BLAZAR SPECTRAL PROPERTIES AT 74 MHz

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ABSTRACT

Blazars are the most extreme class of active galactic nuclei. Despite a previous investigation at 102 MHz for a small sample of BL Lac objects and our recent analysis of blazars detected in the Westerbork Northern Sky Survey, a systematic study of the blazar spectral properties at frequencies below 100 MHz has never been carried out. In this paper, we present the first analysis of the radio spectral behavior of blazars based on the recent Very Large Array Low-frequency Sky Survey (VLSS) at 74 MHz. We search for blazar counterparts in the VLSS catalog, confirming that they are detected at 74 MHz. We then show that blazars present radio-flat spectra (i.e., radio spectral indices of ~0.5) when evaluated, which also about an order of magnitude in frequency lower than previous analyses. Finally, we discuss the implications of our findings in the context of the blazars–radio galaxies connection since the low-frequency radio data provide a new diagnostic tool to verify the expectations of the unification scenario for radio-loud active galaxies.

Key words: BL Lacertae objects: general – galaxies: active – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Blazars are compact, core-dominated, radio-loud sources characterized by a highly variable, non-thermal continuum that extends from radio to γ-rays. Their spectral energy distributions exhibit two main, broadly peaked components: a low-energy one with its maximum between the infrared (IR) and the X-ray band, and a high-energy one peaking in the γ-rays. Their emission also features high and variable polarization, apparent superluminal motions, and high apparent luminosities (e.g., Blandford & Rees 1978a; Urry & Padovani 1995). Recently, we discovered that their IR colors are clearly distinct from those of other extragalactic sources, in particular when considering γ-ray blazar candidates among the unidentified gamma-ray sources detected by Fermi (see Massaro et al. 2013 for more details).

In the present work, we aim at verifying if blazars maintain a flat radio spectrum even below 100 MHz. We found that blazars also have flat radio spectra between 325 GHz and 1.4 GHz and on the basis of this result we proposed a new approach to search for γ-ray blazar candidates among the unidentified gamma-ray sources detected by Fermi (see Massaro et al. 2013 for more details).

In this paper, we extend our previous investigation of low frequency emission of blazars to frequencies below 100 MHz using the archival observations of the Very Large Array Low-frequency Sky Survey6 (VLSS; Cohen et al. 2007). The VLSS is a 74 MHz (4 m) continuum survey covering the entire sky north of ~30° declination. The entire survey region is covered with a resolution of ~80′ with an average root mean square noise of 0.1 Jy beam−1. We investigate the low-frequency spectral shape of blazars, with particular focus on those that are γ-ray emitters. A comparison between this VLSS analysis and that performed using the WENSS is also presented.

In the present work, we aim at verifying if blazars maintain a flat radio spectrum even below 100 MHz. We will also test if their spectral properties are in agreement with the expectations of the unification scenario for radio-loud active galaxies, which suggests that the observed differences between radio galaxies and blazars are mostly due to a different orientation along the line of sight (see Kharb et al. 2010 for a recent discussion on radio properties of blazars and radio galaxies in the context of the unification scenario).

The paper is organized as follows: in Section 2 we search for the counterparts of the blazars listed in the ROMA-BZCAT that lie in area covered by the VLSS while in Section 3 we describe the samples used in our analysis. Section 4 is devoted to a description of the low-frequency radio spectral behavior for the VLSS blazars. Section 5 is dedicated to the discussion of our findings.
2. SPATIAL ASSOCIATIONS OF BLAZARS IN THE VLSS

The starting catalog used in our investigation is the ROMA-BZCAT v4.1, which lists 3149 blazars (e.g., Massaro et al. 2011b)7 distinctly as 1220 BZBs (950 BL Lac objects and 270 BL Lac candidates), 1707 BZQs, and 222 BZUs. However, there are only 2727 ROMA-BZCAT blazars lying above declination ∼−30 deg as in the VLSS survey: 1115 BZBs, 1412 BZQs, and 200 BZUs. In particular, 678 of them are γ-ray emitters: 349 BZBs, 282 BZQs, and 47 BZUs as associated in the Second Fermi Large Area Telescope Catalog and in the Second Fermi LAT Catalog of active galactic nuclei (2FGL, 2LAC; Nolan et al. 2012; Ackermann et al. 2011a, respectively).

