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High Frequency Peakers

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Abstract: There is quite a clear anticorrelation between the intrinsic peak frequency and the overall radio source size in compact steep spectrum (CSS) and gigahertz peaked spectrum (GPS) radio sources. This feature is interpreted in terms of synchrotron self-absorption (although free–free absorption may play a role as well) of the radiation emitted by a small radio source which is growing within the inner region of the host galaxy. This leads to the hypothesis that these objects are young and that the radio source is still developing/expanding within the host galaxy itself.

Very young radio sources must have the peak in their radio spectra occurring above a few tens of gigahertz, and for this reason they are termed high frequency peakers (HFPs). These newly born radio sources must be very rare given that they spend very little time in this stage. $H_0 = 100\,\mathrm{km\,s^{-1}Mpc^{-1}}$ and $q_0 = 0.5$ are used throughout this paper.

Keywords: galaxies: active — radio continuum: galaxies

1 Introduction

The number of radio sources that appear unresolved at arcsecond scale resolution is rather conspicuous in all modern catalogues. The radio spectra of these sources can be separated into two distinct classes: the flat spectrum objects and the steep spectrum ones. Other properties are related to this first distinction: flux density and polarisation variability, and core dominance, which can also be extended to other observing bands from radio frequencies through to X-rays. All these characteristics can be interpreted in terms of unified scheme models (e.g. Urry & Padovani 1995) where a relativistic jet is amplified when its direction is aligned to the line of sight. From this picture it is then possible to infer that a substantial fraction of the ‘small’ sources is indeed shortened by projection and, in particular, the blazars (flat spectrum radio quasars and BL Lacs) are well known in this sense. It is also clear from this simple picture that intrinsically small radio sources are expected to be hosted in galaxies, i.e. where the radio source major axis is at a large angle with respect to the line of sight. In that case, relativistic beaming is not particularly effective, and the radio source should be characterised by low variability and little or no other signatures of an active nucleus as seen in the hosts of gigahertz peaked spectrum (GPS) galaxies, which appear as passively evolving ellipticals (Snellen et al. 1998).

The reason that makes these radio galaxies small can be found in their early evolutionary stage. From the ideas of Phillips & Mutel (1982), who studied a number of ‘compact doubles’, and Carvalho (1985), one can think of some unknown phenomenon that gives rise to the radio activity in the nuclei of some giant elliptical galaxies. Relativistic plasma is channelled into the radio jets, which start to dig their way into the interstellar medium (ISM) of their host, first into the narrow line region (NLR) (corresponding to the GPS stage) and then into the more tenuous and homogeneous ISM (the compact steep spectrum (CSS) stage) before plunging into the intergalactic medium (IGM) (extended radio source, possibly with FR II morphology), reaching projected linear sizes of the order of hundreds of kiloparsecs or even more.

The competing scenario of the ‘frustration’ model (van Breugel 1984), where small radio sources are indeed old and remain confined within the host galaxy by an ‘anomalously’ dense ISM, has been excluded by the lack of any observational evidence of an ISM denser than in the hosts of the extended radio sources (Fanti et al. 2000; Gelderman 1996; de Vries et al. 1998; and many others)

The observation of the increase in the separation of the outer edges (hot spots) in three compact symmetric objects (CSOs, i.e. the modern version of the ‘compact doubles’) by Owsianik & Conway (1998) and Owsianik, Conway, & Polatidis (1998) definitely supported the idea that these objects are young and growing. Such motions have now been measured for a number of CSOs (see Polatidis & Conway 2003), with projected speeds in the range of 0.1–0.3 c.

Radiative ages determined on the basis of the integrated radio spectrum are also consistent with the values derived from hot spot motions, just by assuming a simple model of continuous particle injection and standard equipartition conditions (Murgia et al. 1999; see also Murgia 2003 for local spectral ageing determination).

The ‘youth’ model has been outlined in some detail by various groups (e.g. Fanti et al. 1995; Readhead et al. 1996; Begelman 1996; Snellen et al. 2000); all agree on the most relevant aspects. The source initially increases its luminosity (during the GPS stage), then, once the radio emission leaves the NLR, expansion losses start to compete with synchrotron losses and the radio luminosity smoothly declines by about one order of magnitude from the GPS to the extended radio galaxy stage.

