THE LOW-FREQUENCY RADIO CATALOG OF FLAT-SPECTRUM SOURCES

F. Massaro1, 2, M. Giroletti3, R. D’Abrusco4, N. Masetti5, A. Paggi4,
Philip S. Cowperthwaite4, G. Tosti6, and S. Funk7

1 SLAC National Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, 2575 Sand Hill Road, Menlo Park, CA 94025, USA; fmassaro79@gmail.com
2 Yale Center for Astronomy and Astrophysics, Physics Department, Yale University, P.O. Box 208120, New Haven, CT 06520-8120, USA
3 INAF Istituto di Radioastronomia, Via Gobetti 101, I-40129 Bologna, Italy
4 Harvard–Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
5 INAF—Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, Via Gobetti 101, I-40129 Bologna, Italy
6 Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy

Received 2013 December 31; accepted 2014 April 28; published 2014 June 11

ABSTRACT

A well known property of the γ-ray sources detected by Cos-B in the 1970s, by the Compton Gamma-Ray Observatory in the 1990s, and recently by the Fermi observations is the presence of radio counterparts, particularly for those associated with extragalactic objects. This observational evidence is the basis of the radio–γ-ray connection established for the class of active galactic nuclei known as blazars. In particular, the main spectral property of the radio counterparts associated with γ-ray blazars is that they show a flat spectrum in the GHz frequency range. Our recent analysis dedicated to search blazar-like candidates as potential counterparts for the unidentified γ-ray sources allowed us to extend the radio–γ-ray connection in the MHz regime. We also showed that blazars below 1 GHz maintain flat radio spectra. Thus, on the basis of these new results, we assembled a low-frequency radio catalog of flat-spectrum sources built by combining the radio observations of the Westerbork Northern Sky Survey and of the Westerbork in the southern hemisphere catalog with those of the NRAO Very Large Array Sky survey (NVSS). This could be used in the future to search for new, unknown blazar-like counterparts of γ-ray sources. First, we found NVSS counterparts of Westerbork Synthesis Radio Telescope radio sources, and then we selected flat-spectrum radio sources according to a new spectral criterion, specifically defined for radio observations performed below 1 GHz. We also described the main properties of the catalog listing 28,358 radio sources and their logN–logS distributions. Finally, a comparison with the Green Bank 6 cm radio source catalog was performed to investigate the spectral shape of the low-frequency flat-spectrum radio sources at higher frequencies.

Key words: galaxies: active – quasars: general – radiation mechanisms: non-thermal – surveys

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Since the epoch of the first γ-ray observations performed by Cos-B in the 1970s (e.g., Hermsen et al. 1977) and by the Compton Gamma-Ray Observatory in the 1990s (e.g., Hartman et al. 1999), a link between the radio and the γ-ray sky was discovered. It has been used to associate the high-energy sources with their low-energy counterparts (e.g., Mattox et al. 1997). This radio to γ-ray relation has also been recently highlighted for the extragalactic sources detected by the Fermi mission (Atwood et al. 2009). In particular, nearly all the γ-ray sources associated in the second Fermi Large Area Telescope (LAT) catalog (Nolan et al. 2012) and/or in the second catalog of active galactic nuclei (AGNs; Ackermann et al. 2011a) detected by the Fermi-LAT have a clear radio counterpart. This is the basis of the radio–γ-ray connection specifically discussed for blazars (e.g., Ghirlanda et al. 2010; Mahony et al. 2010; Ackermann et al. 2011b), that constitutes the rarest class of AGNs (e.g., Urry & Padovani 1995; Massaro et al. 2009, 2011a) and the largest known population of γ-ray sources (e.g., Abdo et al. 2010).

We recently addressed the problem of searching γ-ray blazar candidates as counterparts of the unidentified γ-ray sources (UGSs), adopting a new approach that employs the low-frequency radio observations performed by the Westerbork Synthesis Radio Telescope (WSRT). While performing this investigation, we found that the radio–γ-ray connection of blazars can be extended below ~1 GHz (Massaro et al. 2013a). Our analysis was based on the combination of the radio observations from the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) at 325 MHz with those of the NRAO Very Large Array Sky survey (NVSS; Condon et al. 1998) and of the Very Large Array Faint Images of the Radio Sky at Twenty-centimeters (Becker et al. 1995; White et al. 1997) at about 1.4 GHz. A similar analysis was also performed using the Westerbork in the southern hemisphere (WISH) survey (De Breuck et al. 2002) at 352 MHz (Nori et al. 2014). Both of these studies were based on the observational evidence that blazars also show flat radio spectra below ~1 GHz (see also Kovalev 2009; Kovalev et al. 2009; Petrov et al. 2013, for recent analyses).

