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LETTER

Letter to the Editor

Pulsar detection at 87 GHz

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Abstract. Pulsed radio emission at 87 GHz has been detected from the pulsar PSR B0355+54. The observed flux density of 0.5 ± 0.2 mJy is, within the measurement errors, the same as measured previously at 43 GHz and is thus higher than expected. However the errors are such that all the measurements at frequencies higher than 1.2 GHz are just consistent with a single power law spectrum.

A second pulsar, PSR B2021+51, with a reported excess of flux density at 43 GHz, has been observed but not detected. The resulting upper limit for the flux density provides little constraint on the form of its spectrum above 43 GHz.

Key words: Pulsars: general – Pulsars: individual: B0355+54, B2021+51 – Radiation mechanisms: miscellaneous

1. Introduction

The results of recent observations suggest that the spectra of pulsars may flatten out at mm-wavelengths (Wielebinski et al. 1993; Kramer et al. 1996; Kramer et al. 1997b). While five out of eight pulsars detected at 32 GHz showed a continuation of the spectrum known from lower frequencies, three pulsars exhibited flux densities which were significantly larger than expected from extrapolations. It is believed that one of these cases is due to a moding behaviour still persisting at high frequencies (i.e. PSR B0329+54). The data for the remaining two sources (i.e. PSRs B1929+10 and B2021+51), however, led to the conclusion that an unexpected turn-up in the spectrum was being observed (Kramer et al. 1996). Such a change in the spectra of pulsars may be associated with other changes in their emission characteristics at millimeter wavelengths. In addition, we note that the polarization measured at 32 GHz is significantly lower than one would expect from observations at lower frequencies (Xilouris et al. 1996). Thus it was argued by Kramer et al. (1996) and Xilouris et al. (1996) that the emission properties at millimeter wavelengths are significantly different from those at longer wavelengths.

A change in the flux density spectrum could be related to the breakdown of coherence for the radiation process. At lower frequencies, only coherent emission can explain the high radiation temperatures of $> 10^{23}$ K at 400 MHz and generally strong polarization of the received radiation. It is to be expected that a critical frequency exists, above which a transition from the coherent radio emission to the incoherent emission occurs (cf. Michel 1982) (not necessarily caused by the same radiation process). Such a scenario is supported by the known spectrum of the Crab pulsar (e.g. Smith 1977): a steep radio spectrum obviously determined by a coherent process is followed by surprisingly high infrared and optical flux densities, exceeding the radio flux density by several orders of magnitude, and which is supposed to be created by an incoherent process. The determination of such a critical frequency has obviously great potential to contribute to the solution of the pulsar emission mystery (e.g. Melrose 1992).

Kramer et al. (1997b) have recently successfully detected PSRs B0355+54 and B2021+51 at 43 GHz. While PSR B0355+54 showed a continuation of its spectrum, PSR B2021+51 showed an excess in flux density consistent with a flattening of the spectrum. Since pulsars show much variety in their spectra at lower frequencies (Malofeev et al. 1994), it could be suspected that for other pulsars a similar peculiar behaviour occurs at even higher frequencies. In this letter we describe an attempt to observe PSR B0355+54 and PSR B2021+51 at 87 GHz, trying to further confirm the spectral behaviour of PSR B2021+51 and to investigate whether PSR B0355+54 shows a continuation of its spectrum at very high radio frequencies.

2. Observations

The observations were made with the IRAM 30m telescope at Pico Veleta, Spain, in the period 22-25 October 1996. A single

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channel linearly polarized receiver was used in double sideband mode with local oscillator at 87.743 GHz. The receiver had an IF bandwidth of 500 MHz centered at 1.5 GHz and the receiver noise temperature was 50 K. Thus the measurements refer to a frequency range of 3.5 GHz.During the observations the zenith optical depth varied between 0.05 and 0.12 so that the overall system temperature varied from 250 to 300 K. Since each source was observed for several hours a day over a large range of parallactic angles, we have effectively observed the Stokes I parameter. Any residual error in estimating I will be small because of the small linear polarization of pulsar radiation at millimeter wavelengths (Xilouris et al. 1996). In the worst case of PSR B0355+54, with expected polarization at 87 GHz of less than 20%, the calculated rotation of the plane of polarization with respect to the receiver was 170 degrees and 120 degrees on the two days of observation. Any error in the average total power is thus less than 5% and has been neglected. The detected receiver output was sampled every millisecond and stored directly on disk together with absolute time stamps and a period flag (see Sect. 2.1). The folding and integration of the data was done off-line using the topocentric pulse period. The flux density scale was determined from observations of Venus and Saturn for which disk temperatures of 367 K and 149 K, respectively, were assumed. The telescope pointing was checked periodically and was good to a small fraction of the beamwidth, i.e. about $\pm 3''$compared to a beamwidth of $26''$.