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Synchrotron self-absorption is thought to be responsible for the turnover observed in the radio spectra. Bicknell, Dopita, & O'Dea (1997) proposed a model where the expanding lobe creates a cocoon of shocked, ionised material that could account for some amount of free–free absorption. Support for this possibility has been found in several cases (see Kameno et al. 2000, 2003; Mutoh et al. 2002).

Typical examples of small and young radio sources are B2352+495 and B0710+439, with a projected linear size of 160 and 120 pc respectively, where the outer edges (hot spots) have been measured to separate at a speed of the order of 0.2 c, with a consequent age of the order of a few in 10^3 yr (Owsianik & Conway 1998; see also Polatidis & Conway 2003). On the other hand, another of these small and young radio sources, namely B0108+388, is known to possess some diffuse emission on the scale of tens of kiloparsecs. Although there is, as yet, no definitive proof that this diffuse radio emission is indeed physically related to the parsec scale structure, it has been proposed that the radio activity is a recurrent phenomenon and this extended feature is the debris of a previous activity cycle. This interpretation is also supported by the observation of recurrent activity in giant radio galaxies (Schoenmakers et al. 2000).

By examining the diagram relating the intrinsic turnover frequency and the projected linear size published by O'Dea (1998), it should then be easy to find smaller and younger radio sources by searching for convex spectra peaking at a few GHz or even higher frequencies. These objects known as high frequency peakers (HFPs) are briefly discussed in this paper.

2 Rare Gems?

It is easy to show that radio sources with spectra with a turnover at very high frequencies (i.e. tens of GHz) are rare, since the initial stages of radio emission are characterised by quite a rapid evolution in terms of size and peak frequency.

Let us consider a 10 yr old source, sitting at $z = 1$ and growing at a constant rate of 0.2 c, made up of two lobes and hot spots; the jet axis is in the plane of the sky. The source is then 0.61 pc (2.0 ly) in size. To make the computation as simple as possible one can assume that the hot spots are not very bright and that the bulk of the radio emission comes from the two lobes, assumed to be homogeneous ellipsoidal regions with a length of half the size of the source and with an axial ratio of 0.25 (0.31 pc × 0.08 pc). One can assume a total flux density of about 200 mJy at 22.5 GHz (the highest VLA frequency in the HFP sample presented by Dallacasa et al. 2000) equally distributed over two symmetric lobes. Assuming canonic equipartition conditions, one would expect to observe the turnover frequency at 38.4 GHz. Indeed this is a lower limit, given that using a flux density in the optically thick region we underestimate the total energy in the region and thus the turnover frequency. It has also to be noted that radiative losses are very high given that the relativistic electrons are located within very high magnetic fields, and this would steepen considerably the optically thin spectrum for sources having turnover frequencies below 22 GHz. Continuous injection of fresh relativistic particles is expected to make this steepening less effective.

Table 1. Observed turnover frequency observed for a source with a total flux density of 200 mJy at 22 GHz*

Redshift	$\nu_{\rm turn}$ (GHz)		
	10	50	100
0.3	24.6	7.3	4.4
0.5	30.3	9.1	5.4
1.0	38.4	11.4	6.9
2.0	42.9	12.9	7.7

*The three columns on the right refer to a source age of 10, 50, and 100 yr respectively, corresponding to a linear size of 0.6, 3.0, and 6.0 pc.

As the source ages the turnover moves down to 11.4 GHz for a 50 yr old source (two lobes of about 1.5 pc in size) and then to 6.9 GHz for a 100 yr old source. The relative number of sources with peak flux at about 40 GHz compared to those peaking at about 7 GHz will be 1–10. The turnover frequencies have also been computed for sources at $z = 0.3$, 0.5 and 2 (for $z > 1.5$–2 the turnover frequency does not change significantly) and are reported in Table 1.

This simple calculation is complicated by the prediction of basically all 'growth' models that the radio source luminosity in the early stage increases with size until the lobes advance further into the NLR, before starting to decrease (the GPS source becoming a CSS source), proceeding even further into the ISM and finally into the IGM.

