond pulsars, which are very old objects, show no evidence for spectral turn-over down to 100 MHz (Kuzmin & Losovsky 2001) and this result is consistent with our finding. On the other hand, our results are in contradiction with a prospective correlation between $\nu_{\rm peak}$ and P. We suggest that a period dependence of $\nu_{\rm peak} \propto P^{-0.36}$ (Malofeev 1996), does not exist (see for example Figs. 4, 5 and 6).

Now, we turn to the question: what is the possible cause of spectral turn-over in pulsars? In this context, it is interesting to note that two pulsars with turn-over at high frequencies (B1054−62 and B1823−13) have been shown to have very interesting interstellar environments (Koribalski et al. 1995 and Gaensler et al. 2003, respectively). This could suggest that the turn-over phenomenon is associated with the enviromental conditions around the neutron stars, rather than related intrinsically to the radio emission mechanism. Though there are no earlier reports of such a connection, a more detailed study on a larger sample of pulsars is needed to address this idea more quantitatively. In this context, future observations using GMRT (200−1400 MHz), Effelsberg Radiotelescope (>2 GHz) and LOFAR (<200 MHz) will allow us to investigate turn-over in radio pulsar spectra over a much wider frequency range.

Finally, we summarize our main conclusions: First, we find clear evidence for spectral turn-over around 1 GHz for some pulsars. Before, the feeling in the community was that typically the turn-over should lie around a few hundred MHz. Second, more and accurate pulsar flux density measurements are needed for the set of about 45 pulsars that show turn-over spectra, in order to better investigate the nature of the *peak frequency* and its possible relationship with other pulsar parameters. Though the cause of the turn-over in pulsar spectra is still an open question, we believe that our results can help resolve this problem.

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