Faint radio sources with peaked spectra. I. VLA observations of a new sample with intermediate flux-densities.

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Faint radio sources with peaked spectra

I. VLA observations of a new sample with intermediate flux-densities

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Abstract. We present 2 and 20 cm observations with the VLA of 25 candidate peaked spectrum radio sources. These data combined with those from earlier surveys have allowed us to construct radio spectra spanning a range of frequency from 0.3 to 15 GHz. Ten of the 25 sources are found to be variable with no dominant peak in their spectra, four are large extended sources with simple steep spectra, and ten are confirmed as definite peaked spectrum sources, whose spectra are dominated by a peak between 1.0 and 2.5 GHz, with peak flux densities between 0.4 and 3.8 Jy. Two of the latter group are variable in flux density, but their spectra appear to remain peaked during the variation.

Key words: galaxies: active – radio continuum: galaxies – quasars: general

1. Introduction

Compact steep spectrum (CSS) sources have emerged as the third major category of extragalactic radio source in cm wavelength surveys, in addition to extended steep spectrum sources and compact flat spectrum sources. In a survey at 2.7 GHz, 31% of the radio sources was found to be compact ($\theta < 5''$) and to have a steep spectrum ($\alpha < -0.5$, $S \sim \nu^{\alpha}$) (Peacock & Wall 1982). A typical CSS source has a turnover in its spectrum at frequencies around 100 MHz. Compact steep spectrum sources appear to be a subset of a more general class of peaked spectrum sources characterized by a narrow peak in their spectra, and (steep) fall off in flux density above and below the peak. Sources which have peaks in flux density close to 1 GHz have been called Gigahertz Peaked Spectrum (GPS) sources.

Known peaked spectrum sources are intrinsically powerful ($L_{radio} \sim 10^{45}$ erg s^{-1}) yet restricted to small dimensions (< 1 kpc, e.g., Mutel & Phillips (1988). Peaked spectrum sources have low radio polarizations (Rudnick & Jones 1982; O'Dea et al. 1991), which may be caused by a tangled magnetic field or very large Faraday rotation measures. The scale of the radio emission corresponds to the characteristic scale of the narrow emission line region in the optical (~ 1 kpc) for sources whose spectra peak in the 100 MHz range, but for sources whose spectra peak close to 1 GHz, scale sizes of 1 to 10 pc (somewhat larger than the broad line region) are observed. This behaviour is consistent with the spectral turnover being due to synchrotron self absorption, and as expected from synchrotron theory, the shorter the wavelength at which the radio emission peaks, the smaller the emitting source (Slysh 1963; Williams 1963).

The steep fall-off in the spectra at high frequencies probably implies that there is no fresh injection of relativistic plasma in the cores of these objects, or that the electrons are injected with very steep dependence on energy (O'Dea et al. 1991). The first is consistent with the fact that these sources are weakly if at all variable (e.g. OQ 208, de Bruyn 1990). The steepness in the optically thick part of the spectrum strongly suggests that the sources are sharply confined with morphologies not likely to consist of a long jet or series of components peaking at different frequencies (de Bruyn 1991).

The few VLBI observations of peaked spectrum sources in the literature (e.g., Phillips & Mutel 1980; Dallacasa et al. 1994) show that their morphologies are dominated by two components with very similar spectra. It can be expected that changes in the physical conditions in these components caused by component expansion or variability in the supply of relativistic electrons from the central source will generate changes in the spectral shape of the source which are coherent across the spectrum. Variability in flat spectrum sources composed of components

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Send offprint requests to: I.A.G. Snellen peaking at different frequencies is likely not to occur in a coherent manner across the whole spectrum.

The nature of peaked spectrum sources and their relationship in an evolutionary sense, to compact flat spectrum sources and extended steep spectrum sources, is unclear. We do not know if they are small in linear size, because they are (i) young radio sources (Mutel & Phillips 1988), (ii) old sources smothered by a very dense intergalactic medium, (iii) old classical doubles in a second stage of their life (Baum et al. 1990), or (iv) frustrated radio sources (Schilizzi 1990; O'Dea et al. 1991).