Furthermore, the source components are known to be inhomogeneous: the brightest regions are also the smallest and the turnover is somehow higher than that calculated above. All this tends to make the convex spectrum a bit broader than in the case of a pair of homogeneous components; the spectral peak is mostly set by the region with the larger contribution to the total flux density.

It should also be taken into consideration that for a given flux density, the source at high redshift has an energy density and thus an intrinsic peak frequency higher than a source located relatively nearby, and therefore we are comparing objects with intrinsically different luminosities (and magnetic field strengths also).

In any case, if we neglect all the aforementioned effects, the message coming from Table 1 is that generally the turnover moves at frequencies below 10 GHz in a rather fast way if compared to the radio source lifetime.

An additional complication: in the very early days the equipartition fields are very high (of the order of 1 gauss or even stronger) and so the relativistic particles are very shortlived. We thus expect to observe only hot spots and

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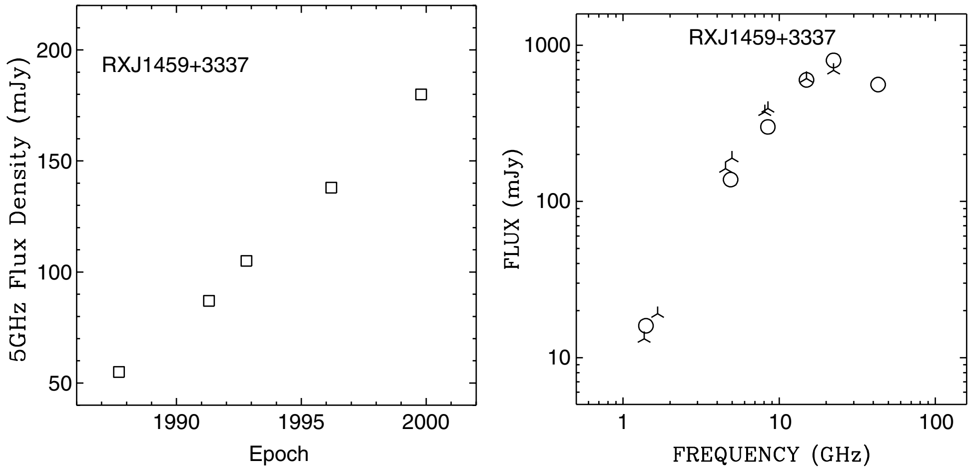

Figure 1 RXJ1459.9+3337. Left: The total flux density at 5 GHz. Right: The VLA radio spectrum in 1996 (open circles) and in 1999 (triangular symbols). Errors are generally smaller than the size of the symbols.

short backflow tails. This implies that the emitting region is smaller than the size considered here to estimate the physical parameters and so the turnover frequency may be somewhat higher than that reported in Table 1.

In summary, HFPs are rare and thus difficult to find; high frequency catalogues (i.e. at cm wavelengths or even shorter) extending over large sky areas are necessary to find newly born radio sources.

3 A Brief History

Edge et al. (1996) noted the existence of GPS sources with a turnover frequency higher than usually found in the samples of Stanghellini et al. (1990, 1998) and Spoelstra, Patnaik, & Gopal-Krishna (1985). In particular RXJ1459.9+3337 (a quasar at $z = 0.65$) had a number of observations at 5 GHz showing a steady increase in the total flux density over a period of about 10 yr, starting at around 50 mJy at the end of 1987 and reaching about 140 mJy in 1996. The 'simultaneous' radio spectrum from the VLA showed a radio spectrum with a peak around 30 GHz (about 50 GHz in the rest frame). The source has been observed again with the VLA in 1999 since it belongs to the 'faint' HFP sample (C. Stanghellini et al., in preparation; the 'faint' sample covers the flux density interval between 50 and 300 mJy in the GB6 catalogue), and the observed flux density at 5 GHz sits exactly on the extrapolation from Edge et al.'s (1996) plot (see Figure 1, left). It is also interesting to note that the spectral peak is likely to have moved down to a slightly lower frequency, possibly indicating that the source and/or component expansion is decreasing the optical depth below the turnover frequency. However, the 1999 VLA data lack the 43 GHz measurements, and thus it is not possible to derive a firm estimate for the spectral peak at this epoch.

