The CLASS blazar survey: testing the blazar sequence

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\textbf{ABSTRACT}

We discuss the properties of the sources in the CLASS Blazar survey which aims at the selection of low radio power ($P_{5\,\text{GHz}} < 10^{25}$ $\text{W Hz}^{-1}$) blazars. We use VLA data from available catalogues and from our own observations to constrain the radio core-dominance of the sample which, together with the flat radio spectral index, is a signature of the blazar activity. X-ray data from the ROSAT All Sky Survey were also collected in order to constrain the radio-to-X-ray luminosity ratio ($\alpha_{RX}$) of the sources. The data analysis shows that more than 30\% of sources at low radio power ($P_{5\,\text{GHz}} < 10^{25}$ $\text{W Hz}^{-1}$) have an $\alpha_{RX}$ steeper than that expected in the framework of the "blazar sequence" recently put forward to unify the high and low power blazars. The possibility that this result is influenced by contaminating sources in the current sample is discussed. The conclusion is that, even if a number of non-blazars (typically CSO/GPS sources) are expected in the survey, it is unlikely that this constitutes the sole reason for the observed deviation. In particular, we show 2 examples for which the blazar nature is confirmed from VLBI data and for which the steep $\alpha_{RX}$ (suggesting a synchrotron peak frequency below $10^{15.5}$ Hz) and the low radio power ($0.6-2 \times 10^{24}$ $\text{W Hz}^{-1}$) put these sources outside the "blazar sequence". The results presented here show the importance of a correct and unbiased sampling of the low-power regime of the blazar population.

\textbf{Key words:} surveys – galaxies: active – BL Lacertae: general – quasars: general

\section{INTRODUCTION}

Blazars distinguish themselves from the rest of the radio-loud AGN by their flat radio spectra, extreme variability, and high polarization in both radio and optical wavelengths. These compact radio sources are embedded in giant ellipticals galaxies and have their Spectral Energy Distribution (SED) dominated by synchrotron and Inverse Compton processes all the way from radio up to gamma-ray frequencies (see Urry & Padovani 1995 for a review). Blazars seem to come in two flavours: Flat Spectrum Radio Quasars (FSRQ), which are more abundant at higher luminosities, and BL Lacs which abound at lower luminosities. The two types of sources differ greatly in their optical spectroscopic properties. Whereas the former show broad and strong emission lines, the latter are spectroscopically dull sources, with only weak or absent emission lines.

Despite their spectroscopic differences, the SEDs of blazars have long been modeled by two broad components: one synchrotron component covering the frequencies from radio to optical, UV or even X-ray, and another, ranging from X-ray to the $\gamma$ frequencies which is attributed to Inverse Compton emission. It has been proposed (Fossati et al. 1998; Ghisellini et al. 1998) that the blazar family could be unified according to a single parameter related to the bolometric luminosity. In particular, it was suggested that there is a 'blazar sequence' established by an anti-correlation between the luminosity of the source and the frequency at which the synchrotron component peaks. In this framework, following a decrease in luminosity and an increase in frequency of the synchrotron peak we find, in order, the FSRQs, the Low-energy peaked BL Lacs (LBL), and finally the High-energy peaked BL Lacs (HBL). The astrophysical explanation put forward by Ghisellini et al. (1998) for this continuity is that the emitting particles suffer of increasing radiative losses as the luminosity increases (see also Ghisellini, Celotti & Costamante 2002). Thus, in the less intrinsically powerful sources - the HBLs - the radiative cooling is less important and the highly energetic particles can carry on producing synchrotron and Inverse Compton emission up to high frequencies. Conversely, the most powerful sources - the FSRQs - suffer stronger cooling and synchrotron emission peaks at much lower frequencies.

It must be noted, however, that the blazar sequence rests on the observational lack of low-power, low-energy peaked, and high-power, high-energy peaked blazars. The question therefore arises: is the lack of such sources real or is it a consequence of selection effects? In this latter case, the seeming 'blazar sequence' could simply be due to limi-
tations of the blazar samples available at the time when the SEDs of the different types of blazar were modeled by Fossati et al. (1998). If this is the case, deeper surveys able to sample the ‘radio power/peak frequency plane’ more homogeneous should find blazars outside the blazar sequence.

A good test to the proposed blazar continuity is to investigate its validity in the low power regime, where primarily HBL should abound. In this power regime, however, the usual classification of a BL Lac or emission line object based on the optical spectral analysis is heavily hampered by the dilution of the nuclear emission due to the presence of the host galaxy. This problem affects mostly the LBL and this may result in a biased view of the blazar population at these powers. An alternative tool to classify an object as blazar is thus required. In this paper we propose to use the radio compactness (on arcsecond scale) as an alternative way to select blazar candidates. The aim of this paper is to present the analysis of the first large and statistically significant sample of low-luminosity blazar candidates selected from the CLASS Blazar Survey (CBS, Marchà et al. 2001) on the basis of their radio compactness. This sample is used to test the validity of the blazar sequence for radio powers below $10^{25}$ W Hz$^{-1}$.

The paper is organised as follows: in the next Section we discuss the lack of samples able to select low-power blazars in an unbiased way. In the following two Sections (3 and 4) we briefly present the selection criteria and optical data of the CBS. In order to avoid subtle bias, we will not make use of the optical data to classify the sources as blazar. Instead, we exploit the radio data (Section 5) to assess the blazar nature of the selected sources. The X-ray data used to derive the X-ray-to-radio spectral indices are presented in Section 6, and in Section 7 we discuss the consistency of the data with blazar unified model. In Sections 8, 9 and 10 we investigate some explanations for the observed departure from the blazar sequence. Finally, in Section 11 the summary and conclusions are presented. Throughout the paper the following quantities are used: $H_0 = 50$ Kms$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$.

2 THE NEED OF A BETTER SAMPLING OF THE $\alpha_{RX}$-P$_{5GHz}$ PLANE

The blazar unified model (Fossati et al. 1998) has been proposed on the basis of the remarkable continuity observed in the SED behaviour as a function of the radio power. Three blazar samples were used to derive this correlation, namely the X-ray selected sample of 48 BL Lacs extracted from the Einstein Slew Survey (Porlman et al. 1996), the radio selected sample of 34 BL Lacs taken from the 1 Jy survey (Stickel et al. 1991) and the radio selected sample of 233 FSRQ of the 2 Jy survey (Padovani & Urry 1992).

The key point of the blazar sequence rests on the lack of low-power ($P_{5GHz} < 10^{25}$ W Hz$^{-1}$) low-energy peaked ($\nu < 10^{15.5}$ Hz) blazars and high power ($P_{5GHz} > 10^{26}$ W Hz$^{-1}$) high energy peaked blazars ($\nu > 10^{16}$ Hz).

In the low-power regime (which is the subject of the analysis presented in this paper) the lack of low-energy peaked blazars is introduced by the lack of low-power blazars showing a low X-ray-to-radio flux ratio (i.e. a “steep” radio-to-X-ray spectral index $\alpha_{RX}^*$): In fact, all the blazars considered by Fossati et al. (1998) with a radio power below $10^{25}$ W Hz$^{-1}$ have $\alpha_{RX} < 0.7$ (see discussion in Section 8).

The important point we would like to stress here is that in the Fossati et al. (1998) analysis all the low-power blazars come from the Slew Survey which is strongly biased against steep $\alpha_{RX}$ objects, due to the presence of an X-ray flux limit.

To better clarify this point, let us consider a blazar with a radio power of $10^{24}$ W Hz$^{-1}$. Depending on the $\alpha_{RX}$ value its X-ray luminosity (0.3-3.5 keV) ranges from $\sim 6 \times 10^{42}$ erg s$^{-1}$ ($\alpha_{RX} = 0.9$) to $\sim 6 \times 10^{43}$ erg s$^{-1}$ ($\alpha_{RX} = 0.5$). Given the flux limit of the Slew Survey ($\sim 5 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$) the detectability of an object with $\alpha_{RX} = 0.9$ is thus limited up to a low redshift, corresponding to a relatively small volume of universe ($\sim 3 \times 10^{5}$ Mpc$^{-3}$, considering the area of sky covered by the Slew Survey) when compared to the low BL Lac density expected at these X-ray luminosities ($\sim 10^{-6}$ Mpc$^{-3}$, based on the extrapolation of the X-ray luminosity function presented in Wolter et al. 1994). Thus, the Slew Survey is not expected to select such steep low-power sources, even if they exist and have the same volume density as the HBL objects.

A similar argument can be applied to the new samples based on the cross correlation between radio and X-ray catalogues, like the the ROSAT Green-Bank Survey (RGB, Laurent-Muehleisen et al. 1998) and the REX survey (Caccianiga et al. 1999). Even if these surveys go deep in the radio band ($\sim 5$–$50$ mJy), the requirement of an X-ray emission greater than $\sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (REX), or even $\sim 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (RGB), makes these surveys not sensitive to steep $\alpha_{RX}$ low-power blazars.