To be able to address these issues it is important to investigate the properties of peaked spectrum sources as a function of luminosity, redshift and rest-frame peak frequency. Until now such studies (Fanti et al. 1990; O'Dea et al. 1991) have only concentrated on the bright members of the class, due to the lack of a significant sample of peaked spectrum sources at lower flux densities. In this paper we present the results of VLA observations at 2 and 20 cm of 25 candidate peaked spectrum sources. These data combined with earlier survey data allow us to construct radio spectra for the sample, and select the truly peaked spectrum objects. This is the first part of a general program to investigate a low flux density sample of peaked spectrum radio sources. The median peak flux density of a source in our sample is ~ 0.7 Jy, a factor 4 lower than the median flux density of the Fanti et al. and Stanghellini et al. samples (Fanti et al. 1990; O'Dea et al. 1991).

2. Sample selection

Sources from the Texas 365 MHz and NRAO/Condon 1.4 and 5 GHz surveys were compared to select objects with optically thick spectral behaviour at frequencies below 1 GHz. Because initially only the images were available for the NRAO data, it was necessary to measure the flux densities for the Texas sources at 1.4 and 5 GHz ourselves (Röttgering et al. 1994). We restricted our attention to the most reliable sources from the Texas catalogue, i.e. those that had no indication of position or structure lobe shifts and whose structure were well modeled (code='+++', see Douglas et al. 1980). At the location of these Texas sources a gaussian brightness distribution was fitted to the 4850 MHz and 1400 MHz maps using the standard program 'JMFIT' from the NRAO image processing system AIPS. In cases of source confusion, the fitting algorithm can be unstable and give incorrect answers. Rejecting sources that have 4850 MHz and 1400 MHz positions that differ from the Texas positions by more than the specified uncertainties alleviates this problem. However, with this selection criterion, the number of sources will be incomplete and biased against sources whose structures and centroid positions change with frequency. The resulting sample consists of 13000 sources (Röttgering 1994). Fifty three sources were selected which had positive spectral indices ($\alpha \geq 0.2$) in the range 365-1400 MHz. Ten of these were at that time included in the O'Dea and Stanghellini et al. sample and have been excluded from our sample.

3. Observations and reduction

Twenty five sources from our sample (all sources with $3^h < R.A. < 15^h$) were observed with the VLA* in B array at wavelengths of 20 and 2 cm on 13 October 1991. A bandwidth of 50 MHz was used at both wavelengths. The resolutions are $3''.5$ at 20 cm and $0''.25$ at 2 cm. Observations of 3C286 were used for amplitude calibration. The phases were calibrated using standard nearby VLA phase calibrators, observed about every half hour. The sources were observed in "snapshot"mode for about 2.5 minutes at 20 cm and about 3.5 minutes at 2 cm. All the reduction was performed using AIPS. The maps for the 20 and 2 cm data were produced and cleaned using the ungridded subtraction method (Schwab 1984) implemented in the AIPS task MX. Self calibration was applied with two iterations on the phases alone and one on both phases and amplitudes. The rms noise in the maps is typically 0.5 mJy at both 2 and 20 cm. The flux densities and positions are determined using a gaussian fitting procedure as incorporated in the AIPS task IMFIT.

4. Results

Table 1 shows the position and flux density information for the 25 sources observed. The cores are sufficiently bright that the uncertainty in the flux density is dominated by systematic errors (2% at 20 and 3% at 2 cm, e.g. Carilli et al. 1991), except for the faintest sources at 2 cm. In column 1 the IAU name is given, in columns 2 to 7 the position determined from the 2 cm observations. The position uncertainty $\sim 0.1''$ is estimated from comparing our positions with the positions in the Patnaik sample (Patnaik 1992) for the ten sources which appear in both samples. Columns 8 to 12 give the Texas flux density, the Greenbank 20 and 6 cm flux densities and the 20 and 2 cm VLA flux densities. Since the different surveys have been carried out with widely varying beamwidths, we first checked for confusion. Since the beam for the 20 cm Greenbank survey is 12 arcminutes, we looked at the 6 cm Greenbank maps, and the 20 cm VLA maps for confusing sources. We found no cases in which confusion can be the reason for discrepancies between 20 cm Greenbank and VLA flux densities. The last column of Table 1 gives the source type. With our selection criteria, we find three types of radio sources: truly peaked spectrum sources (10), flat spectrum variables (10) and large extended sources (4). These sources are indicated by peaker, var and ext. For 0805+269, no 2 cm observations were obtained, so although we could not confirm that it is a peaked spectrum source, it remains a candidate.