We concentrated on two sources, i.e. PSRs B0355+54 and B2021+51. The first source is the strongest pulsar detected at mm-wavelengths (0.9 mJy as equivalent continuum flux density at 32 GHz; Kramer 1995) and exhibits a rather flat spectrum ($S \propto \nu^{-1.15}$) at lower frequencies (between 1.2 and 43 GHz). Its period is 0.156 s with a pulse width (i.e. full width at half maximum) w_{50} of about 8°.The second source chosen is somewhat weaker at 32 GHz (about 0.3 mJy; Kramer 1995), but is one of the pulsars showing an apparent flattening or possible turn up in its spectrum. Its period is 0.529 s and its pulse width is about 11° at high frequencies. With dispersion measures of 57 cm^{-3}pc and 23 cm^{-3}pc, respectively, any pulse broadening due to interstellar dispersion is negligible for our observations.

2.1. Data acquisition system

The data were recorded by a modified version of the standard continuum system at Pico Veleta. Normally the detector outputs are converted to a pulse train by voltage-to-frequency (V/f) converters and then integrated for a suitable time by counting these pulses in CAMAC latch scalers.The contents of the latch scalers are then read and written to disk together with other "real-time housekeeping" information. Several channels can be recorded in this way. For our purpose this recording system was modified in four ways:

1) Firstly the telescope control program was streamlined so that four channels could be recorded every millisecond - the maximum rate for the existing equipment. Two channels were allocated to receiver outputs, with a view to the eventual recording of two polarizations, while the remaining two were reserved for timing information.

2) The second change to the system was to introduce a 'DC block', in the form of a high-pass RC filter (time constant 33 ms) between detector and the V/f converters. This served the dual purpose of removing low frequency noise and of increasing the dynamic range of the digitisation.

3) Thirdly, an accurate time stamp (UTC) was applied to each sample of receiver output. The two latch scalers that were not used to record the receiver output, were fed with 1 Hz and 10 kHz pulses from the observatory rubidium time standard. The rubidium standard was in turn synchronised with UTC to within 3 microseconds by using signals from the Global Positioning System (GPS). Hence the absolute time of *each data sample* was known within 0.1 ms. An independent set of scalers was run in parallel as a check for spurious counts.

4) Finally an unused bit of the 1 Hz latch scalers was set by pulses from a pulsar timing generator at the beginning of each topocentric pulse period. The timing signals were generated by a specialised PC-card running independently of the observing system except for an initial clock synchronisation. This flag enabled us to independently verify the accuracy of the time stamps.

An "artificial pulsar" signal was fed into the intermediate frequency connection between receiver and detector at regular intervals. It consisted of a noise source pulsed at a rate of 0.53 Hz and synchronized with the observatory time standard. We thus had a third possibility to verify the accuracy of the time stamps and to check the period flags and the off-line folding algorithms.

2.2. Data reduction

The observations were made as a series of scans lasting about 1200 seconds. Each scan was folded off-line using either the time stamp of each sample to calculate its phase or by using the period flag. Both methods gave the same results to within a fraction of a ms. The pulse phase at a given time was calculated using timing models kindly provided by A. Lyne (priv. communication), JPL DE200 ephemeris (Standish et al. 1992) and a modified version of the standard timing software TEMPO (Taylor & Weisberg 1989). The individual folded scans were then weighted and averaged to yield the final pulse profile. Corrections for extinction and the attenuation (0.87%) of the DC block were applied.

Finally the intensity scale was converted to flux density (Jansky) by application of the scaling derived from the planetary calibrations.