The possibility that the steady increase of flux density with time is only apparent has also to be taken into account, and could be due to the sparse time sampling of a more irregular flux density variability with the typical 'random' pattern that, however, appears to be linear due to the sampling carried out with a certain amount of 'cosmic conspiracy'.

4 A Complete Sample of HFPs

As mentioned above, the ideal, intrinsically small and young radio sources are those identified with galaxies. However, it is nearly impossible to select samples by starting from optical identification, particularly when rare objects are searched for. Then the conventional approach to select samples on the basis of the radio spectrum (the usual convex bell-shape with a clear optically thin region) has to be used.

Among the signatures of young radio sources, the turnover frequency above a few GHz is probably the most characterstic of this class, and also the easiest to investigate. Then, by comparing the NVSS (Condon et al. 1998) with the GB6 (Gregory et al. 1996) catalogues one would expect that the young sources must have a rather inverted spectrum and must also appear unresolved on both surveys. However, this fairly simple selection is spoiled by the relatively long time lag between the GB6 and the VLA observations. In fact, variable sources at a high state of activity during the GB6 campaign are selected in this way as well. Therefore it was definitely necessary to carry out simultaneous multifrequency observations to define the spectral shape of all the candidates.

Dallacasa et al. (2000) defined a sample of 'bright' HFPs, with flux density in excess of 300 mJy in the GB6 catalogue and inverted spectra (steeper than 0.5 if $S \propto \nu^{-\alpha}$) between 1.4 (the NVSS measurement) and 4.9 GHz. About 100 candidates were then observed at the VLA to get simultaneous radio spectra between 1.4 and 22 GHz and then separate variable flat spectrum sources from those with intrinsically convex-shaped radio spectra. The final sample of genuine HFP sources consists of 55 objects and covers the area of the GB6 catalogue, although a few small areas have not yet been covered by the NVSS.

About 1750 sources brighter than 300 mJy in the GB6 catalogue were found in the NVSS catalogue and the final

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number of HFPs represents a rather conspicuous fraction (3%) if compared to the expectations, bearing in mind a model of a young radio source quite rapidly developing within the host galaxy. The selection does not impose any condition on the optical identification. Indeed we should restrict our attention to galaxies only, possibly also rejecting those broad line hosts classified as galaxies given that they are indeed relatively nearby and it is possible to reveal consistent starlight around them. About half of the bright HFPs already had been identified in the literature and a project to complete such information is continuing (Dallacasa, Falomo, & Stanghellini 2002). Most of the HFPs are identified with high redshift quasars and only about 25% (15 objects in total, including two nearby broad line radio galaxies) can be considered non-quasar or BL Lac.

Therefore, the intrinsically young radio sources (i.e. narrow line galaxies) become less than 1% and it is no surprise to find that the intrinsic peak frequency is generally much smaller than in HFP quasars also as a consequence of the different redshift range spanned by the two populations, with the majority of the quasars found at redshift larger than 1.5.

The expected number of very young (about 100 yr old) sources can be calculated from the ratio of their typical age and the average age of extended radio sources (about 10^7 yr). This would imply a fraction of the order of 0.01%, but we must also consider that in all the 'youth' models the sources progressively decrease their radio luminosity as the mini-lobes leave the NLR, and then we should have considered a larger sample of 'old' radio sources by decreasing the flux density limit by about one order of magnitude. In this case, nearly all the 54 000 sources in the GB6 catalogue would form the 'old' radio source sample to be used in the determination of the fraction of young radio sources in catalogues.

Among the 31 sources with measured redshift only 11 have an intrinsic peak frequency above 22 GHz, and all of them are quasars. There are two more sources with an observed peak frequency beyond 22 GHz, and both are identified with stellar objects (redshifts are not yet available). The few galaxies with a measured or estimated redshift have peak frequencies in the range 5–12 GHz.