Extended steep spectrum sources appear in the sample because the interferometer used for the Texas survey underestimates flux densities of sources larger than $> 15''$ and does not detect emission on angular scales greater than $2'$ (due to poor sampling of the uv plane), while the 20 cm Greenbank beam is $12'$, so an extended source with emission on scales of the order

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Table 1. The sample of candidate peaked spectrum sources observed.

IAU name	Position(J2000) RA h	m	s	Dec °	′	″	S^{80}_{texas} (mJy)	S^{20}_{gb} (mJy)	S^{20}_{vla} (mJy)	S^{6}_{gb} (mJy)	S^{2}_{vla} (mJy)	type
0312+149	03	14	47.786	15	08	43.78	235	400	128	145	2	ext
0428+205	04	31	03.760	20	37	34.26	2760	3883	3710	2767	1110	peaker
0506+056	05	09	25.969	05	41	35.31	509	805	459	1010	429	var
0642+449	06	46	32.028	44	51	16.55	392	574	460	1188	2756	var
0700+470	07	04	09.563	47	00	55.86	518	817	824	437	226	peaker
0705+486	07	09	08.008	48	36	55.53	498	672	260	240	69	ext
0706+460	07	10	10.507	45	57	24.80	227	418	412	102	17	peaker
0727+409	07	30	51.345	40	49	50.82	215	401	387	461	303	var
0754+100	07	57	06.642	09	56	34.86	731	1058	805	761	1756	var
0805+269	08	08	36.742	26	46	36.53	287	507	438	257	-	cand
0829+046	08	31	48.880	04	29	39.13	641	959	1200	2113	1113	var
0851+202	08	54	48.875	20	06	30.59	1216	2259	1937	2621	5750	var
0930+493	09	34	15.760	49	08	21.81	460	725	774	573	285	peaker
1048+556	10	51	47.396	55	23	08.50	270	426	132	135	10	ext
1059+282	11	02	14.289	27	57	08.70	303	430	270	400	281	var
1128+385	11	30	53.282	38	15	18.54	652	879	717	729	787	var
1131+493	11	33	59.223	49	03	43.42	779	1066	150	346	30	ext
1133+432	11	35	55.983	42	58	44.65	640	1443	1385	449	118	peaker
1144+542	11	46	44.201	53	56	43.07	289	410	406	477	300	peaker
1144+352	11	47	22.126	35	01	07.45	370	679	600	670	359	peaker
1145+268	11	47	59.762	26	35	42.26	260	419	300	377	407	var
1225+368	12	27	58.724	36	35	11.69	1249	2151	2070	812	154	peaker
1324+574	13	26	50.570	57	12	06.70	198	472	506	236	224	peaker
1355+441	13	57	40.592	43	53	59.80	294	781	709	452	225	peaker
1418+546	14	19	46.592	54	23	14.75	720	1547	1140	1704	1450	var

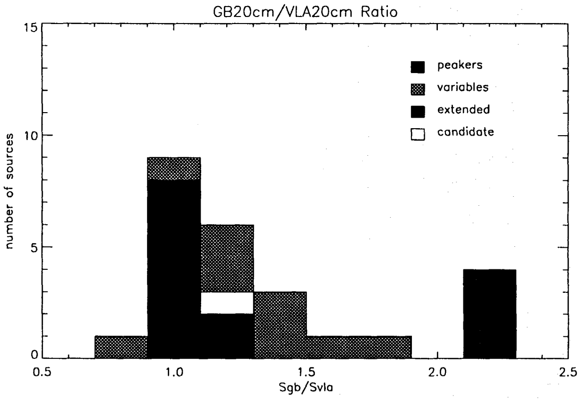

Fig. 1. The ratio between the Greenbank and VLA 20 cm flux densities

of 10′ will also appear with a peaked spectrum when the two surveys are combined. In this case the 20 cm VLA flux density is much smaller (like 50%) than the 20 cm Greenbank flux density and the VLA map shows extended structure.