The positional uncertainties on the coordinates reported in the ROMA-BZCAT are not uniform since they have been taken from different surveys but the accuracy on the blazar positions is of the order of 1″ with only several exceptions. Thus, to identify low radio frequency counterparts of blazars at 74 MHz, we used the following approach, which has already been successfully adopted to search for blazar counterparts in the WENSS (Massaro et al. 2013). We searched for all the ROMA-BZCAT correspondences in the VLSS within circular regions of different radii \( R \) ranging between 0″ and 30″. To perform our investigation the VLSS catalog available on the HEASARC Web site8 was used.

We calculated the number of correspondences \( N(R) \) as a function of \( R \), and the difference between the number of associations at a given radius \( R \) and those at \( (R - \Delta R) \):

\[
\Delta N(R) = N(R) - N(R - \Delta R),
\]

where \( \Delta R = 0.5 \). Figure 1 shows the curves corresponding to \( N(R) \) and \( \Delta N(R) \) as a function of \( R \). We found that the number of VLSS sources positionally associated with ROMA-BZCAT blazars does not increase significantly (i.e., \( \Delta N(R) \) is systematically lower than 5) at radii larger than 21″. This is also highlighted by the corresponding differential curve \( \Delta N(R) \), clearly flat for radii greater than 21″ (see the lower panel of Figure 1). Thus, we chose the angular separation of 21″ as the radial association threshold \( R_A \) for assigning VLSS counterparts to ROMA-BZCAT blazars.

The number of spatial associations between the ROMA-BZCAT and the VLSS sources is 697 out of the 2727 (i.e., ∼26%); all are unique matches within \( R_A \). The probability of spurious associations, evaluated by shifting the coordinates of the ROMA-BZCAT blazars in random directions of the sky by 1°, is extremely small, being less than 0.1% (see Maselli et al. 2010 and references therein for details on the method to estimate the fraction of spurious associations).

3. SAMPLE SELECTION

We have defined two samples of blazars to carry out our analysis as described below. The main sample, labeled the VLSS blazar (VLB) sample, contains 697 blazars with a unique radio counterpart in the VLSS within 21″, while the subsample, labeled VLSS gamma-ray blazar (VLGB), lists only the 233 γ-ray emitting blazars out of 697 sources.

In Figure 2 we show the scatter plot of the angular separation between the ROMA-BZCAT positions and that of the VLSS catalog vs. the flux density at 74 MHz, \( S_{74} \), for the whole VLB sample.

(A color version of this figure is available in the online journal.)

We found that the number of correspondences \( N(R) \) as a function of \( R \), and the difference between the number of associations at a given radius \( R \) and those at \( (R - \Delta R) \):

\[
\Delta N(R) = N(R) - N(R - \Delta R),
\]

where \( \Delta R = 0.5 \). Figure 1 shows the curves corresponding to \( N(R) \) and \( \Delta N(R) \) as a function of \( R \). We found that the number of associations at a given radius \( R \) and those at \( R - \Delta R \) as a function of the radius \( R \) between 0″ and 30″. Lower panel: the difference \( \Delta N(R) \) between the number of associations at a given radius \( R \) and those at \( R = \Delta R \) as a function of the radius \( R \) in the same range as the plot above. The radial threshold \( R_A \) selected for our ROMA-BZCAT–VLSS crossmatches is indicated by the vertical dashed red line (see Section 2 for more details).

(A color version of this figure is available in the online journal.)

For our numerical results, we use cgs units unless stated otherwise, and we assume a flat cosmology with \( H_0 = 72 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.26 \), and \( \Omega_{\Lambda} = 0.74 \) (Dunkley et al. 2009). Spectral indices, \( \alpha \), are defined by flux density, \( S_{\nu} \propto \nu^{-\alpha} \).