The radio morphology is also an important tool to assess whether a source is indeed young (lobe dominated) or just a knot in a jet which is dominant over the entire radio emission (as in 4C39.25, Alberdi et al. 2000), and in fact the CSO or MSO (medium-size symmetric object) samples also contain a few quasars. VLBA imaging in the optically thin part of the spectrum is a useful tool in this respect (see also Tinti et al. 2003).

4.1 *Polarisation*

Intrinsically small sources are in regions close to the active nucleus where a substantial amount of high energy radiation is produced and where ionisation and magnetic field strength are important. Consequently Faraday rotation is likely to be significant, and where the Faraday screen is not homogeneous and not resolved by the observations, then the (beam) depolarisation becomes dominant at relatively high frequencies.

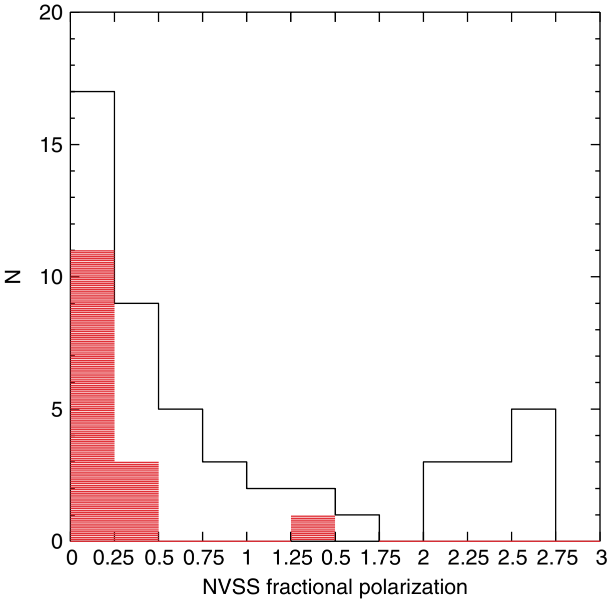

Figure 2 NVSS fractional polarisation: galaxies are represented by shaded areas, quasars by the unshaded areas; most of the values below 0.5% must be considered as upper limits; the 2.5–2.75% bin contains all the sources with fractional polarisation in excess of 2.5%.

Among the bright HFPs, polarisation information is still not available in a systematic way except in the NVSS catalogue, which happens to be in the optically thick part of the spectrum of all the sources. However, it is possible to distinguish the behaviour of the HFP quasars (and the two BL Lacs) from the other HFPs identified with galaxies or still empty fields. As can be be seen in Figure 2, the former span a wide range of fractional polarisation, with measured values up to 5%, while the latter are not polarised at all with one exception. This is what it is expected in the case that HFP quasars are mostly larger radio sources seen with the jet aligned to the line of sight and thus the radiation comes from outside the region with high local ionisation. In a study concerning CSS and GPS sources done in a similar way Cotton et al. (2003) find that there is a quite sharp change in the fractional polarisation which rises to significant values once the source emerges from a region of about 2–3 kpc in radius. Given that HFPs are well within this region, they are expected to be unpolarised.

4.2 *Variability*

It is well known that flux density variability may substantially modify the observed spectrum of blazars in all the bands of the electromagnetic spectrum, sometimes even challenging the optical identification (e.g. BL Lac itself, Vermeulen et al. 1995).

Little is known about the radio variability in HFP sources, except for a very few objects already known for other reasons: the HFP galaxy B0108+388 (also in the Stanghellini et al. (1998) GPS sample) is known

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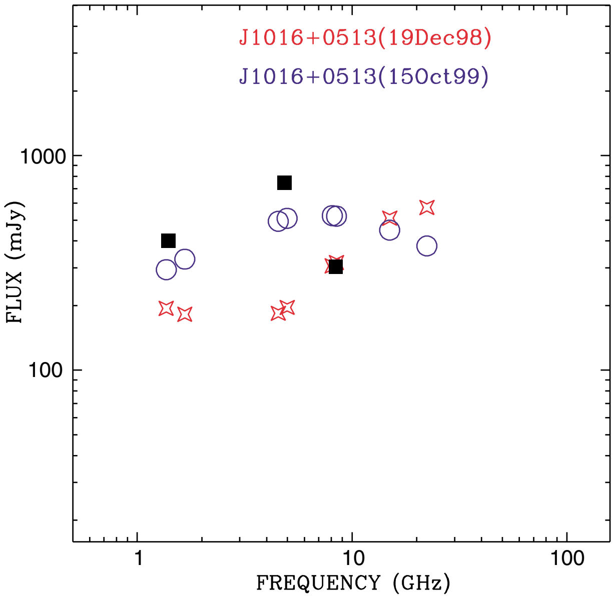