We are sensitive to flat spectrum variable sources, because the three finding surveys were produced at different epochs. For example, a flat spectrum source whose flux density increased in the middle range of wavelengths will appear to have a peaked spectrum. In this case the 2 and 20 cm VLA flux densities can not be related to the Greenbank and/or Texas flux densities. We conclude that a source appears in our sample because of variability, if (1) the difference between the Greenbank and VLA 20 cm flux densities is larger than 20% (see Fig. 1) or (2) additional fluxpoints introduce a large scatter and the eventually cone shape of the spectrum disappears. For 19 of the sources we have found additional fluxpoints in literature. Two additional sources were found in this way to appear in our sample because of variability (0727+409 and 0851+202).

The sources 1144+542 and 1144+352 do show variability but are not excluded from the sample of true peaked spectrum sources because their spectral morphology appears to remain peaked during the variability. This is discussed in more detail in Sect. 5.

Of the ten peaked spectrum sources in our sample, two appear also in the O'Dea et al. and Fanti et al. samples (see Table 2). A curve of the form

$$\log S = a + b \times \log \nu + c \times \log^2 \nu \qquad (1)$$

has been fitted to the four spectral data points (Texas, 6 cm Greenbank and 2 and 20 cm VLA) to determine the peak frequency and peak flux density (columns 2 and 3 of table). Column 4 gives the spectral index ($S \sim \nu^{\alpha}$) below the peak, which is the spectral index between the Texas and the 20 cm VLA data point. Because this spectral index is measured very close to the

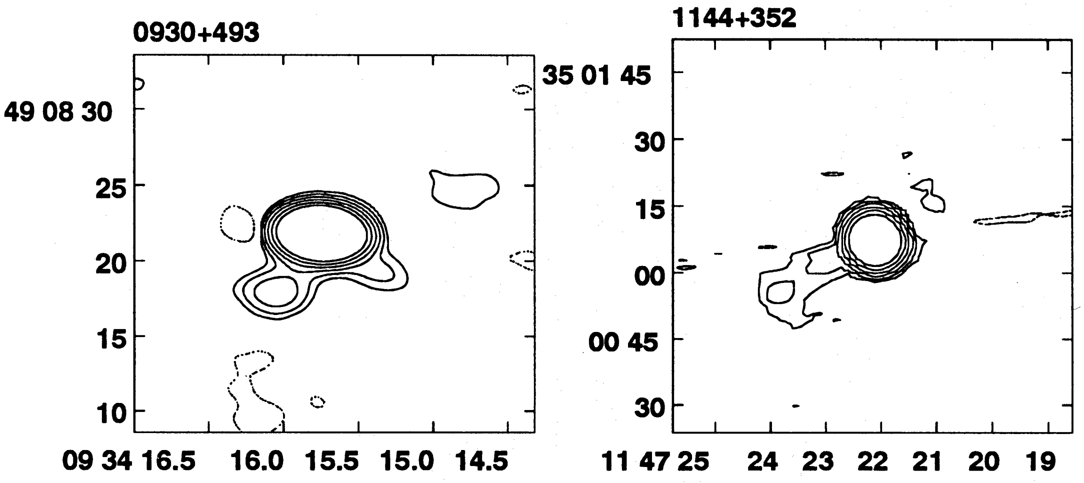

Fig. 2. (left) 20 cm VLA map of the components associated with 0930+493. Contourlevels are at 0.3 mJy x(-3, 3, 6, 12, 24, 48, 96, 192). (right) 20 cm VLA map of the jet eminating from the core of 1144+352. Contours at 0.7 mJy x(-3, 3, 6, 12, 24, 48, 96, 192)