4. BLAZAR SPECTRAL PROPERTIES AT 74 MHz

4.1. Spectral Shape at 74 MHz

The ROMA-BZCAT blazars are associated with NVSS or FIRST counterparts so their flux density at 1.4 GHz, \( S_{1400} \), is...
available in the catalog. In particular, for 692 out of the 697 in the VLB sample, the flux at 4.85 GHz is also reported in the ROMA-BZCAT. Thus, we calculated the following two radio

\( \Delta \alpha = \alpha_{1400}^{4850} - \alpha_{1400} \). \hspace{1cm} (2)

Thus, sources with \( \Delta \alpha < 0 \) show radio spectral shapes that steepen moving toward low frequencies while those with \( \Delta \alpha > 0 \) below 1.4 GHz appear to be flatter than they are at high radio frequencies. The relative uncertainties on the radio flux densities are \(-0.13\%\), \(0.03\%\), and \(0.09\%\) at 74 MHz, 1.4 GHz, and 4.85 GHz, respectively; in particular, they are systematically lower than 0.10 for more than 90% of the VLB sources at 74 MHz. This corresponds to a mean uncertainty on the spectral indices of 0.04 and 0.08 for \( \alpha_{74}^{1400} \) and \( \alpha_{74}^{4850} \), respectively, and to a mean error on \( \Delta \alpha \) of 0.09.\footnote{For \( \alpha = \log(S_2/S_1)/\log(v_2/v_1) \), the corresponding error is \( \sigma_\alpha = 1/\log(v_2/v_1) \ln(10) \cdot \sqrt{\sigma_i^2 + \sigma_j^2}, \) where \( \rho_i = \sigma_i/S_i \) (with \( i = 1, 2 \)) is the relative error on each flux density.} Thus, the uncertainties on the spectral indices are definitely not affecting our analysis since the standard deviation of the distributions for the entire VLB sample is systematically larger than them.

In Figure 3, we show the distribution of \( \alpha_{1400}^{74} \) for the blazars in the VLB sample, distinguishing between the BZBs and BZQs. The large fraction of radio spectral indices, \( \alpha_{74}^{1400} \), for blazars are systematically smaller than 1.0 (i.e., \(-99\%\)), with the 80% lower than \(-0.75\). In particular, the two \( \alpha_{1400}^{74} \) distributions for the BZBs and the BZQs appear to be similar at a 99% level of confidence according to a Kolmogorov–Smirnov (K-S) test. These distributions indicate that they also have relatively flat radio spectra at frequencies below 100 MHz, in agreement with their behavior at 325 MHz (Massaro et al. 2013). The flatness of the blazar radio spectra is expected from the high radio frequency data in the GHz energy range (e.g., Healey et al. 2007; Ivezic et al. 2002; Kimball & Ivezic 2008); this spectral property has also been used for the identification of \( \gamma \)-ray sources since the EGRET era (e.g., Mattox et al. 1997). However, low-frequency radio observations, such as those of the VLSS at 74 MHz, were never previously investigated to confirm this trend for a systematic study of the blazar population.

In Figure 4, we show the comparison between the BZB and the BZQ spectral index distributions, considering only \( \gamma \)-ray blazars in the VLB sample. Here we note that all the \( \textit{Fermi} \)-detected blazars have spectral indices systematically flatter than those in the VLB sample. As observed in the VLB sample (see Figure 3), a K-S test also indicates that in this case, these two \( \alpha_{74}^{1400} \) distributions of BZBs and BZQs in the VLB sample are similar at a 99% level of confidence. In addition, we did not find any correlation or net trend between \( \alpha_{74}^{1400} \) and the \( \gamma \)-ray spectral index \( \gamma \), for the whole VLB sample.

### 4.2. Flux Densities at 74 MHz

We computed the distributions of the \( S_{74} \) flux densities, comparing the BZBs and the BZQs for the VLB sample as shown in Figure 5, that appear similar at a 99% level of confidence evaluated according to a K-S test. In Figure 6 we show the scatter plot of the NVSS flux density at 1.4 GHz \( S_{1400} \) with respect to that at 74 MHz \( S_{74} \), where it is worth noting that 99% of the blazars detected in the VLB sample have \( S_{1400}^{74} = 0.05 \times S_{74} \), as indicated by the black dashed line.