Figure 3 Flux density and spectral variability in the HFP source J1016+0513. VLA data are represented in stars and circles, while NVSS, 87GB, and JVAS flux densities are represented by the filled squares.

to possess a rather constant flux density at all radio frequencies; the BL Lac B1749+096 and the quasars B0923+392 (4C39.25) and B2134+004 (the latter is also in the Stanghellini et al. (1998) GPS sample) are known to possess some amount of flux density and polarisation variability (see the VLA/VLBA polarisation calibration webpage). On the other hand, the broad line galaxy B1404+286 (OQ208, also a GPS in the Stanghellini et al. (1998) sample) showed a steady decrease of its flux density at 5 GHz in the 1980s, but now this decrease has stopped. The flux density at 1.4 GHz, however, did not show any significant variability.

For most of the 55 HFP sources in the bright sample there are only the simultaneous multifrequency VLA datapoints in Dallacasa et al. (2000), the NVSS, the GB6 and the JVAS measure at 8.4 GHz, where it is however possible to see a significant amount of flux density variability (Dallacasa et al. 2000). The VLA multifrequency observations of HFP candidates were split into several runs separated by weeks or months, and a handful of sources were observed twice. Among these sources, J1016+0518 (B1013+054) shows a remarkable change: the two simultaneous radio spectra are shown in Figure 3. At both epochs, the overall radio spectrum maintains a convex shape, although the first epoch is characterised by a complex structure. The peak has moved from >22 GHz down to 7 GHz over about 10 months. If we assume classical equipartition conditions and use O'Dea's (1998) plot, we can estimate the size of the source by means of the spectral peak. The increase in size is then evaluated to be from 1.0 to 3.0 pc and this would correspond to an expansion velocity of about 16 c, which is clearly unrealistic, i.e. we cannot interpret this source in terms of a young object where the lobes are expanding within the host galaxy, but rather as a beamed object whose radio emission is dominated by a single knot in the jet.

In this respect HFP quasars can be considered the counterpart of steep spectrum radio quasars (SSRQ) in the population of powerful and extended radio sources, i.e. objects oriented at angles intermediate to the line of sight and where relativistic beaming is effective although not so strongly as in blazars.

Further VLA polarisation-sensitive multifrequency observations are under examination in order to evaluate the incidence of variability (also in spectral shape) among HFP sources and also to estimate the degree of polarisation in the optically thin part of the spectrum. If significant polarisation is also detected below the turnover frequency, these data will allow one to study the mechanism responsible for self-absorption (see also Kameno et al. 2003).

5 Summary

The hosts of the 'bright' HFPs are mostly quasars (with two BL Lac objects), and galaxies are rather rare, as expected from the estimate of the radiative age as derived from the spectral peak. Only 15 out of the 55 bright HFP sources can be considered galaxies, although two are classified as broad line galaxies, and the final number of prototype young radio sources is likely to be smaller. Accurate VLBI morphological studies in the optically thin part of the spectrum play a key role in the correct classification.

If we consider unified scheme models for powerful (type 1) but **small** radio loud objects, we could think of a sequence of sources with the radio jets oriented at decreasing angles to the line of sight formed by HFP/GPS/CSS galaxies, then HFP/GPS/CSS quasars and finally a small number of OVV/FSRQ/blazars.

Indeed there could be some bias towards HFP/GPS/CSS quasars: these are likely to be dominated by a knot in the jet were some degree of relativistic beaming increases the apparent luminosity of the object, and therefore high frequency catalogues are biased towards them and against galaxies.

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