The DXRBS is more sensitive to LBL-like objects, as can be seen from the quite large number of sources with a steep $\alpha_{RX}$ (e.g. see Padovani et al. 2003). However, this sample does not contain many low-power sources. It is interesting to note that, even if based on small numbers, the DXRBS shows a relatively large fraction ($\sim 33\%$) of low-energy peaked ($\dot{u}_{peak} < 10^{15.5}$ Hz) BL Lacs in the low-power regime ($P_{5GHz} < 2 \times 10^{25}$ W Hz$^{-1}$) contrary to what is expected from the blazar unified model (Padovani et al. 2003).

We conclude that the $\alpha_{RX}$-$P_{5GHz}$ plane has not been covered homogeneously so far and, in particular, the low radio power regime has been systematically sampled only for flat values of $\alpha_{RX}$. Therefore, caution must be taken before deriving any conclusion about any power/peak frequency correlation. The lack of any significant anti-correlation between the synchrotron peak frequency and the radio power among the sources of the DXRBS recently found by Padovani et al. (2003) seems to support this idea.

One of the goals of the CLASS Blazar Survey (CBS, Marchà et al. 2001, herein paper I) is to sample the low-power regime without a bias against steep $\alpha_{RX}$ blazars in
order to verify the statements about the blazars unified models.

3 THE CLASS BLAZAR SAMPLE

In Marcha et al. (2001, herein paper I) the CLASS blazar sample (CBS) has been presented and discussed. In summary, 325 flat spectrum radio sources have been selected out of the CLASS survey (Myers et al. 2003) with the following criteria:

(i) $35^\circ \leq \delta \leq 75^\circ$
(ii) $|b| \geq 20^\circ$
(iii) $S_{\nu} \geq 30$ mJy
(iv) flat spectrum, i.e. $\alpha_{1.4} \leq 0.5$ ($S_{\nu} \propto \nu^{-\alpha}$)
(v) red magnitude $\leq 17.5$

A closer analysis of the radio maps have then excluded 23 “fake” flat-spectrum sources originally included in the sample as a result of the different resolution of the radio catalogues (GB6 and NVSS) used for the selection (see paper I for the details). Thus, the final CBS sample includes a total of 302 sources.

Even though the selection criteria summarized above are optimised to select blazars, there remain some “interlopers” in the CBS. The exclusion of the 23 “fake” flat-spectrum sources described in paper I was based on the analysis of the NVSS data which does not have the resolution required to exclude that some extended radio galaxies or quasars are still contaminating the sample. Also, Compact Symmetric Objects (CSO), which have a compact morphology on the kpc scales and often a flat radio spectrum (at the frequencies used for the selection), can be “confused” with a blazar and hence included in the CBS.

In order to separate the “real” blazars in the sample from other sources with physical properties unrelated to the blazar activity, we have collected data over a wide range of different frequencies. In principle, the most common signatures of the blazar activity, like the variability, the optical polarization, or a featureless optical continuum observed in a BL Lac object could be used to separate the blazars from other contaminating sources in the CBS. However, at the radio power regimes considered here (between $10^{23}$ and $10^{25}$ W Hz$^{-1}$), the optical emission of a blazar is expected to be easily overwhelmed by the light of the host galaxy in a significant fraction of cases. Thus, direct evidence of the presence of a featureless synchrotron continuum is difficult to obtain. Even if these problems are not expected to affect all the selected blazars, it is important to note that the blind use of the optical features to classify an object as blazar could introduce subtle selection effects. For this reason, we make use primarily of the radio properties to constrain the presence of a blazar in the CBS sources. The optical observations are used to determine the redshift of the sources. For completeness, the phenomenological classification based on the optical data is also briefly summarized in the next section.

4 THE OPTICAL DATA

So far, optical classification has been collected, either from the literature or from specific observations for 91% of the objects in the sample. The majority of objects with spectroscopic classifications are presented in Caccianiga et al. (2001, hereafter paper II) together with a discussion of the criteria used to classify the sources. Basically, the objects have been broadly divided into those with no emission lines (type 0 objects), including BL Lacs and Passive Elliptical Galaxies (PEGs), objects with broad emission lines (type 1), and objects showing only narrow emission lines (type 2). Since paper II was published, however, new observations have been carried out. The current percentage of sources in the three classes is, respectively, 44% (type 0), 40% (type 1) and 16% (type 2).

As we have already mentioned, the present optical classification is very sensitive to the contribution of the host galaxy in the observed spectrum. Given the nature of the sample, which is mainly focused on the selection of low-power and low redshift sources, the host galaxy can even overshadow the nuclear emission making the spectroscopical classification of the source very difficult. This problem affects mainly the featureless objects (BL Lac objects) but also weak emission lines can be undetected because of the host galaxy.

The problem of emission line strength in the classification of low-power blazars has no simple solution and a specific discussion will be presented in a forthcoming paper. In the present work, instead, we concentrate on the fact that the essential common feature of all blazars is their flat radio spectrum and radio compactness.

5 RADIO DATA: ESTABLISHING THE COMPACTNESS OF THE SAMPLE

Blazars are thought to be radio galaxies whose jet is well aligned with the line of sight, and therefore highly affected by relativistic beaming (e.g. Urry & Padovani 1995). It is in this framework that their flat radio spectra are interpreted as the superposition of several compact, self-absorbed components in the jet. Hence, blazars should have their radio emission dominated by a compact region. In this Section we analyse the compactness of sources in the CBS using VLA data taken in different configurations and frequencies.

5.1 The VLA B-array data

The GB6 and NVSS data available by definition for all the sources in the sample are not very effective to distinguish the compactness of the sources. For instance, the large beam of the NVSS (FWHM=45″) corresponds to a linear scale of ~300 kpc at $z=0.3$.

Observations in the B configuration of VLA represent the best compromise in terms of resolution and sensitivity to extended structures to allow the study of the radio “compactness” of the CBS sources. The resolution in this configuration (~5″at 1.4 GHz) corresponds to a linear scale of about 30 kpc ($z=0.3$) and thus allows us to determine whether the radio emission comes from within the host galaxy or from some more extended structure. At this resolution a typical radio galaxy will appear clearly extended. On the contrary, a core-dominated source will be unresolved. At the same time, the largest angular scale ($\theta_{LAS}$) detectable in this configuration and frequency (about 2′′) is large enough
to avoid any flux loss for the majority of the CLASS sources which are typically unresolved (integrated flux \(\sim\) peak flux) at the NVSS resolution. For the few sources clearly extended even at the NVSS resolution we can use the NVSS integrated flux which is reasonably representative of the total flux (\(\theta_{\text{LAS}}=15^\prime\)).

For 61% of the entire CBS sources data from the FIRST survey (Becker et al. 1995) are available. The FIRST survey (Faint Image of Radio Sky at Twenty centimeters) is made with the B-array of VLA at 1.4 GHz reaching an rms of \(\sim 0.15\) mJy/beam. In particular, we have used the most recent version of the FIRST catalogue (April 2003). We have collected additional VLA data with the same configuration and frequency, and similar rms as FIRST. Observations were made on May 11th and 27th, 2001 (24 hours in total) of 68 sources (48 with \(z<0.3\)). The typical time-on-source of these snapshots ranges from 4 to 5 minutes reaching an rms of 0.1-0.6 mJy/beam. The calibrators used during the observations of May 11th were J0029+349 and J0137+331 while the calibrators used in May 27th were J0614+607, J0921+622, J1331+305, J1435+760 and J1927+612. The data have been reduced using the AIPS (Astronomical Imaging Processing System) package of the National Radio Astronomy Observatory (NRAO).

In Table 1 the VLA B-array data are presented. In total, VLA B-array 1.4 GHz data are now available for 78% of the entire CBS sample, and for 84% of the sources with \(z<0.3\). Apart from 7 objects that turned out to have a double morphology (see Table 1), all the remaining objects show a clear core plus (sometimes) one sided extended emission. Using these data we have computed a core-dominance parameter (\(R\)) defined as follows:

\[
R = \frac{S_{\text{core}}}{S_{\text{ext}}} \times (1+z)^{-1}
\]

where we have assumed the core flux density \(S_{\text{core}}\) equal to the peak flux density of the brightest component, and the extended flux density \(S_{\text{ext}}\) equal to the total flux density minus the peak flux density. The total flux density is the integrated flux density computed by us or derived from the FIRST catalogue. If more than one component is present in the FIRST catalogue the total flux density is the sum of all these components. For the few extended sources (46 in total, 37 with \(z<0.3\)) where a fraction of the flux density could have been missed in the VLA B-configuration, we have used the NVSS integrated flux density as total flux density. These objects are clearly among the less core-dominated ones: the large majority (96%) of these sources have \(R<10\) and the average value of \(R\) is equal to 1.6.