For the blazars in the VLB sample, we also searched for a trend between the radio and the \( \gamma \)-ray emissions (e.g., Ghirlanda et al. 2010; Mahony et al. 2010; Ackermann et al. 2011b) as we did previously using the WENSS observations at 325 MHz (Massaro et al. 2013); however, as shown in Figure 7, there is not a clear trend or correlation between the \( \gamma \)-ray and the radio flux density at 74 MHz.

We remark that only 697 out of 2727 ROMA-BZCAT sources have a unique association in the VLSS survey within a radius of 21′′, thus \(-74\%\) of them were either not associated or not detected at 74 MHz. Most of these undetected blazars could lie below the completeness threshold of the VLSS; that for the 50%
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Massaro et al.

point-source detection limit is roughly 0.7 Jy for a typical noise level of 0.1 Jy beam$^{-1}$, evaluated by taking into account both ionospheric smearing and the clean bias (Cohen et al. 2007). In addition, the noise levels are not constant throughout the survey region and only the differential completeness as a function of signal-to-noise ratio has been defined (see Section 8 of Cohen et al. 2007 for more details). Consequently, it is not possible to extrapolate the $S_{1400}$ flux densities to 74 MHz to test if blazars with no VLSS counterparts lie above or below the completeness of the survey. This situation is even more complicated because blazars could be variable at 74 MHz, making any expectation less reliable.

However, to evaluate if we should expect to detect the remaining 2030 blazars, we assigned a spectral index $\alpha_{74}^{1400}$ equal to the peak of the spectral index distributions of the BZBs, BZQs, and BZUs in the VLB sample to those blazars that do not have a VLSS counterpart within 21″ and we computed the extrapolated $S_{74}$ flux density on the basis of their measured $S_{1400}$. We adopted a value of $\alpha_{74}^{1400}$ equal to 0.43, 0.34, and 0.51 for the BZBs, the BZQs, and the BZUs, respectively. Comparing the VLSS radio sources with the blazars in the VLB sample, we found that 63% of the VLSS objects have flux densities $S_{74}$ greater than ~1 Jy while only ~16% of the undetected blazars have extrapolated $S_{74}$ above this threshold, indicating that a large fraction of them are not expected to have a counterpart in the VLSS, which is what occurs.

5. DISCUSSION AND CONCLUSIONS

We investigated the distribution of the radio spectral index $\alpha_{74}^{1400}$ for the blazars with a VLSS counterpart, also focusing on those that are associated with $\gamma$-ray sources. We found that about 60% of $\gamma$-ray emitting blazars have flat radio spectra (i.e., $\alpha_{74}^{1400} < 0.5$), with 99% even smaller than 0.9 (see Section 4.1 for more details) as occurs when analyzing radio data at higher frequency (e.g., Healey et al. 2007; Massaro et al. 2013). This strongly suggests that blazar spectra are still dominated by the beamed radiation arising from particles accelerated in their relativistic jets even at 74 MHz.

There are several implications of our results in the context of the unification scenario of radio-loud active galactic nuclei. In 1974, Fanaroff and Riley proposed a classification scheme for extragalactic radio sources, distinguishing two classes on the basis of the correlation between the relative positions of regions of high and low surface brightness in their extended components (Fanaroff & Riley 1974). They introduced the ratio $R_{FR}$ of the distance between the regions of highest surface brightness on opposite sides of the central galaxy and/or quasar to the total extent of the source up to the lowest brightness contour in the radio map. Sources with $R_{FR} \lesssim 0.5$ were placed in Class I (i.e., FR I) and sources with $R_{FR} \gtrsim 0.5$ in Class II (i.e., FR II). At radio frequencies, FR Is show higher surface brightness toward their cores while FR IIIs show higher surface brightness toward their edges. It was also found that nearly all sources with luminosity $L_{178 MHz} \lesssim 2 \times 10^{25}$ $h_{70}^2$ W Hz$^{-1}$ str$^{-1}$ were FR I while the brighter sources were nearly all FR II. The luminosity boundary between them is not very sharp, and there is some overlap in the luminosities of sources classified as FR I or FR II on the basis of their structures.