Table 2. Sources with Definite Peaked Spectra

IAU name	ν_{max} (GHz)	S_{max} Jy	Spectral Index α^{365}_{1400}	α^{4850}_{14700}	Opt. ID	z	θ_{eq} mas	References for additional flux densities
0428+205[1]	1.3	3.8	0.21	-0.82	G	0.22	7	a, d, g
0700+470	1.3	0.7	0.33	-0.60	G			c, e, f, h
0706+460	1.0	0.4	0.43	-1.62				e
0930+493	1.7	0.8	0.37	-0.63	Q	2.57	4	h
1133+432[3]	1.2	1.16	0.55	-1.21				c, e, f
1144+542	2.6	0.5	0.24	-0.42	Q	2.20	2	c, h, i
1144+352	2.4	0.7	0.35	-0.56	G	0.06	2	b, f, h
1225+368[1,2]	1.1	2.02	0.36	-1.50	Q	1.98	12	c, h
1324+574	2.2	0.4	0.34	-0.05	G			h
1355+441	1.9	0.6	0.57	-0.63	G			c, e

[1] also in O'Dea et al. sample
[2] also in Fanti et al. sample
[3] also in Ghopal-Krishna'93 sample
additional data from literature:
a) Blake (1970)
b) Colla (1975)
c) Pauliny-Toth et al. (1978)
d) Parkes Catalogue (Bolton et al. 1979)
e) Bologna Sky Survey (Ficarra et al. 1985)
f) Cambridge 6C2 Survey (Hales et al. 1988)
g) Wright et al. (1991)
h) Patnaik et al. (1992)
i) Okudaira (1993)

peak this is an lower limit to the spectral index below the peak. The spectral index above the peak, given in column 5, is formed from the Greenbank 6 cm and the VLA 2 cm data points. Because of the curvature in the spectrum, these spectral indices are peak-frequency dependent. When the peak frequency is higher, the spectral index above the peak will be flatter, because it is measured closer to the peak.

Three sources have previously been optically identified with quasars, and two with galaxies (column 6, Véron-Cetty and P. Véron 1983; Stickel et al. 1994). Their redshift is known and is listed in column 7. We looked for optical identifications on the POSS-plates for the other sources. Faint optical identifications on the POSS plates (using APM data supplied by Richard McMahon, McMahon & Irwin 1992) are found for three additional sources, which are probably galaxies. To have an estimate