Finally, for the 7 sources with a double morphology, we have considered the 8.4 GHz flux taken at the VLA in A-configuration (see also Myers et al. 2003 for a detailed description of the data). All the 8.4 GHz fluxes of the CBS sources have been reported in paper I. The resolution achieved with these observations is about 0.24 arcsecond, hence a factor 20 higher resolution than the B-array data. These data are useful to further constrain the compactness of the sources although it must be kept in mind that flux on scales larger than 7 arcsec can be lost in this configuration. Thus a steep spectral index between 1.4 and 8.4 GHz is an indication that the source is not very compact on \(\sim\)arcsecond scale.

In Figure 2 the core-dominance parameter computed for the sources with VLA B-array data is plotted against the spectral index \(\alpha_{1.4}^{8.4}\) between 1.4 GHz (using the NVSS total flux) and 8.4 GHz. The evident correlation between the two quantities supports the idea that the \(\alpha_{1.4}^{8.4}\) can be used to constrain the compactness of the sources, when the VLA B-array is not available. In particular, based on Figure 2 we find that the large majority (95%) of the sources with \(\alpha_{1.4}^{8.4}<0.6\) (continuous line in Figure 2) have \(R>1\). At the same time, the large majority (94%) of the sources with \(R>1\) have \(\alpha_{1.4}^{8.4}<0.6\). Thus, for the sources for which the

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**Figure 1.** The distribution of the core-dominance parameter computed as described in the text for all the sources for which VLA B-array data at 1.4 GHz are available. The shaded area indicates the sources with \(z<0.3\).
VLA B-array is not available the constraint $\alpha_{8.4}^{8.4} < 0.6$ is almost equivalent to require $R>1$.

In Figure 3 the distribution of $\alpha_{8.4}^{8.4}$ is presented for all the sources in the CBS and for those with no VLA B-array data available (shaded histogram). Only about 20% of the sources without VLA B-array data have $\alpha_{8.4}^{8.4} > 0.6$ and are thus expected to have (mostly) $R<1$.

In conclusion, the analysis of the VLA data collected so far strongly indicates that the majority ($\sim 80\%$) of the sources selected in the CBS sample is actually core-dominated ($R>1$).

5.3 A working definition of blazar candidate

As already described, our aim is to use the radio data to pin-point the blazars selected in the CBS. By using the VLA data described above, we consider an object as “bona-fide” blazar if $R>1$ or, in case the B-array data are not present, if $\alpha_{8.4}^{8.4} \leq 0.6$.

In the context of the beaming model, the R parameter is directly linked to the beaming parameter ($\delta^p$): \[ R = f \delta^p \]

where $f$ is the ratio of intrinsic jet to unbeamed luminosity (Urry & Padovani 1995). Assuming the fiducial values for $f(=0.01)$, $\Gamma (=5)$ and by using the mean $\alpha$ for the sample ($=0.4$), the imposition of $R>1$ corresponds to observing angles below $\sim 8$ degrees. Hence, the definition of a blazar based on the R parameter has a direct physical meaning in terms of degree of beaming and viewing angle.

Based on this definition, 244 sources in the CBS sample are thus classified as blazar candidates. In the following sections the term blazar candidate will be used to specify these 244 sources whose properties will be analysed and discussed.

6 THE X-RAY DATA

In order to collect X-ray information for the CBS sources we have used the publicly available ROSAT All Sky Survey (RASS) catalogue which reaches flux levels of about $10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in the 0.1-2.4 keV energy band (the Bright Source Catalogue, BSC, Voges et al. 1999), and $\sim 5 \times 10^{-13}$ erg s$^{-1}$ its faint extension (the Faint Source Catalogue, FSC, Voges et al., http://www.xray.mpe.mpg.de/rosat/survey/rass-fsc/).

We have thus cross-correlated the CBS against the two RASS catalogues with a positional tolerance of 40$''$. The reliability of the cross-correlation has been assessed by performing the same cross-correlation after having positionally shifted the two catalogues one from each other by an offset much larger than 40$''$, so that only chance coincidences are obtained. The percentage of spurious matches is estimated to be about 1% (BSC) and about 5% (FSC) (i.e. about 3 - 4 sources in total).

$\delta$ is the Doppler factor defined as $[\Gamma (1 - \beta \cos \theta)]^{-1}$, where $\Gamma$ and $\beta$ are the Lorentz factor and the ratio between the bulk velocity and the light speed, respectively. The exponent $p$ is equal to $\alpha+2$ for a continuous jet where $\alpha$ is the spectral index (see Urry & Padovani 1995 for a detailed description of the beaming model).
than among the total sample (42%). Only about 30% of the low-power blazar candidates ($P \leq 10^{25}$ W Hz$^{-1}$) have been detected in the RASS.

The X-ray fluxes have been computed from the published count-rates by assuming a photon index of 2 ($\alpha_X=1$) and de-absorbed for the galactic absorption by using the galactic column density presented in Stark et al. (1992). For the sources not detected in the RASS catalogues we need an estimate of the upper limit on the X-ray flux. This is not a simple task since the RASS does not have a “flat” sky coverage and the actual count-rate limit depends on the sky position. We have estimated a “statistical” upper limit in the following way. We have performed a positional cross-correlation of the RASS catalogues with a deeper X-ray catalogue, based on the pointed ROSAT PSPC images, used to define the REX survey (see Caccianiga et al. 1999 for the details). This catalogue is based on the analysis of 1202 pointed ROSAT PSPC images and reaches flux limits of $\sim 3.5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in the 0.5-2.0 keV energy range on a sky region of 2183 deg$^2$. We have only considered the sources in the area covered by the CBS sample to check the sensitivity of the RASS in the right sky position, and those detected with a high significance ($\sigma > 10$, see Caccianiga et al. 1999). We have then evaluated the count-rate above which more than 90% of the sources included in the deep X-ray catalogue have a counterpart in the RASS catalogue. We have used this count-rate as an upper limit for the non-detection. We note that this value (CR=0.05 counts s$^{-1}$) is higher than the faintest count-rates found in the RASS FSC, which reach values as faint as 0.01 counts s$^{-1}$.

The upper-limits of the X-ray fluxes were then computed by assuming this conservative limiting count-rate of 0.05 counts s$^{-1}$, and converted into a de-absorbed X-ray flux on the basis of the galactic column density.

Figure 4 shows the X-ray luminosity distribution for the CBS sources. The X-ray fluxes are used in the next section to estimate the radio-to-X-ray luminosity ratio of the sources in the CBS sample detected in the RASS catalogues.

7 THE $\alpha_{RX}$ DISTRIBUTION AND THE BLAZAR SEQUENCE

According to the blazar sequence, the low-power regime should be dominated by high-energy peaked sources, characterized by small (flat) values of the radio-to-X-ray spectral index ($\alpha_{RX} \leq 0.75$).

To better quantify this statement, we have reproduced here two figures (Figure 5 and Figure 6) taken from Fossati et al. (1998). The blazar sequence as defined by Fossati et al. (1998) is reported in Figure 5. According to this sequence, all the blazars with a radio power below $10^{25}$ W Hz$^{-1}$ (corresponding to $P_{2-2.4\text{ keV}}=10^{41.7}$ erg s$^{-1}$) are expected to have a synchrotron peak frequency larger than $\sim 10^{15.5}$ Hz. If we now look at Figure 6 we see that this high peak frequency translates into a very flat $\alpha_{RX}$ value. Although the correlation between $\alpha_{RX}$ and the synchrotron peak frequency has quite a large scatter, it is true that all the sources considered by Fossati et al. (1998) with a synchrotron peak frequency larger than $\sim 10^{15.5}$ Hz have a $\alpha_{RX}$ in the range 0.4-0.75. This statement holds also using the blazars in the DXRBS sample (see Figure 11 from Padovani et al. 2003), although the number of objects in this sample with a synchrotron peak frequency larger than $\sim 10^{15.5}$ Hz is very small (3 sources in total)†.

Thus, we expect that all the blazar candidates in the $10^{24}$-$10^{25}$ W Hz$^{-1}$ power range have an $\alpha_{RX}$ flatter than 0.7-0.75, if they fit the blazar sequence.

We note that such a flat $\alpha_{RX}$ value would correspond to X-ray fluxes larger than $1.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (0.5-2.0 keV) given the radio fluxes of the CBS sources ($S_{3\text{GHz}} > 30$ mJy). Thus, many of the low-power blazar candidates should have been detected in the RASS survey. Instead, as described in the previous section, only 30% of the low power objects have been detected in the RASS survey.