Several observational evidences support the idea originally proposed by Blanford and Königl in 1979 that suggested powerful FR II radio galaxies are the parent populations of BZQs while BZBs were assumed to be intrinsically similar to weak
Figure 8. Angle subtended by extended structures of 100 kpc (black line) and 200 kpc (red dashed line), respectively, as a function of the redshift. The two horizontal blue dashed lines represent the typical angular resolution of the WENSS (Rengelink et al. 1997) and VLSS (Cohen et al. 2007) surveys. It is clear that for blazars at redshifts larger than \( \sim 0.1 \), extended structures of size smaller than 200 kpc cannot be resolved. This indicates that the flux densities measured at low radio frequencies arise from both nuclear- and large-scale components. The 100 kpc and 200 kpc sizes are representative of the scale observed in radio galaxies.

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FR Is (e.g., Urry & Padovani 1995; Scarpa & Urry 2001 and reference therein for more details). Both radio galaxies and blazars have similar host galaxies, i.e., giant ellipticals (e.g., Scarpa & Urry 2000a, 2000b), and deep radio observations of selected blazars at 1.4 GHz show extended structures remarkably similar to those of lobes and plumes of radio galaxies (e.g., Antonucci & Ulvestad 1995). Thus, according to the unification scenario of radio-loud active galaxies (e.g., Blandford & Rees 1978b; Blandford & Königl 1979; Urry & Padovani 1995), radio galaxies are generally interpreted as misaligned blazars.

The low-frequency radio observations of blazars presented here allow us to directly test the unification scenario of radio-loud active galaxies and of the blazars–radio galaxies connection. At MHz frequencies radio galaxies clearly show steep radio spectra as, for example, highlighted in the Third Cambridge Catalog of radio sources (Edge et al. 1959; Spinrad et al. 1985) by Kellermann et al. (1968) and Pauliny-Toth & Kellermann (1968; see also Kellermann et al. 1969; Kellermann & Pauliny-Toth 1969). The main reason for this spectral behavior is the combination of emission arising from compact cores, having typically flat radio spectra, with that from extended structures, such as plumes (in FR Is) or lobes (in FR IIs) characterized by steep radio spectra. Consequently, their combined spectra at low frequency, such as at 74 MHz, where the large beam of the radio surveys does not allow us to resolve different components, is dominated by that of large-scale (i.e., kpc) structures, thus resulting in steep radio spectra. In particular, Figure 8 shows the angle subtended by 100 kpc and 200 kpc extended structures as a function of redshift \( z \). It is clear that above \( z \sim 0.1 \), both the VLSS and the WENSS surveys cannot distinguish between the emission arising from the core and that from the extended components in radio galaxies and blazars. Thus flux densities measured at 74 MHz include both these contributions.

Since the emission arising from large-scale structures is isotropic, it is not dependent on the orientation relative to the line of sight. So, according to the unification scenario, we expect to detect steep radio spectra, typical of extended components, also when observing blazars at low radio frequencies, as occurs in radio galaxies. To describe the above situation, we can consider the schematic representation of the radio spectra of a BZQ in comparison with that of an FR II radio galaxy as shown in Figure 9. Given the resolution of the low-frequency radio surveys (e.g., Figure 8), which cannot resolve and distinguish between the contributions of extended and nuclear components, the integrated spectrum of a BZQ is expected to be similar to that of an FR II radio galaxy at low frequencies, unless the core emission overcomes that of the extended structures (i.e., \( \Delta \alpha > 0 \)).