3. Results

The average 87 GHz pulse profile (9 hours integration) for PSR B0355+54 shows a clear detection of the pulse at the phase expected from lower frequency observations. This is illustrated in Fig. 1 which compares the 87 GHz profile (bottom) with a selection of lower frequency observations made with the 100-m

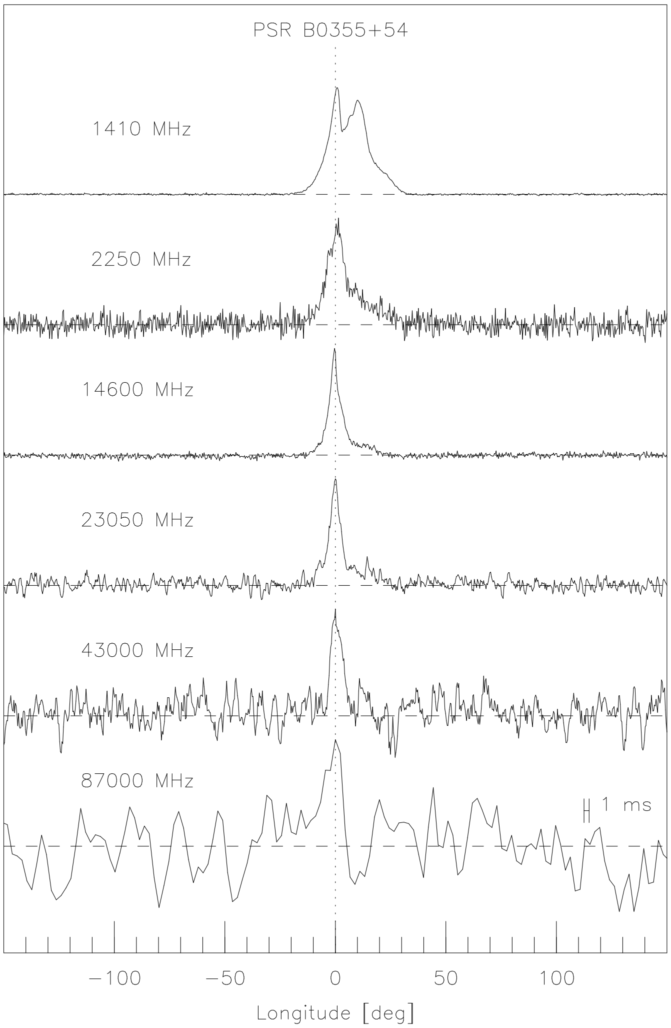

Fig. 1. Observed pulse profiles of PSR B0355+54 at several radio frequencies between 1.4 GHz and 87 GHz. Flux density on an arbitrary scale, and different for each frequency,has been plotted vertically. The time resolution is $153\mu s$ for frequencies between 1.4 and 14.6 GHz, $458\mu s$ for 23.05 GHz and $763\mu s$ for the 43 GHz observations.The 87 GHz profile represents the Pico Veleta measurement smoothed to a time resolution of 4 ms.

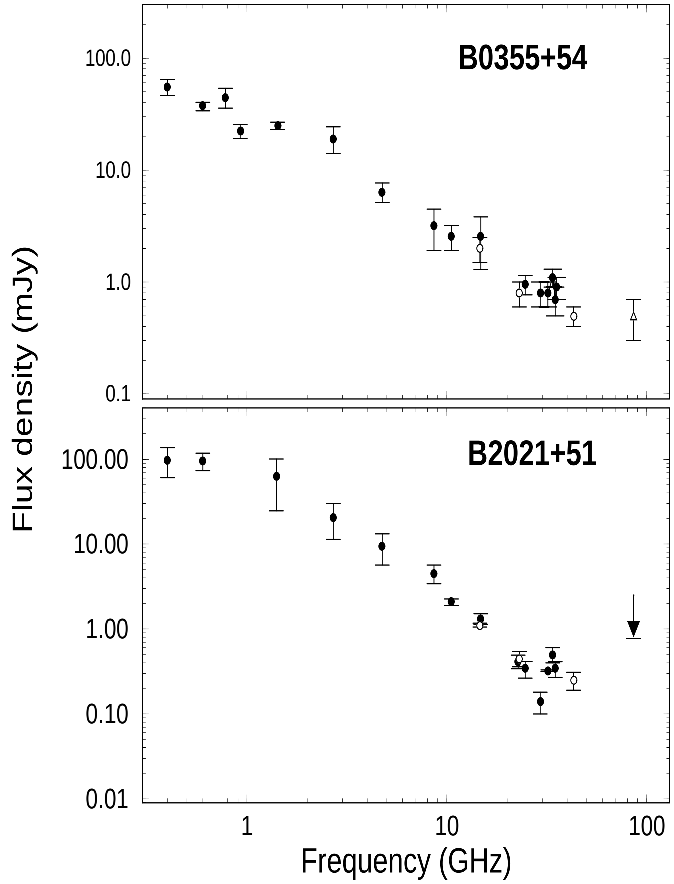

Fig. 2. Pulse spectra for PSRs B0355+54 (top) and B2021+51 (bottom). The measurements made at 87 GHz are presented as an open triangle and as an upper limit (at a 5σ level), respectively. For references of flux densities at lower frequencies see text.