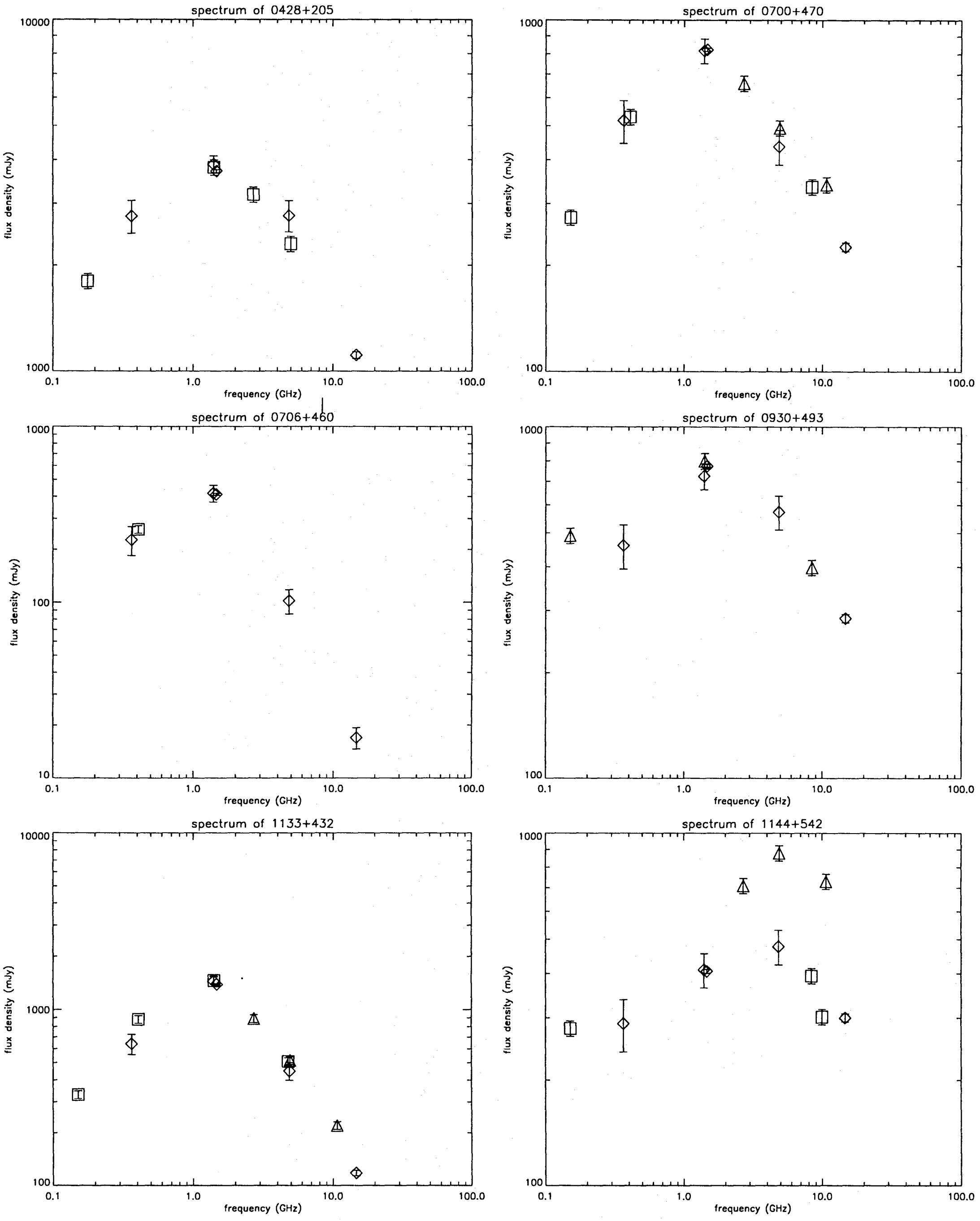

Fig. 3. Spectra of true peaked spectrum sources. The dotted line in the figure of 1144+352 indicates the spectrum of the extended emission

of the physical extent of the radio sources, we use the "equipartition angular size", θ_{eq}, derived by Scott & Readhead (1977). This is the size which a source with the given flux density and frequency at the synchrotron self-absorption turnover must have to be in equipartition. The angular size is only weakly dependent on the internal energy. Even if the source is ten times more energetic than assumed by the equipartition condition, the angular size will only be 25 percent larger. The equipartition angular size is given in column 8 of Table 2, assuming $H_0 = 50\ km\ s^{-1} Mpc^{-1}$ and $\Omega_0 = 1$. Upper limits for the angular sizes, obtained from our 2 cm VLA observations, are consistent with the equipartition angular sizes ($\theta < 20$ mas). 0428+205 and 1225+368 have been observed by Spencer et al. (1989) at 2 cm with the VLA in A configuration. 1225+368 is unresolved, but 0428+205 has probably a double or multi-component morphology, spread out over 100 mas. The true angular sizes and radio morphologies should be revealed using VLBI techniques.