The flatness of the blazar radio spectra is a well-known property expected from radio data in the GHz frequency range (e.g., Ivezić et al. 2002; Healey et al. 2007; Kimball & Ivezić 2008, for recent analyses). This spectral property was also used in the past for the associations of γ-ray sources since the EGRET era (e.g., Mattox et al. 1997). However, despite a small survey of BL Lac objects at 102 MHz (Art'yukh & Vetukhnovskaya 1981), the low radio frequency spectral behavior of blazars was still an unexplored region of the electromagnetic spectrum until our recent analyses (Massaro et al. 2013a; Nori et al. 2014). Using WSRT data at 325 MHz and at 352 MHz along with very low frequency observations of the Very Large Array Low-Frequency Sky survey (VLAS) would provide high-quality spectral data of blazars. This could be used in the future to search for new, unknown blazar-like counterparts of γ-ray sources. First, we found NVSS counterparts of Westerbork Synthesis Radio Telescope radio sources, and then we selected flat-spectrum radio sources according to a new spectral criterion, specifically defined for radio observations performed below 1 GHz. We also described the main properties of the catalog listing 28,358 radio sources and their logN–logS distributions. Finally, a comparison with the Green Bank 6 cm radio source catalog was performed to investigate the spectral shape of the low-frequency flat-spectrum radio sources at higher frequencies.
Sky Survey\(^7\) (Cohen et al. 2007) at 74 MHz, we showed that blazars maintain a flat radio spectrum even below \(~100\) MHz and we extended the radio--\(γ\)-ray connection below \(~1\) GHz (Massaro et al. 2013b).

Thus, motivated by these recent results, we assembled a catalog of low-frequency flat-spectrum radio sources using the combination of both the WENSS and the WISH surveys with the NVSS. The main aim of this investigation is to provide the counterpart, at longer wavelengths, of the Combined Radio All-Sky Targeted Eight-GHz Survey (CRATES) used to associate \(\text{Fermi}\) objects with blazar-like sources (Healey et al. 2007).

The paper is organized as follows. In Section 2, we briefly present the main properties of the low-frequency radio survey performed by WSRT and used to carry out our investigation (i.e., the WENSS and the WISH). In Section 3, we search for the NVSS counterparts of WSRT sources. Then in Section 4, we extract the main low-frequency catalog of flat-spectrum radio sources (LORCAT) from the combined WSRT--NVSS surveys and we discuss its main properties. Section 5 is devoted to the comparison the Green Bank 6 cm (GB6) radio source catalog (e.g., Gregory et al. 1996) to investigate the spectral behavior of LORCAT sources at higher frequencies. Finally, Section 6 is dedicated to a summary and conclusions.

For our numerical results, we use cgs units unless stated otherwise; spectral indices, \(α\), are defined by flux density, \(S_ν \propto ν^{-α}\). The WSRT catalogs used to carry out our analysis are available from both the HEASARC\(^8,\)^9 and the VIZIER\(^10,\)^11 databases as well as that of the NVSS.\(^12\); \(^13\)

2. WESTERBORK LOW-FREQUENCY RADIO SURVEY

The WENSS is a low-frequency radio survey that covers the northern sky above \(+30°\) in declination (decl.) performed at 325 MHz to a limiting flux density of \(~18\) mJy at the 5\(σ\) level (Rengelink et al. 1997). The version of the WENSS catalog used in our analysis was implemented as a combination of two separate catalogs obtained from the WENSS Web site\(^14\): the WENSS Polar Catalog that comprises 18,186 sources above \(+72°\) in declination and the WENSS Main Catalog including 211,234 objects in the declination range between \(+28°\) and \(+76°\).