In Figure 7 we have plotted the values of $\alpha_{RX}$ for the CBS blazar candidates including the lower-limits on $\alpha_{RX}$ for the sources not detected in the RASS. The objects without spectroscopic classification, and the BL Lacs without redshift have been excluded from the plots.

The important conclusion which can be drawn from the analysis of Figure 7 is that a large fraction of the objects in the low power regime show $\alpha_{RX}$ values (or lower limits) much steeper than 0.75.

More quantitatively, we have considered only the sources with a radio power between $10^{23}$ and $10^{25}$ W Hz$^{-1}$ and we have plotted the distribution of the corresponding

† The lack of objects in this region of the parameter space is an obvious consequence to the fact that the DXRBS is not very sensitive to the extreme HBLs so the high peak frequency range (between $10^{16}$ and $10^{18}$ Hz) is poorly sampled.
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Figure 5. The radio power (multiplied by the frequency) in erg s\(^{-1}\) versus the synchrotron peak frequency (in Hz) of the blazars considered by Fossati et al. (1998) to derive the “blazar sequence”. According to this sequence, all the blazars with a radio power below \(10^{25}\) W Hz\(^{-1}\) should have a synchrotron peak frequency larger than \(\sim 10^{15.5}\) Hz (shaded area). Adapted from Fossati et al. (1998).

Figure 6. The \(\alpha_{\text{RX}}\) values versus the synchrotron peak frequency for the blazars studied by Fossati et al. (1998). The expected values of \(\alpha_{\text{RX}}\) for blazars with a radio power below \(10^{25}\) W Hz\(^{-1}\) (shaded area, see previous Figure) are in the range between 0.35 and 0.7. Adapted from Fossati et al. (1998). 

\(\alpha_{\text{RX}}\) values (Figure 8). If we consider the lower limits as actual detection, the fraction of sources with \(\alpha_{\text{RX}}\) steeper than 0.75 is 30%. This should be considered as a lower limit since the non detections are expected to be distributed at larger values of \(\alpha_{\text{RX}}\). By using the non-parametric method described in Avni et al. (1980), which provides an analytic solution for the best estimate of a distribution function of one (binned) independent variable (the \(\alpha_{\text{RX}}\)) taking into account the lower limits, we have derived the expected real \(\alpha_{\text{RX}}\) distribution (lower panel in Figure 8). Based on this distribution, the percentage of sources in the low radio power range with \(\alpha_{\text{RX}} > 0.75\) is 68%.

It is worth noting that for a number of objects detected in the RASS, the X-ray emission could be partly due to the presence of hot gas associated to the host galaxy. Since the thermal X-ray luminosity of elliptical galaxies can reach values up to \(10^{42}-10^{43}\) erg s\(^{-1}\) (Forman et al. 1994), only the few sources in the low luminosity tail of the distribution presented in Figure 4 can be affected by this problem. In any case, after having taken into account the thermal contribution from the host galaxy, the corrected values of \(\alpha_{\text{RX}}\) are expected to be steeper than uncorrected ones, thus populating even more the steep \(\alpha_{\text{RX}}\) region of Figure 7.

We conclude that a large fraction (between 30% and 68%) of the core-dominated sources selected in the CBS with a radio power between \(10^{23}\) and \(10^{25}\) W Hz\(^{-1}\) have \(\alpha_{\text{RX}}\) values steeper than 0.75, thus they lie outside the blazar sequence.

In the next sections we investigate 3 possible explanations for the large spread of the \(\alpha_{\text{RX}}\) values observed at low-powers:

- The sources found outside the predicted sequence are spurious optical identifications (Section 8);
- At low-powers the orientation effects become important and some weakly beamed but intrinsically high-power objects are selected (Section 9);
- For powers below \(10^{23}\) W Hz\(^{-1}\) a population of sources different from blazars and characterized by a weak (or even absent) X-ray emission, is getting into the sample thus spreading the blazar sequence (Section 10);

8 SPURIOUS IDENTIFICATIONS?

Among the 24 low-power sources (\(P_{5\text{GHz}} = 10^{23-10^{25}}\) W Hz\(^{-1}\)) with \(\alpha_{\text{RX}} > 0.75\) (or the lower limit on the \(\alpha_{\text{RX}} >\) larger than this value) there are 10 galaxies with no obvious signs of activity in their optical spectra (6 have the typical spectrum of an elliptical galaxy and 4 have narrow emission lines probably associated with the host galaxy), and another 10 objects showing a broad H\(\alpha\) emission line. The remaining 4 sources are classified in the literature as Sy2/LINERS due to the presence of narrow emission lines in the optical spectrum. In principle, some of the “normal” galaxies could be objects included by mistake in the cross-correlation with the optical catalogue (APM\(^\circ\)), while the real counterpart of the radio source could be a fainter (more distant) blazar. In this case, the redshift (and thus the radio power) would

\(^{\circ}\) www.ast.cam.ac.uk/~apmcat/
Figure 7. Two-point spectral index ($\alpha_{RX}$) versus the radio power at 5 GHz for the CBS blazar candidates. For the objects not detected in the RASS survey the lower limits on $\alpha_{RX}$ are indicated (see text for details). The two continuous lines define the range of radio power where, according to the blazar sequence, we should have found only blazars with “flat” ($<0.75$) $\alpha_{RX}$ values. The dashed line indicates $\alpha_{RX}=0.75$

Figure 8. The two-point spectral index ($\alpha_{RX}$) distribution for the sources in the CBS blazar candidates and with a radio power between $10^{23}$ and $10^{25}$ W Hz$^{-1}$. top panel: sources detected in the RASS; middle panel: sources not detected in the RASS; lower panel: the expected “real” distribution computed with the method described in Avni et al. (1980) (see text for details)

be underestimated while the $\alpha_{RX}$ value would be the one relative to the powerful blazar (i.e. a steep $\alpha_{RX}$, according to the blazar sequence). This could explain, in principle, the peculiar position of these sources in the $\alpha_{RX}/P_{5\text{GHz}}$ plane.

In Paper I we have described in detail the technique used to find the optical counterparts of the radio sources in the CLASS sample. In order to assess the reliability of that identification procedure we have run ten times the positional cross-correlation between the CLASS and the APM catalogues, after having applied a positional offset to the CLASS sources from $\Delta\delta=+1^\prime$ to $+10^\prime$, plus an additional cross-correlation with $\Delta\delta=+1$ degree. In this way, all the matches are expected to be of spurious origin. After having applied the same selection criteria used to select the CBS sample, we have found 12 spurious point-like sources (APM classification equal to “1”), plus 3 galaxies (APM classification = “2”), and 4 blends (APM classification = “2”). So far, 5 objects have been spectroscopically identified as stars and they probably make up the point-like spurious matches. The case of spurious galaxies, however, is clearly a less simple one, as these represent credible counterparts of the radio source. Nevertheless, the fact that we only expect $\sim$3-7 (including the blends) spurious matches means that this would be insufficient to explain the deviation from the ‘blazar sequence’. In any case, we performed another check by plotting the very accurate ($\sim$arcsec) 8.4 GHz positions taken with VLA A-array on the optical finding chart of some of the 24 sources with a steep $\alpha_{RX}$ in the low power regime. We found that in all cases the radio position is consistent with the optical nucleus thus confirming that the radio and the optical emission come from the same source.

Hence, the spurious radio/optical matches do not explain the discrepancy observed in the $\alpha_{RX}/P_{5\text{GHz}}$ plane.

9 ORIENTATION EFFECTS?

In this Section we investigate the possibility that orientation effects are responsible for the deviation from the blazar sequence found in the CBS sample.

If an intrinsically high-power blazar, with a steep $\alpha_{RX}$, like those observed in the 1 Jy sample, is observed at larger angles, the Doppler factor ($\delta$) decreases with the observing angle $\theta$ and the observed radio power is expected to decrease rapidly, i.e. proportionally to $\delta^p$, with $p=2+\alpha \sim 2.4$ (see Urry & Padovani 1995). The observed $\alpha_{RX}$, instead, changes only if the radio and the X-ray spectral indices are different (see, for instance, Chiaberge et al. 2000). Therefore, a mis-alignment jet/observer can spread the blazar sequence and, in particular, it may populate the low-power/steep $\alpha_{RX}$ region.

The possibility that the spread in $\alpha_{RX}$ observed at low radio powers is due to some orientation bias can be tested by analysing the radio properties of the CBS sources. In particular, if this hypothesis is correct, we would expect low-power/high-$\alpha_{RX}$ sources to be less core-dominated than the others.

More quantitatively, the distribution of the core-dominance parameter for the sources with radio power be-
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Figure 9. The core-dominance parameter distribution for the blazars with $P_{5\,\text{GHz}} < 10^{25}\,\text{W Hz}^{-1}$: with $\alpha_{RX} < 0.75$ (upper panel), and with $\alpha_{RX} > 0.75$ (bottom panel).