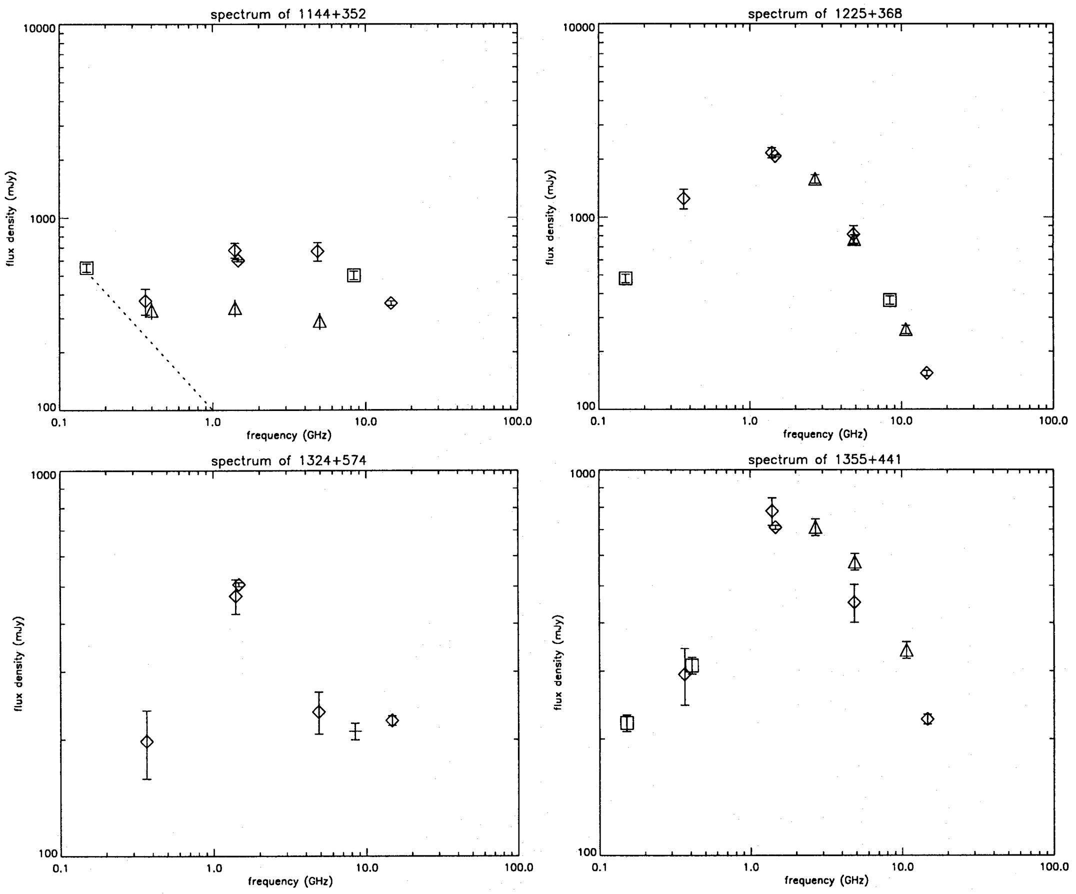

Fig. 3. (continued)

Figure 3 shows the radio spectra of the ten definitely peaked spectrum sources. The diamond symbols represent the VLA data points and the 6 and 20 cm Greenbank and Texas flux densities. The squares are data points from various papers in the literature, and the triangles are data points from Pauliny-Toth et al. (1978). The triangles in the figure of 1144+352 are data points from Colla et al. (1975).

5. Discussion on individual sources

The presence or lack of variability can give us information about the evolution of peaked spectrum sources. We shall attempt to explain this variability in terms of expansion of the radio core. We distinguish expansions with and without continuous injection of electrons by a central engine.

i) A radio source expanding isotropically and adiabatically from radius r to fr, without fresh injection of relativistic electrons, will cause the peak flux density to *decrease* by

$$f^{(10-14\alpha)/(5-2\alpha)} \tag{2}$$

where α is the spectral index of the optically thin part of the spectrum (Moffet 1975). The peak frequency will decrease by

$$f^{(10-8\alpha)/(5-2\alpha)} \tag{3}$$

ii) A radio source expanding with continuous injection of electrons will undergo an *increase* in flux density of f^2 and f^3 for respectively the optically thick and thin part of the spectrum, assuming that the magnetic field strength and electron density is constant during the expansion. In this case, the internal energy density and pressure remains the same during the expansion. The peak flux density will increase by a factor of