We also used the WISH catalog\(^15\), which is the southern extension of the WENSS. WISH is a low-frequency (352 MHz) radio survey covering most of the sky between \(−26°\) and \(−9°\) at 352 MHz to the same limiting flux density of the WENSS. It is worth noticing that the Galactic plane regions at Galactic latitudes \(|b| <10°\) are excluded from the WISH observations. Due to the very low elevation of the observations, the survey has a much lower resolution in declination than in right ascension (R.A.). A correlation with the NVSS shows that the positional accuracy is less constrained in declination than in right ascension, but there is no significant systematic error (see De Breuck et al. 2002, for more details). Finally, we highlight that the WISH catalog contains multiple observations of the same source for many objects as well as measurements of individual components of multi-component sources.

3. RADIO SPATIAL ASSOCIATIONS

We adopted the following statistical approach to find the radio NVSS counterparts at 1.4 GHz for the sources in the WSRT low radio frequency surveys, namely, the WENSS and the WISH.

For each radio source listed in either the WENSS or the WISH surveys, we searched for all of the NVSS counterparts that lie within elliptical regions that correspond to the positional uncertainty at a 95\% level of confidence (i.e., 2\(σ\)). We took into account the uncertainties on both the right ascension, \(α\), and the declination, \(δ\), in the WSRT and in the NVSS surveys.

We found that the total number of correspondences is 225,933 out of the 268,425 radio sources included in both of the WSRT surveys. We excluded from our analysis all of the WSRT sources with radio analysis flags (i.e., \(P\) and \(Y\) as reported in the WENSS and WISH catalog, respectively, to indicate that there were problems in the model fitting for a source) and variability flags in the WISH observations, all of the double matches, and all of the sources labeled as components of a multi-component source (flag “C”) in the WSR catalogs. In addition, for this version of the LORCAT catalog, we also excluded 2707 multiple matches from our sample because their WSRT radio flux densities could be due to the emission of several, unresolved, NVSS sources, which could contaminate our estimates of the low-frequency spectral index.

We then built 100 mock realizations of the WSRT catalog by shifting each source position to a random direction of the sky by a fixed length of \(1°\). This shift was adopted to create mock WSRT catalogs, which were chosen not far from the original WSRT position and within the NVSS footprint, to obtain fake catalogs with sky distributions similar to that of the original WSRT and to perform a cross-match with each fake catalog and the NVSS, accounting for the local density distribution of the WSRT radio sources. The total number of WSRT sources in each mock realization is also preserved.

For each mock realization of the WSRT catalog, we counted the number of associations with the NVSS occurring at angular separations, \(R\), smaller than \(300°\). Then, we computed the mean number, \(λ(R)\), of these mock associations, averaged over the 100 fake WSRT catalogs and verifying that \(λ(R)\) has a Poissonian distribution. Increasing the radius by \(ΔR = 5°\), we also computed the difference \(Δλ(R)\) as

\[ Δλ(R) = λ(R + ΔR) − λ(R). \] (1)

In Figure 1, we show the comparison between \(ΔN(R)\) and \(Δλ(R)\). For radii larger than \(R_{max} = 95°\), the \(Δλ(R)\) curve superimposes that of \(ΔN(R)\), indicating that WSRT--NVSS cross-matches could occur by chance at angular separations larger than \(R_{max}\). Thus, we choose \(R_{max}\) as to the maximum angular separation between the WSRT and the NVSS position in order to consider the 1.4 GHz radio source a reliable counterpart for a WSRT object.

In addition, we calculated the chance probability of spurious associations, \(p(R)\), as the ratio between the number of real associations, \(N(R)\), and the average of those found in the mock realizations of the WSRT catalog, \(λ(R)\), corresponding to a value of \(~10\%) for \(R = R_{max}\) (see, e.g., Maselli et al. 2010; Massaro et al. 2011b, 2013c; D’Abrusco et al. 2013, for a similar procedure to estimate the probability of spurious associations).

We then computed the uncertainties of the WSRT positions according to the procedure described in Rengelink et al. (1997) and combined them with the NVSS ones (Condon et al. 1998).
Massaro et al.