Figure 10. Two-point spectral index ($\alpha_{RX}$) versus the radio power at 5 GHz for the sources in the CLASS Blazar Survey for the sources with $z<0.3$ and with $R>10$.

low $10^{25}\,\text{W Hz}^{-1}$ is shown in Figure 9. The top panel shows the distribution of the sources with $\alpha_{RX} < 0.75$, and the bottom panel shows the distribution of those sources with $\alpha_{RX} > 0.75$. The two distributions are not significantly different (Kolmogorov-Smirnov probability = 75% for the null hypothesis).

In Figure 10 we have re-produced Figure 7 using only the blazar candidates with $z<0.3$ and $R>10$. If the orientation was really the cause for the observed spread at low-power of Figure 7, we would expect that by using only the highly core-dominated sources, the resulting plot would show a better power/$\alpha_{RX}$ correlation. This, however, is not the case, and we find that the sources with low-power and high/$\alpha_{RX}$ are still present. This result suggests that orientation is not the main reason for the big spread of $\alpha_{RX}$ values observed at low radio powers.

In Figure 11 we show the radio maps (VLA B-array at 1.4 GHz) for the 24 low-power blazar candidates that do not fit the blazar sequence, i.e. with $\alpha_{RX} > 0.75$. Given the redshift range covered by these 24 sources (0.01 – 0.1) the resolution of the maps corresponds to linear scales between 1.4 kpc and 14 kpc.

10 CONTAMINATION BY NON-BLAZARS

In this Section we investigate the possibility that the spread in the $\alpha_{RX}/P_{5\,\text{GHz}}$ plane found in the CBS is the result of contamination by sources that are not true blazars but which slipped in the sample because of the selection criteria. These non-blazars must have the following properties:

1) weak X-ray emission when compared to the radio emission;

2) radio power at 5 GHz between $10^{23}$ and $10^{25}\,\text{W Hz}^{-1}$ with only few cases of sources with a radio power below $10^{23}\,\text{W Hz}^{-1}$;

3) flat–spectrum and core-dominated (at arcsecond resolutions).

Overall this population must have 5 GHz radio powers consistent with those of the HBLs typically selected in X-ray survey (Slew Survey, EMSS) but with X-ray luminosities more than 10 times lower.

Different possibilities are analysed below.

10.1 GPS/CSO objects

A viable possibility is that these sources are Gigahertz Peaked Sources (GPS) or Compact Symmetric Objects (CSO). These sources are compact at these resolutions and, in many cases, they appear as flat spectrum objects between 1.4 and 5 GHz. A number of CSO/GPS are actually expected in the CLASS survey. Current data suggests that the percentage of CSO/GPS sources in radio selected samples varies from 2 to 11% (Peck & Taylor 2000). The problem, however, resides in estimating the percentage of this type of sources at the powers sampled by the CBS. In fact, the Luminosity Function (LF) of CSO/GPS sources is very badly determined, particularly at radio luminosities below $10^{25}\,\text{W Hz}^{-1}$ (see for instance, Snellen et al. 2000).

In order to address this issue we make use of current investigations concerning the 200 mJy sample (Marchâa et al. 1996), which has similar selection criteria to the CBS and for which VLBI data exist for the majority of the sources. The 200 mJy sample has ~60 flat radio spectrum objects with flux density limit of 200 mJy, and optical selection similar to that of the CBS. VLBI observations of the 200 mJy sample do indeed find a number of CSOs sources (Polatidis et
al. in prep). An \(\alpha_{RX}-P_{5GHz}\) plot for the 200 mJy sample yields a similar excess of sources to the one found in the CBS (\(\sim 30\%\)) above the blazar sequence for radio powers \(<10^{23}\)WHz\(^{-1}\). Making use of the VLBI data currently available we find that among the eleven sources outside the sequence, three have a CSO morphology, while the remaining show a core-jet morphology, as expected in the case of blazars. At present we do not have similar results for the CBS, but radio observations at higher (VLBA) resolutions of some of these sources are underway. However, if the percentage of the CSOs is the same as in the 200 mJy sample, these sources cannot represent a completely satisfactory explanation for the observed excess of steep \(\alpha_{RX}\) objects in the CBS.

### 10.2 The high luminosity end of radio-quiet sources

Another possible population which can be present in the CBS sample is that of the radio-quiet AGNs (i.e. Seyfert galaxies) whose radio powers range from \(10^{18}\) to \(10^{24}\) W Hz\(^{-1}\) (e.g. Ulvestad & Wilson 1989; Ulvestad & Ho 2001a). It must be considered, however, that the majority (\(\sim 90\%\), Ulvestad & Wilson 1989) of powerful Seyferts have steep radio spectra and they should not be efficiently selected in the CBS sample. An important exception is that of Low-luminosity Seyferts: the analysis of the radio properties of 45 low-luminosity Seyfert galaxies (type 1 and type 2) taken from the Palomar spectroscopic survey of nearby galaxies undertaken by Ulvestad & Ho (2001a) has shown that a significant fraction (\(\sim 50\%\)) of them have flat or inverted radio spectra. The origin of the flat radio radio emission in these sources could be related to a jet-like (but not necessarily beamed) structure, to an ADAF activity or to a combination of the two mechanisms (see for instance Ulvestad & Ho 2001b).

The radio powers observed in these AGNs are typically below \(10^{23}\) W Hz\(^{-1}\) and, even if the 8 objects in Figure 7 with a radio power below \(10^{23}\) W Hz\(^{-1}\) were potentially similar to the Seyfert galaxies studied by Ulvestad & Ho \(\ddag\), the mean radio power of the 24 sources under study here (\(10^{24}\) W Hz\(^{-1}\)) is 4 orders of magnitude larger than the mean radio power of the Seyfert galaxies from the Palomar spectroscopic survey (\(10^{20}\) W Hz\(^{-1}\)). Therefore, the contamination by this kind of objects in the CBS sample must be very low and should affect only the very low-power range (<\(10^{23}\) W Hz\(^{-1}\)).

### 10.3 ULIRG

Among the 24 objects that are ‘out of the sequence’, there are two well known Ultra Luminous Infrared Galaxies (ULIRG), namely Mrk 231 and Mrk 273, in which the extremely intense starburst activity contributes to a significant fraction of the radio power (e.g. Ulvestad, Wrobel & Carilli 1999; Carilli & Taylor 2000). In the case of Mrk 231 the nuclear radio component not related to the starburst activity (about 100 mJy) could be associated to a CSO (Lonsdale et al. 2003). The SEDs of these 2 sources are dominated by the far-IR emission (detected with IRAS). Among the 24 sources there are 3 more objects which are detected in IRAS but with a FIR luminosity below the \(10^{12}\) L\(_\odot\) and are not classified as ULIRG.

Except for the two ULIRG Mrk 231 and Mrk 273, in the other objects the starburst emission (if present) is not expected to be the dominant component. In any case, accurate VLBI measurements are needed in order to separate the emission due to the starburst phenomenon from the genuine AGN emission. A similar analysis must be done also in the X-ray band.

### 10.4 Conclusion about the contaminating sources

From the discussion above we can conclude that some contamination from non-blazars is expected in the CBS, something that indicates that also a selection criterion based solely on the radio compactness (at the VLA resolution) may not be 100\% reliable in selecting blazar, in particular in the low-power regime. Clearly, higher resolution data (VLBI) will be needed to disentangle the non-blazars from the blazar population. For this reason a systematic observation of the CBS sources with VLBI is in progress. At present, however, we already have 2 good confirmations of low power blazars which defy the proposed ‘blazar sequence’:

GB6J022526+371029 (CGCG523-037). This object (z=0.0334) shows an optical spectrum dominated by the host galaxy with a few emission lines (H\(\beta\), [OIII]\(\lambda 5007\)A, [OII], Ho, [NII], [SII]) (Caccianiga et al. 2002). It belongs also to the B2 catalogue and it has been classified as Low-power compact sources (LPC, Giovannini et al. 2001) due to its low-power and high compactness. The object has been observed with the European VLBI Network (EVN) and with the VLBA by Giovannini et al. (2001). In both observations an unresolved source has been detected with a total flux density comparable to the arcsecond core flux density. Based on these observations, Giovannini et al. (2001) suggested for this object a classification as low-power (\(P_{5GHz}=7\times10^{23}\) W Hz\(^{-1}\)) BL Lac whose observed core power is too low to dominate the optical emission. The non-detection in the RASS implies \(\alpha_{RX}\) >0.77.