In order to test these expectations of the unification scenario, we computed the \( \Delta \alpha \) for all the sources in the VLB sample that have data at 4.85 GHz as reported in the ROMA-BZCAT. In Figure 10, we show the distribution of the \( \Delta \alpha \) for the BZBs and the BZQs; it is quite evident that the large fraction of the VLB sources (i.e., \( \sim 70\% \)) show the spectral shape expected from the interpretation of blazars being intrinsically similar to radio galaxies. In addition, we plot the \( \Delta \alpha \) as a function of the radio spectral index evaluated at high frequencies \( \alpha_{1400} \) (Figure 11) and of the radio flux density at 1.4 GHz \( S_{1400} \) (Figure 12). These two additional plots also show trends in agreement with the unification scenario of radio-loud sources, since radio emission from steep components tend to be more evident in blazars with flatter or even inverted radio spectra (see also Figure 11) and brighter sources tend to maintain their flat spectra also at low frequencies, because their nuclear-beamed radiation overwhelms the radiation arising from their extended structures. However, one controversy arises from the above results. It is indeed clear that a significant fraction of blazars having \( \Delta \alpha > 0 \) is present. This spectral difference could be interpreted as, for example, being due to synchrotron self-absorbed components in the blazar compact cores, or to intrinsic source variability of the epochs when the radio observations were taken, since they are not simultaneous.
In particular, blazars show intrinsic variability over a wide range of wavelengths and their flux variations, even at radio wavelengths, occur stochastically, so this could affect the estimate of the spectral indices. However, the VLB sample is selected on the basis of the source detection at 74 MHz, implying that these blazars have 1.4 GHz and 4.85 GHz flux densities well above the sensitivity limit of the high-frequency radio surveys. We expect that the flux densities measured at 1.4 GHz and 4.85 GHz are well representative and thus the spectral indices between these two frequencies are also well representative of the average state of the source. In the X-ray band, this generic survey property has been extensively used to select blazars as targets for investigating the absorption lines in the warm hot intergalactic region (see, e.g., Nicastro et al. 2003, 2005, 2013).

Consequently, given the absence of any duty cycle in the blazar variability pattern and the random occurrence of their flaring activity, for each VLB source having $\Delta \alpha > 0$, due, for example, to a high state occurring while measuring the flux density at 1.4 GHz, we could expect a blazar with $\Delta \alpha < 0$ due to a flare at 74 MHz while the VLSS observations were performed.

In addition, the scatter induced on the $\Delta \alpha$ distribution remains below $\sim 0.17$, i.e., half as small as the standard deviation of the real distribution ($\sim 0.33$; see Figure 10), for flux variations up to a factor of 1.5. This value is larger than the typical variations observed for most blazars over the course of a dedicated multi-year monitoring at 15 GHz, where the flux changes are expected to be even larger than those at 1.4 GHz or below (Richards et al. 2011). Thus the presence of VLB sources with $\Delta \alpha > 0$, if not affected by variability, is not completely in agreement with the unification scenario of radio-loud active galaxies since it would imply the presence of an appreciable fraction of blazars for which radio emission from extended structures (plumes and/or lobes) is not detected (as indeed expected).

This discovery could imply new insights into the unification scenario of radio-loud active galaxies, opening new questions such as, for example: (1) is the distinction between blazars and radio galaxies driven not only by the orientation along the lines of sight but also by a different parameter or by a combination of them (e.g., accretion rate, black hole mass)? (2) Is it possible that the difference between radio-loud active galaxies could also be due to their surrounding environments? The unsolved issues deserve further investigation to confirm the peculiar spectral behavior of blazars. Independent analysis can be carried out using the low-frequency observations of the Murchison Widefield Array (Tinagly et al. 2013) radio telescope combined with existing Australia Telescope Compact Array surveys at 20 GHz (e.g., Frater et al. 1992; Murphy et al. 2010; Massardi et al. 2011). Future investigations with the new generation of low-frequency radio telescopes such as the LOw Frequency ARRay (e.g., van Haarlem et al. 2013), and the Square Kilometer Array (e.g., Dewdney et al. 2009; Schilizzi...
et al. 2010) will also be crucial to resolve nuclear and extended components in blazars.

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Facilities: VLA, WSRT

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