Figure 1. Upper panel: the values of $\Delta \lambda (R)$ (red circles) and $\Delta N(R)$ (black squares) as functions of the angular separation, $R$. Our choice of $R_{\text{max}}$ is marked by the vertical dashed line. It occurs at the first $R$ value for which $\Delta \lambda (R) \simeq \Delta N(R)$. Lower panel: the probability of having spurious associations, $p(R)$, as functions of the angular separation, $R$. (A color version of this figure is available in the online journal.)

Figure 2. Left panel: the ratio distributions between angular separations, $R$, and the positional uncertainties for the right ascension (black straight line) and for the declination (red dashed line), respectively, for the selected 224,438 WSRT–NVSS radio sources. Right panel: the cumulative distribution of the ratio $R/\sigma$. The dotted blue line marks the 90% limit (see also Section 3). (A color version of this figure is available in the online journal.)

The distributions of the ratio between the angular separation, $R$, and the combined positional uncertainty $\sigma$ for right ascension and declination, respectively. In order to build the final sample of WSRT–NVSS correspondences that will be used to extract the low-frequency radio catalog of flat-spectrum sources, we selected only sources with $m < 3$. This WSRT–NVSS final sample lists 224,438 radio sources out of 225,933 previously selected. We note that we found a potential NVSS counterpart for about 85% of the WSRT sources, and since we adopted a threshold of $m = 3$, this corresponds to a completeness, $C$, of about 80%, evaluated according to the relations described in Condon et al. (1975). Moreover, this is also in agreement with

using the following relation:

$$
\sigma_{\text{RA,Decl.}} = \sqrt{\sigma_{\text{RA,Decl.}}^2 (\text{WSRT}) + \sigma_{\text{RA,Decl.}}^2 (\text{NVSS})}. \quad (2)
$$

We also defined the angular separation normalized to the values of the positional uncertainties, $m$, as

$$
m = \sqrt{\left(\frac{R_{\text{RA}}}{\sigma_{\text{RA}}}\right)^2 + \left(\frac{R_{\text{Decl.}}}{\sigma_{\text{Decl.}}}\right)^2}, \quad (3)
$$

where $R_{\text{RA}}$ and $R_{\text{Decl.}}$ are the angular separations in right ascension and in declination, respectively. In Figure 2, we show
the reliability of our associations, estimated via Monte Carlo simulations, occurring at $R_{\text{max}}$ which is of the order of 10% (see Figure 1).

### 4. LOW-FREQUENCY RADIO CATALOG OF FLAT-SPECTRUM SOURCES

#### 4.1. Radio Spectral Index Distribution at Low Frequencies

For the WSRT–NVSS associations, we defined a low-frequency radio spectral index: $\alpha_{\text{low}}$, using the integrated flux densities at 325 MHz from the WENSS and those at 352 MHz reported in the WISH, $S_{325}$ and $S_{352}$, respectively, in combination with the NVSS $S_{1400}$ at 1.4 GHz as

$$\alpha_{\text{low}} = -k_1 \cdot \log\left(\frac{S_{1400}}{S_{\text{low}}}\right),$$

where the $k_1$ factor is equal to 1.58 and 1.67 (i.e., $[\log(1400/325)]^{-1}$ and $[\log(1400/352)]^{-1}$) for the WENSS and the WISH surveys, respectively, $S_{\text{low}}$ is the flux density at 325 MHz (WENSS) or at 352 MHz (WISH) with all flux densities in units of mJy. The uncertainties of $\alpha_{\text{low}}$ were computed according to the following relation:

$$\sigma_{\alpha_{\text{low}}} = k_2 \cdot \sqrt{\left(\frac{\sigma_{1400}}{S_{1400}}\right)^2 + \left(\frac{\sigma_{\text{low}}}{S_{\text{low}}}\right)^2},$$

where the $k_2$ factor is equal to 0.68 and 0.72 (i.e., $|\ln(1400/325)|^{-1}$ and $|\ln(1400/352)|^{-1}$) for the WENSS and the WISH surveys, respectively, while $\sigma_{1400}$ and $\sigma_{\text{low}}$ are the uncertainties on the WSRT and NVSS flux densities.