Effelsberg radiotelescope of the MPIfR (unpublished data and data presented by Kramer et al. 1997b). The 87 GHz profile has been smoothed by applying a 4 ms running mean to the data, and yields a 5σ detection. The profiles presented have been aligned in time, referring to time of arrival at the solar system barycentre calculated for an infinite frequency. A detailed description of this procedure can be found in Kramer et al. (1997a). The occurance of the 87 GHz pulse at phase zero confirms the detection convincingly.

We estimate the average flux density to be 0.5 mJy with a 3σ uncertainty of ± 0.2 mJy. This error estimate is based on the observed noise level together with a contribution to allow for calibration uncertainties ($\pm 20\%$). As a pulse width for PSR B0355+54 we estimate $w_{50} = 6° \pm 4°$, which is consistent with observations at 43 GHz.If we assume a Gaussian pulse shape this corresponds to a pulse width at 10% of pulse maximum of $w_{10} = 11° \pm 7°$ where the quoted error contains an allowance for the undetected trailing component of the pulse which is observed at lower frequencies.

In the case of PSR B2021+51 no pulse was detected in a total of 10 hours integration. In accordance with previously published work (e.g. Kramer et al. 1996), we estimated a (5σ) upper limit of 0.78 mJy for the flux density by assuming the pulse width as observed at 43 GHz (Kramer et al. 1997b).

The resulting spectra of the two pulsars are presented in Fig. 2, including data published by Malofeev et al. (1994), Lorimer et al. (1995), Kramer (1995) and Kramer et al. (1996). For PSR 0355+54 we note that, within the measurement errors, the present result for the flux density at 87 GHz appears to be the same as measured at 43 GHz (Kramer et al. 1997b). It is thus larger than expected from an extrapolation of a fit to the lower frequency points. However the errors are such that all points at frequencies greater than 1.2 GHz are just consistent with a single power law spectrum with a spectral index of -1.14 ± 0.03 and a χ^2-probability of 0.04.

Unfortunately the upper limit for the flux density of PSR B2021+51 provides no strong constraint on the form of its spectrum above 43 GHz.

4. Discussion and Conclusions

Using the w_{10} value, deduced above, we can deduce the opening angle ρ of the emission cone if the geometry of the pulsar is known, i.e. the relative orientation of the magnetic and spin axes to the observer's line-of-sight (e.g. Gil et al. 1984). Since the geometry of B0355+54 can be deduced from polarization data (Lyne & Manchester 1988, Rankin 1993), we find $\rho = 6^{\circ} \pm 4^{\circ}$ using the geometry published by Rankin(1993)[1]. Assuming dipolar field lines (for a justification of this assumption see Kramer et al. 1997a), this can in turn now be translated into an emission height of only 40 ± 30 km. We believe that this height may be underestimated, since a detection of the trailing part of the profile, visible at lower frequencies, could result in a larger emission height. It becomes nevertheless clear that the emission is created close to the pulsar surface. We note that the good alignment of the 87 GHz profile with lower frequency data excludes the existence of significant magnetic multipole field components at this altitude, which in any case would have to be extremely strong in order to have a noticeable influence at a distance of larger than three stellar radii above the surface.

Although the involved uncertainties are large, the measured 87 GHz flux density for PSR B0355+54 may already have some very interesting implications. Using the measured flux density,the observed pulse width, and the pulsar geometry deduced from polarization data (Lyne & Manchester 1988,Rankin 1993) we can estimate the luminosity emitted by the pulsar at 87 GHz. We obtain (cf. Kramer 1995) a luminosity of about $2.1 \cdot 10^{26}$ erg/s in a bandwidth of 500 MHz. This luminosity can be compared to the energy output of proposed emission models such as curvature radiation which was an early favoured model to explain pulsar radio emission (e.g. Ruderman & Sutherland 1975). We note that based on this calculated luminosity, Lesch et al. (1997) have demonstrated that the emission observed at mm-wavelengths (i.e. at frequencies higher than 32 GHz) can indeed be generated by an *incoherent* superposition of the radiation from coherently emitting volumes.

In order to obtain reliable information about the actual shape of the pulse spectra, higher sensitivity measurements are necessary to reduce the current uncertainties. We may envisage the recording of two polarizations and an increase in bandwidth.

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[1] The geometry published by Lyne & Manchester (1988) yields very similar results.

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