GB6J164734+494954 (JVAS J1647+499). The blazar nature of this source (z=0.0475) has been clearly confirmed by the detection of a high and variable optical polarization (Jackson & Marcha 1999). The VLBA map at 4.9 GHz (Bondi et al. 2001) shows a bright core plus a collimated one-sided jet. In the X-ray, the source has been detected in the RASS with a count rate of 0.097 counts/s corresponding to an unabsorbed X-ray flux in the 0.1-2.4 band of \(1.4\times10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) (assuming a power law spectrum of \(\Gamma=2\)). The corresponding \(\alpha_{RX}\) is 0.75-0.77, using the core flux at 4.9 GHz published by Bondi et al. (2001) or the GB6 flux respectively. The radio power at 5 GHz is \(1.9\times10^{24}\) W Hz\(^{-1}\).

The existence of these 2 low-power blazars with a steep \(\alpha_{RX}\) value (thus suggesting a synchrotron peak frequency below \(10^{15.5}\) Hz) constitutes confirmation that there is indeed a deviation from the proposed blazar sequence. What remains to be established is the quantification of this deviation, something that will require the collection of more data.
11 SUMMARY AND CONCLUSIONS

In this paper we have analysed the radio and X-ray data of the CLASS Blazar Survey sample which is, until now, the best radio selected sample to study blazars in the low radio power regime. In order to avoid any bias introduced by the optical classification in this luminosity regime, we have used the radio data to classify an object as blazar candidate. Specifically we have used VLA data at 1.4 GHz and B-array (FWHM~5′′), and at 8.4 GHz and A-array (FWHM~0.24′′) to constrain the actual core dominance of the sources included in the CBS. Based on these data, we have defined as blazar candidates those sources which are core-dominated (R>1). We have then used the X-ray information derived from the ROSAT All Sky Survey to compute the radio-to-X-ray flux ratios ($\alpha_{RX}$) of the blazar candidates in the sample. The main goal of this study was to test the so called “blazar sequence” proposed to unify the blazar class (Fossati et al. 1994 RAS, MNRAS). According to this model, and in the range of radio powers under study, we should find only High-energy peaked BL Lac (HBL), i.e. blazars whose synchrotron emission extends up to the X-rays, producing a high X-ray-to-radio flux ratio ($\alpha_{RX} < 0.75$). This is not what we find. The main results of the study can be summarised as follows:

- In the $10^{23}$-$10^{25}$ WHz$^{-1}$ radio power regime, a large fraction (between 30% and 68%) of the sources have a steeper (larger) $\alpha_{RX}$ than what is expected from the blazar sequence traced by previous BL Lac/blazars samples;
- The deviation from the blazar sequence found in the sources of the CBS is unlikely to be due to orientation effects. This is supported by the fact that the deviation from the sequence is still observed when we consider only those sources which are strongly radio core-dominated (R>10) at a linear scale of $\lesssim30$ kpc;
- The possibility that contaminating sources could be at the origin of the observed deviation from the ‘blazar sequence’ was also investigated. The most likely candidates for this contamination are the Compact Symmetric Sources (CSOs) that also appear as compact radio sources at these spatial resolutions. However, we conclude that, if the percentage of CSOs in the CBS is similar to that found in other samples, then it is insufficient to justify the observed deviation. VLBA observations are in progress to distinguish core-jet from double morphology;
- Based on the data available so far we have extracted 2 sources out of the 24 objects that do not fit the blazar sequence, with a core-jet or compact radio morphology at the m.a.s. resolution, thus ruling out the CSO nature.

One of the prime motivations for the selection of the CBS was widening the range of blazar parameter space sampled. Indeed, due to its low radio flux density limit and no X-ray selection, the CBS has made it possible to find sources at low radio powers and with steep $\alpha_{RX}$, i.e. outside the expected sequence across that plane. Even if the contamination by sources other than blazars can be important at these luminosities we have found at least two good cases where the blazar nature of the source is suggested from high resolution (VLBI) maps. We stress here that this kind of source is heavily undersampled in current surveys sensitive to low-power blazars because of the presence, in these surveys, of relatively bright X-ray flux limits.

This result suggests that the ‘blazar sequence’ could be, at least partly, due to selection effects resulting from poor sampling of the relevant parameter space, thus confirming recent results from the DXRBS survey (Padovani et al. 2003).

According to the models which unify the blazar class, the observed peak of the emission is determined by the cooling processes at work (e.g. Ghisellini, Celotti & Costamante 2002). While the existence of an intrinsic physical limit to the synchrotron peak frequency for the most powerful blazar seems to be supported by recent work (Padovani et al. 2003), the large spread in the $\alpha_{RX}$ values observed in the CBS sample may suggest that in the low-power regime different levels of cooling, and thus of peak frequency, may be present. The physical reason of this spread must be investigated. It has been noted by Ghisellini et al. (1998) that the increasing importance of an external radiation field due to instance to the presence of the broad emission lines could increase the cooling level dictating in this way the peak energy of the emitting particles. Therefore, it will be interesting to test whether the observed $\alpha_{RX}$ values are correlated with the optical properties of the sources and, in particular, with the presence and intensity of the emission lines. As already discussed in Section 3, a careful analysis of the nuclear optical spectra at these power regimes can be done only by properly taking into account the presence of the host galaxy. This will be the subject of a forthcoming paper.

ACKNOWLEDGMENTS

We would like to thank I.W.A. Browne and an anonymous referee for useful comments and discussions and G. Fossati, for providing us with the data on the blazar sequence. This research has received partial financial support from the Portuguese Fundação para a Ciência e Tecnologia (FCT, PRO 15132/1999 and SFRH/BPD/3610/2000).

REFERENCES

Avni, Y., Soltan, A., Tananbaum, H., Zamorani, G. 1980, ApJ, 238, 800
Bondi, M., Marchā, M.J.M., Dallacasa, D., Strangelli, C., 2001, MNRAS, 325, 1109
Becker, R.H., White, R.L., Helfand, D.J., 1995, ApJ, 450, 559
Carilli, C.L., Taylor, G.B., 2000, ApJ, 532, 95
Caccianiga A., Maccacaro T., Wolter A., Della Ceca R., Gioia, I.M. 2002, ApJ, 566, 181
Caccianiga A., Maccacaro T., Wolter A., Della Ceca R., Gioia, I.M. 1999, ApJ, 513, 51
Caccianiga A., Marchā M.J.M., Antón A., Mack K.-H., Neeser M., 2001, MNRAS, 329, 877 (paper II)
Chiaberge M., Celotti A., Capetti A., Ghisellini G., 2000, A&A, 358, 104
Forman, W., Jones, C., Tucker, W., 1994, 429, 77
Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G., 1998, MNRAS, 299, 433
Ghisellini G., Celotti, A, Costamante, L., 2002, A&A, 386, 833
Ghisellini G., Celotti, A, Fossati, G., Maraschi, L., Comastri, A., 1998, MNRAS, 301, 451.
Giovannini, G., Cotton, W.D., Feretti, L., Lara, L. Venturi, T., 2001, ApJ, 552, 508
Jackson, N., Marcha, M.J.M., 1999, MNRAS, 309, 153
Landt, H., Padovani, P., Perlman, E.S., Giommi, P., Bignall, H., Tzioumis, A., 2001, MNRAS, 323, 757
Laurent-Muehleisen S.A., Kollgaard R.I., Ciardullo R., Feigelson E.D., Brinkman W., Siebert J., 1998, ApJS, 118, 127
Lonsdale, C.J., Lonsdale, C.J., Smith, H.E., Diamond, P.J., 2003, ApJ, in press (astro-ph/0304335)
Marcha M.J.M., Browne I.W.A., Impey C.D., Smith P.S., 1996, MNRAS, 281, 425
Marcha M.J.M., Caccianiga A., Browne I.W.A., Jackson N., 2001, MNRAS, 326, 1455 (paper I).
Morris S.L., Stocke J.T., Gioia I.M., Schild R.E., Wolter A., Maccacaro T., della Ceca R., 1991, ApJ, 380, 49
Myers S.T., et al. 2003, MNRAS, 341, 1
Padovani, P., Perlman E., Landt H., Giommi P., Perri M., 2003, ApJ, 588, 128
Padovani, P., Urry, C.M., 1992, ApJ, 387, 449
Peck A.B. & Taylor G.B., 2000, ApJ, 534, 90.
Perlman E.S., Padovani P, Giommi P, Sambruna R., Jone L., Tzioumis A., Reynolds J., 1998, AJ, 115, 1253
Perlman, E.S., Stocke, J.T., Schachter, J.F., Elvis, M., Ellingson, E., Urry, C.M., Potter, M., Impey, C.D., Kolchinsky, P., 1996, ApJS, 104, 251
Snellen I.A.G., Schilizzi R.T. Miley G.K., de Bruyn A.G., Bremer M.N., Röttgering H.J.A., 2000, MNRAS, 319, 445.
Stark A.A., Gammie C.F., Wilson R.W., Bally J.,Linke R.A., Heiles C., Hurwitz M., 1992, ApJS, 79, 77
Stickel M., Fried J.W., Kühr H., Padovani P., Urry C.M., 1991, ApJ, 374, 431
Terlevich R., Tenorio-Tagle G., Franco, J., Melnick J., 1992, MNRAS, 255, 71 3
Ulvestad J.S., & Ho L.C., 2001a, ApJ, 558, 56
Ulvestad J.S., & Ho L.C., 2001b, ApJ, 562, L133
Ulvestad, J.S., Wrobel, J.M., & Carilli, C.L., 1999, ApJ, 516, 127
Ulvestad, J.S., Wilson, A.S., 1989, 343, 659
Carilli, C.L. & Taylor, G.B., 2000, ApJ, 532, 95
Urry C.M., Padovani P., 1995, PASP, 107, 803
Voges W. et al., 1999, A&A, 349, 389
Wolter A., Caccianiga A., Della Ceca R., Maccacaro T., 1994, ApJ, 433, 29