In radio astronomy it is conventional to indicate flat-spectrum radio sources as those with a two-point spectral index $\alpha(v_1, v_2) \sim 0$ or typically lower than 0.5 (e.g., Condon 1984a). The origin of these thresholds resides in the distribution of the two-point spectral indices measured between $\sim$1.4 GHz and $\sim$5 GHz for a number of flux-limited source samples (Witzel et al. 1979; Owen et al. 1983; Condon 1984a, 1989). As shown in these analyses, the (unnormalized) spectral-index distributions consist of a narrow steep-spectrum component with $\alpha(v_1, v_2) \sim 0.7$ and a broader flat-spectrum component centered on $\alpha(v_1, v_2) \sim 0$. As the sample selection frequency is lowered, the number of steep-spectrum sources rapidly increases and the median spectral indices of both components increase (e.g., Kellermann 1974; Condon 1989). As reported by Kellermann (1964), the increase in $\alpha(v_1, v_2)$ of each spectral component is proportional to the square of its width, so the median spectral index of the flat-spectrum component changes more rapidly with frequency.

As shown in Figure 3, even considering three or more flux-limited subsamples of the WSRT–NVSS associated sources, we were not able to identify a bimodal behavior in the spectral-index distribution of $\alpha_{\text{low}}$. This, in addition to the frequency dependence highlighted by Kellermann (1964), suggests that a different criterion has to be chosen to indicate flat-spectrum radio sources at low frequencies.

We noticed that both blazars and Fermi blazars detected in the WENSS show values of $\alpha_{\text{low}}$ between −1 and 0.65 for the largest fraction of their samples (Massaro et al. 2013a). Specifically,
in our previous analysis, we considered low-frequency flat-spectrum radio sources as those having $\alpha_{\text{low}} < 0.65$. This occurred for 90% of the blazars detected by Fermi and for more than 80% of those listed in the ROMA-BZCAT (Massaro et al. 2009, 2011a). However, to assemble the LORCAT, we adopted a more conservative threshold based on the following statistical criterion.

First, we established the number of blazars and Fermi blazars that we expect to find within this subsample simply performing the cross-match with the ROMA-BZCAT within 8.5 as adopted in our previous analysis. We found that the number of expected blazars with a WSRT counterpart is 979, including 274 Fermi blazars. For a given value of the threshold $\alpha^*$, we defined the fractional efficiency $g(\alpha_{\text{low}})$ as the ratio between the difference of the total number of sources having $\alpha_{\text{low}} < \alpha^*$ and those with $(\alpha_{\text{low}} - \Delta \alpha) < \alpha_{\text{low}}$, and the total number of expected sources, $N_{\text{exp}}$, within the WSRT–NVSS associations with $-1 < \alpha_{\text{low}} < 0.7$:

$$g(\alpha_{\text{low}}) = \frac{N(\alpha_{\text{low}} < \alpha^*) - N((\alpha_{\text{low}} - \Delta \alpha) < \alpha^*)}{N_{\text{exp}}}.$$  

where $\Delta \alpha = 0.1$. In particular, $g(\alpha_{\text{low}})$ has been computed for all blazars (i.e., $g_B(\alpha_{\text{low}})$) and the subsample of Fermi blazars (i.e., $g_F(\alpha_{\text{low}})$) with $-1 < \alpha_{\text{low}} < 0.7$ (see Figure 4). Since the main goal underlying the LORCAT is to have a catalog of potential counterparts for the UGSs, we chose $\alpha^*_{\text{low}} = 0.4$ as the threshold value corresponding to the peak of the $g(\alpha_{\text{low}})$. According to the above threshold, the total number of low-frequency sources with a flat radio spectrum listed in the LORCAT is 28,358 having $-1 < \alpha_{\text{low}} < 0.40$. If we adopt the above criterion for the choice of $\alpha_{\text{low}}$, the LORCAT catalog will be less complete. However, the selected low-frequency flat-spectrum radio sources are more reliable as $\gamma$-ray blazar candidates since this criterion ensures the avoidance of the heavy contamination caused by steep spectrum radio sources.