$$f^{(12-4\alpha)/(5-2\alpha)} \tag{4}$$

and the peak frequency will increase by a factor of

$$f^{2/(5-2\alpha)} \tag{5}$$

The most striking example of a *decrease* in flux of a radio source in our sample is 1144+542. Three flux density measurements, taken by Pauliny-Toth et al. (1978) in 1972, are a factor two higher than our measurements. If this is caused by an adiabatic expansion, the expansion factor f is ~ 1.3 (using $\alpha = -0.4$). This expansion mechanism would decrease the peak frequency by a factor 1.8. We do indeed see a peak frequency decrease of this size (see Fig. 3), but unfortunately there are only observations available at 2 epochs. Using the equipartition size, and taking the redshift from literature, we determine the expansion velocity to be of the order of 0.5 c.

A second source 1144+352 has *increased* in flux density over the last 20 years. In the early seventies the flux densities at 0.4, 1.4 and 5 GHz were respectively 330, 340 and 290 mJy (Colla et al. 1975), so it appears that the spectrum was flat. However, taking into account the non-variable extended emission ($S_{1.4GHz}$=100 mJy, α=-0.75, see below), the flux densities of the core can be estimated to be 70, 240 and 250 mJy at these three frequencies. Hence the spectrum of the core was peaked at that epoch, and has remained peaked during the flux density increase. The flux density at 6 cm has increased from 290 mJy in 1974 to 670 mJy in 1987 (30 ± 5 mJy/year, e.g. Ekers et al. 1983). An increase of this magnitude in the optically thin part of the spectrum can be caused by an expansion of 5×10^4 km/s, assuming expansion with continuous injection of electrons. The presence of a jet in the VLA map at 20 cm hints at a continuous outflow of matter. The flux density at 1.4 GHz in the optically thick region of the spectrum of the core increased from 340 mJy in 1974 (Colla et al. 1975) to 600 mJy in 1991. In the expansion scenario the optically thick flux density increase should be equal to the increase in the optically thin part of the spectrum to the power 2/3 (see (ii) above), which is what we see for 1144+352.

No variability is seen for the other sources in our sample, for which the redshift is known, on timescales of 5 to 15 years. The flux density measurements however are not accurate enough to give useful upper limits to the expansion velocities.

Two of our peaked spectrum sources, 0930+493 and 1144+352 show a change in spectral index at low frequencies from inverted to steep. We attribute this to contributions from extended structure with a steep spectrum, which dominates at the low frequencies. The 20 cm VLA maps of both sources show clearly the presence of extended structure; three components with a combined flux density of $\sim$ 15 mJy, within a radius of 10 $''$ of the core of 0930+493 are detected, and a one sided jet about 25$''$ in extent with a flux density of $\sim$ 28 mJy emanating from the 1144+352 core (see Fig. 2). The 20 cm Greenbank flux density of 1144+352 is 80 mJy higher than the total 20 cm VLA flux density, which is probably due to large scale extended emission, not detected with the VLA. Hence the total flux density of the extended emission is about 100 MJy at 1.4 GHz. Assuming a spectral index of $\alpha = -0.75$ for the extended emission, its contribution at 151 MHz is more than 90% of the total flux density.

The spectrum of 1324+574 shows a flattening at high frequencies, which implies the existence of an even more compact component whose spectrum peaks at frequency $>$ 20 GHz.

VLBI and optical studies will be undertaken to investigate their properties and compare them with those of bright peaked spectrum sources. We have also begun to define even fainter samples of peaked spectrum sources in the Westerbork Northern Sky Survey (WENSS).

6. Conclusions

We have presented 10 radio sources whose spectra peak between 1 and 2.5 GHz, with flux densities in the 1 Jy range. For 1144+542, a flux density decrease of a factor $\sim$ 2 in about 20 years is seen, which can be explained by the source expanding without fresh injection of relativistic electrons and with a velocity on the order of 0.5 c. For 1144+352, an increase in flux density over the last 20 years has been observed, which can be explained if the radio source expands with continuous injection of relativistic electrons.

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