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Figure 11. The VLA B-array maps at 1.4 GHz of the blazar candidates with $\alpha_{RX} > 0.75$ and $P_{5\,\text{GHz}}$ between $10^{23}$ and $10^{25}$ W Hz$^{-1}$. Given the redshift of these sources, the resolution of these maps corresponds to a linear scale between 1.4-14 kpc.
Figure 11 – continued
Figure 11 – continued
Figure 11 – continued
Table 1. VLA data

| name             | core flux | total flux | R     | data (core) | data (total) | comments   |
|------------------|-----------|------------|-------|-------------|--------------|------------|
| GB6J002538+400830| 17.00     | 36.90      | 0.77  | may11       | NVSS         |            |
| GB6J012626+395406| <1.4      | 175.00     | <0.01 | u.l.        |              | NVSS       |
| GB6J013631+390623| 58.80     | 58.80      | >888  | may11       | B            |            |
| GB6J014156+392325| 94.90     | 97.70      | 31.38 | may11       | B            |            |
| GB6J015451+362746| 118.10    | 247.20     | 0.81  | may11       | B            |            |
| GB6J021625+400101| 175.00    | 197.60     | 7.49  | may11       | B            |            |
| GB6J022526+371029| 620.70    | 625.30     | 55.90 | may27       | B            |            |
| GB6J025848+500934| 40.90     | 59.60      | 2.18  | may27       | B            |            |
| GB6J032835+502410| 481.90    | 793.80     | 1.55  | may27       | B            |            |
| GB6J033935+553430| 495.50    | 503.44     | 62.41 | FIRST       | B            |            |
| GB6J035005+403610| 109.87    | 118.29     | 13.05 | FIRST       | B            |            |
| GB6J035225+503136| 306.81    | 313.57     | 41.84 | FIRST       | B            |            |
| GB6J035531+682824| 278.00    | 287.75     | 28.51 | FIRST       | B(m)         |            |
| GB6J04215+452547 | 65.53     | 67.67      | 12.73 | FIRST       | B            |            |
| GB6J04352+374232| <1.4      | 55.70      | <0.03 | u.l.        |              | NVSS       |
| GB6J045954+430610| 109.87    | 118.29     | 13.05 | FIRST       | B            |            |
| GB6J050808+593054| 11.56     | 13.07      | 2.83  | FIRST       | B            |            |
| GB6J05317+682824| 41.20     | 288.60     | 0.16  | may27       | NVSS         |            |
| GB6J05416+532731| 21.34     | 22.07      | 8.56  | FIRST       | B            |            |
| GB6J055101+621900| 278.00    | 287.75     | 28.51 | FIRST       | B            |            |
| GB6J060536+470603| 88.10     | 92.81      | 18.70 | FIRST       | B            |            |
| GB6J060615+463633| 306.81    | 313.57     | 41.84 | FIRST       | B            |            |
| GB6J060960+412426| 56.00     | 58.21      | 24.66 | FIRST       | B            |            |
| GB6J060975+493558| 38.07     | 38.45      | 96.77 | FIRST       | B            |            |
| GB6J06214+501323| 495.50    | 503.44     | 62.41 | FIRST       | B            |            |
| GB6J062932+625637| 22.34     | 55.50      | 0.67  | FIRST       | NVSS         |            |
| GB6J063254+673654| 23.20     | 229.80     | 0.11  | may27       | NVSS         |            |
| GB6J064319+361447| 73.77     | 74.91      | 63.29 | FIRST       | B            |            |
| GB6J064542+575739| 69.28     | 78.29      | 7.69  | FIRST       | B            |            |
| GB6J064557+461907| 29.87     | 31.62      | 15.57 | FIRST       | B            |            |
| GB6J064914+581932| 25.16     | 61.31      | 0.61  | FIRST       | B            |            |
| GB6J064932+553538| 26.22     | 28.59      | 9.89  | FIRST       | B            |            |
| GB6J065227+504837| 104.85    | 110.36     | 7.47  | FIRST       | B            |            |
| GB6J065531+693857| 104.00    | 127.90     | 4.35  | may27       | B            |            |
| GB6J065552+694047| 664.60    | 6859.80    | 0.11  | may27       | B            |            |
| GB6J065736+552258| 2804.17   | 3056.17    | 5.83  | FIRST       | B            |            |
| name               | core flux | total flux | R   | data (core) | data (total) | comments |
|--------------------|-----------|------------|-----|-------------|--------------|----------|
| GB6J100055+533158  | 38.49     | 108.80     | 0.23| FIRST       | NVSS         |          |
| GB6J100712+502346  | 29.23     | 36.64      | 20.73| FIRST       | B            |          |
| GB6J100724+413209  | 160.16    | 167.47     | 21.91| FIRST       | B            |          |
| GB6J101028+413209  | 258.74    | 261.21     | 1.97 | FIRST       | B            |          |
| GB6J101244+243009  | 69.90     | 70.99      | 6.99 | FIRST       | B            |          |
| GB6J101504+492606  | 385.85    | 388.16     | 26.12| FIRST       | B            |          |
| GB6J101859+591126  | 74.30     | 84.70      | 7.14 | may27       | B            |          |
| GB6J102310+394759  | 807.88    | 1078.67    | 1.32 | FIRST       | B            |          |
| GB6J102521+372641  | 17.47     | 64.20      | 0.35 | FIRST       | NVSS         |          |
| GB6J103550+375646  | 52.76     | 54.26      | 14.02| FIRST       | B            |          |
| GB6J103742+571158  | 127.84    | 130.02     | 58.64| FIRST       | B            |          |
| GB6J105551+405557  | 29.94     | 29.73      | >299.40| FIRST       | B            |          |
| GB6J105837+601231  | 35.25     | 35.82      | 54.87| FIRST       | B            |          |
| GB6J105915+551232  | 207.96    | 211.38     | 186.27| FIRST       | B(m)         |          |
| GB6J110242+591432  | 416.15    | 419.19     | 48.37 | FIRST       | B            |          |
| GB6J110428+381228  | 557.26    | 768.50     | 2.56 | FIRST       | NVSS         |          |
| GB6J110508+465311  | 55.88     | 56.18      | 186.27| FIRST       | B            |          |
| GB6J110552+394649  | 22.44     | 39.93      | 1.28 | FIRST       | B            |          |
| GB6J110657+603345  | 28.51     | 32.40      | 6.50 | FIRST       | B            |          |
| GB6J110939+383046  | 9.85      | 9.62       | >98.50| FIRST       | B            |          |
| GB6J111106+522751  | 39.53     | 115.70     | 0.52 | FIRST       | NVSS         |          |
| GB6J111200+352207  | 47.21     | 49.21      | 23.04| FIRST       | B            |          |
| GB6J111903+602832  | 9.35      | 60.30      | 0.16 | FIRST       | nvss         |          |
| GB6J111912+623938  | 37.26     | 39.23      | 17.04| FIRST       | B            |          |
| GB6J111914+600459  | 186.43    | 191.98     | 9.23 | FIRST       | B            |          |
| GB6J112047+421206  | 24.63     | 25.09      | 47.63| FIRST       | B            |          |
| GB6J112157+431459  | 44.66     | 45.75      | 40.97| FIRST       | B            |          |
| GB6J112413+513350  | 43.87     | 49.86      | 5.93 | FIRST       | B            |          |
| GB6J112832+583322  | 30.00     | 575.60     | 0.05 | A           | B            | double   |
| GB6J113626+700931  | 136.40    | 353.80     | 0.60 | may27       | B            |          |
| GB6J113629+673707  | 40.10     | 50.80      | 3.30 | may27       | B            |          |
| GB6J114047+462027  | 78.85     | 81.57      | 26  | FIRST       | B            |          |
| GB6J114115+595309  | 92.30     | 92.70      | 227.92| may27       | B            |          |
| GB6J114300+730413  | 39.30     | 42.90      | 9.72 | may27       | B            |          |
| GB6J114312+621214  | 65.88     | 69.40      | 18.72| FIRST       | B            |          |
| GB6J114722+350109  | 608.81    | 637.60     | 19.90| FIRST       | NVSS         |          |
| GB6J114850+592459  | 446.40    | 477.90     | 14.02| may27       | B            |          |
| GB6J115470+525432  | 95.75     | 100.43     | 7.47 | FIRST       | B            |          |
| GB6J115495+552832  | 137.80    | 142.53     | 29.13| FIRST       | B            |          |
| GB6J115526+585913  | 137.20    | 192.40     | 2.49 | may27       | B            |          |
| GB6J115757+552713  | 93.45     | 98.51      | 18.41| FIRST       | B            |          |
| GB6J120209+444452  | 46.97     | 106.00     | 0.80 | FIRST       | NVSS         |          |
| GB6J120304+603130  | 157.10    | 194.50     | 3.94 | may27       | B            |          |
| GB6J120328+480316  | 66.83     | 68.53      | 21.63| FIRST       | B            |          |
| GB6J120334+451050  | 31.85     | 33.56      | 9   | FIRST       | B            |          |
| GB6J120922+411938  | 397.21    | 398.39     | 336.62| FIRST       | B            |          |
| GB6J121008+355224  | 16.70     | 27.00      | 1.82 | may27       | NVSS         |          |
| GB6J121331+504446  | 99.65     | 102.73     | 31.38| FIRST       | B            |          |
| GB6J121510+402710  | 161.18    | 278.59     | 0.80 | FIRST       | B(m)         |          |
| GB6J121541+361924  | 1.60      | 34.80      | 0.05 | may27       | NVSS         |          |
| GB6J121801+593406  | 10.63     | 48.08      | 0.25 | FIRST       | B            |          |
| GB6J121736+515502  | 78.51     | 80.67      | 17.39| FIRST       | B            |          |
| GB6J122208+581427  | 41.20     | 45.60      | 8.51 | may27       | B            |          |
| GB6J122306+582659  | 18.90     | 122.50     | 0.18 | may27       | NVSS         |          |
| GB6J122405+500130  | 44.44     | 46.22      | 12.11| FIRST       | B            |          |
| name              | core flux | total flux | R   | data (core) | data (total) | comments |
|-------------------|-----------|------------|-----|-------------|--------------|----------|
| GB6J123012+470031 | 85.24     | 87.47      | 36.78 | FIRST       | B            |          |
| GB6J123151+353929 | 40.25     | 40.96      | 49.90 | FIRST       | B            |          |
| GB6J123530+502630 | 67.42     | 283.30     | 0.26  | FIRST       | NVSS         |          |
| GB6J123413+475408 | 352.13    | 362.18     | 25.48 | FIRST       | B            |          |
| GB6J12417+505441  | 50.70     | 52.40      | 25.44 | FIRST       | B            |          |
| GB6J123532+522839 | 82.14     | 83.92      | 17.42 | FIRST       | B            |          |
| GB6J124313+362755 | 114.70    | 147.30     | 3.52  | may27       | NVSS         |          |
| GB6J124732+672322 | 252.00    | 360.00     | 2.10  | may27       | NVSS         |          |
| GB6J124818+582029 | 179.90    | 184.10     | 42.83 | may27       | B            |          |
| GB6J125311+530113 | 378.29    | 420.34     | 9     | FIRST       | B            |          |

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Table 1. VLA data

| name          | core flux | total flux | R   | data (core) | data (total) | comments |
|---------------|-----------|------------|-----|-------------|--------------|----------|
| GB6J162612+512044 | 20.08     | 50.30      | 0.56| FIRST       | NVSS         |          |
| GB6J162636+580914 | 134.84    | 175.00     | 0.16| may27       | B(m)         |          |
| GB6J163813+572029 | 1005.87   | 1091.69    | 6.69| FIRST       | B            |          |
| GB6J164258+394842 | 6050.06   | 6598.61    | 6.92| FIRST       | B            |          |
| GB6J164420+454644 | 104.53    | 183.50     | 1.08| FIRST       | NVSS         |          |
| GB6J164734+494954 | 103.62    | 178.00     | 1.33| FIRST       | NVSS         |          |
| GB6J165138+400227 | 42.73     | 49.60      | 11.01| FIRST       | B            |          |
| GB6J165353+394541 | 1394.38   | 1420.36    | 51.92| FIRST       | B            |          |
| GB6J165503+540754 | 16.01     | 49.60      | 1.59| FIRST       | B            |          |
| GB6J16553+394541  | 32.57     | 33.26      | 43.87| FIRST       | B            |          |
| GB6J165721+570556 | 813.53    | 972.15     | 2.25| FIRST       | B            |          |
| GB6J170123+395432 | 250.98    | 254.93     | 63.54| FIRST       | B            |          |
| GB6J170449+713840 | 43.70     | 44.40      | 60.79| FIRST       | B            |          |
| GB6J170716+453607 | 681.65    | 795.00     | 3.65| FIRST       | NVSS         |          |
| GB6J171523+572434 | 43.70     | 44.40      | 60.79| FIRST       | B            |          |
| GB6J171718+422711 | 128.29    | 132.47     | 25.93| FIRST       | B            |          |
| GB6J171813+422759 | 83.05     | 111.60     | 2.47| FIRST       | NVSS         |          |
| GB6J171914+485839 | 145.66    | 158.66     | 10.94| FIRST       | B            |          |
| GB6J171937+480404 | 61.37     | 62.45      | 27.26| FIRST       | B            |          |
| GB6J171941+354700 | 7.46      | 34.40      | 0.22| FIRST       | NVSS         |          |
| GB6J172100+354217 | 386.51    | 821.00     | 0.70| FIRST       | NVSS         |          |
| GB6J172353+585127 | 52.00     | 72.40      | 2.55| may27       | B            |          |
| GB6J172722+551059 | 141.79    | 149.13     | 15.49| FIRST       | NVSS         |          |
| GB6J172818+503135 | 210.70    | 220.13     | 21.17| FIRST       | B            |          |
| GB6J172859+383819 | 240.27    | 245.41     | 19.56| FIRST       | B            |          |
| GB6J173047+371451 | 62.01     | 102.10     | 1.55| FIRST       | NVSS         |          |
| GB6J173410+421933 | 8.0       | 50.80      | 0.19| A           | NVSS         | double   |
| GB6J174231+594513 | 105.50    | 110.50     | 21.10| may27       | B            |          |
| GB6J174555+554220 | 446.70    | 644.50     | 2.19| may27       | B            |          |
| GB6J174900+432151 | 235.00    | 254.50     | 12.05| may27       | B            |          |
| GB6J175516+629652 | 272.10    | 278.70     | 40.13| may27       | B            |          |
| GB6J175704+535153 | 67.20     | 67.50      | 200.18| may27       | B            |          |
| GB6J175728+552309 | 74.60     | 77.70      | 22.59| may27       | B            |          |
| GB6J175833+663801 | 131.70    | 815.30     | 0.19| may27       | B            |          |
| GB6J180028+481932 | 17.00     | 17.00      | >150.58| may27       | B            |          |
| GB6J180651+694391 | 1192.00   | 1887.10    | 1.63| may27       | NVSS         |          |
| GB6J183850+480237 | 50.50     | 51.70      | 42.08| may27       | B            |          |
| GB6J184033+621257 | 44.90     | 48.50      | 11.88| may27       | B            |          |
| GB6J184941+642522 | 13.0      | 111.00     | 0.13| A           | B            | double   |
| GB6J185852+682747 | 43.90     | 213.50     | 0.26| may27       | B            |          |
| GB6J191212+660926 | 31.30     | 35.70      | 6.61| may27       | B            |          |
| GB6J194553+705455 | 969.70    | 976.80     | 124.16| may27       | B            |          |

Column 2: the core flux density;
Column 3: the total flux density;
Column 4: the core-dominance parameter R (when the core flux is equal to the total flux or slightly larger due to the statistical fluctuation, the computed R is indicated as a lower limit);
Column 5: a flag explaining the data used to compute the peak flux density: “FIRST” means from the FIRST data, “may27” or “may11” are the dates of our own observations, “A” means from VLA A-array data and “u.l.” means that the core has not been detected and we have assumed an upper-limit of 1.4 mJy;
Column 6: a flag explaining the data used to compute the total flux density: B means VLA B-array data and NVSS means from the NVSS data;
Column 7: a comment indicating whether the source has a double morphology;