In Figure 4, we also show the completeness, $\varphi$, of the sample considered above, defined as the ratio between the total number of sources and the expected sources $N_{\text{exp}}$. Our criterion is then supported by the comparison at high frequency, described in Section 5, ($\alpha_{\text{low}} < \alpha^*_\gamma$) and the total number of expected sources:

$$\varphi(\alpha_{\text{low}}) = \frac{N(\alpha_{\text{low}} < \alpha^*_\gamma)}{N_{\text{exp}}}.$$  

Thus, we noticed that for our choice of $\alpha^*_\gamma = 0.4$, we are able to re-associate 80% of the Fermi blazars with all the blazars listed in the WSRT–NVSS with $\alpha_{\text{low}}$ between $-1$ and 0.65 (Massaro et al. 2013a).

In Table 1, we list all LORCAT sources with their WSRT and NVSS names. For all of these sources, we also report the NVSS coordinates, the angular separation, $R$, between the NVSS and the WSRT positions, the $\alpha_{\text{low}}$ value with its uncertainty, $\sigma_{\text{low}}$, and the WSRT survey name which each original source belongs to: WISH or WENSS.

Finally, we note that, as found by our previous analysis (e.g., Massaro et al. 2013a), the source density of the LORCAT sources is $\sim 1.8$ sr deg$^{-2}$, given the total 4.7 sr of the footprint of the combined WENSS–WISH survey (3.1 sr in the WENSS plus 1.6 sr in the WISH), while, according to the ROMA-BZCAT the blazar density is currently of the order of 0.1 sr deg$^{-2}$. Therefore, we can expect that only about 10% of the sources in the LORCAT are blazar-like. However, to confirm this insight, optical spectroscopic observations and high-frequency radio
Moreover, since the ROMA-BZCAT is not a survey and it is not a complete catalog, the above estimate on the expected fraction of blazars present in the LORCAT has to be carefully considered.

### 4.2. Flux Density Distributions at Low Frequencies

Comparing the radio flux densities at 1.4 GHz, $S_{1.4}$ (i.e., 325 for the WENSS and 352 MHz for the WISH), as shown in Figure 5, there is a good match between the two WSRT and NVSS observations: bright sources below ∼1 GHz tend to be among the brightest also above 1 GHz. In Figure 5, we also report the line corresponding to a radio spectrum of $\alpha_{\text{low}} = 0$. Then, in Figure 6, we also compare the low-frequency radio spectral index $\alpha_{\text{low}}$ with the archival WSRT and NVSS flux densities. The logN−log$S$ distribution for all of the WSRT–NVSS associations per range of low-frequency spectral indices between −1 and 1.5 as well as that of our LORCAT are reported in Figure 7. Figure 8 shows the logN−log$S$ distributions of the LORCAT sample for both the WSRT and the NVSS flux densities. These logN−log$S$ distributions are in agreement with the evolution of the radio source counts (e.g., Condon 1984b; Condon et al. 1998). These logN−log$S$ distributions computed with both the $S_{\text{low}}$ and $S_{1.4}$ for all the LORCAT sources appear to have the same shape. This is expected because the flux densities are mildly correlated, as shown in Figure 5. In Figure 8, we also show the $N \propto S^{-1.5}$ line expected in the case of a uniform source distribution at a redshift that is not too large (i.e., in a Euclidean universe). It is well-known that blazars show a broken luminosity function due to the relativistic effects of their beamed emission (e.g., Urry & Shafer 1984), this could also be reflected in the logN−log$S$ distribution in agreement with that of the LORCAT. However, to prove this effect, redshift estimates will be necessary for these low-frequency sources with flat radio spectra.

### 5. COMPARISON WITH THE GREEN BANK 6 CM RADIO SOURCE CATALOG

A detailed identification of the complete LORCAT sample is out of the scope of the present analysis and a multifrequency analysis of the optical and the IR counterparts of the LORCAT sources will be presented in a separate, forthcoming paper (Massaro et al. 2014). However, to understand the nature of the selected low-frequency flat-spectrum radio sources, we performed a cross-match with the GB6 radio source catalog (Gregory et al. 1996) to investigate the spectral properties of the LORCAT sources at ∼5 GHz.

It is worth noting that among all of the radio surveys at a frequency greater than ∼1 GHz the GB6 is the most recent one covering the largest portion of the LORCAT footprint since it was performed between 0° and +75° in declination. The GB6 radio source catalog is also complete above 50 mJy (Gregory et al. 1996). Since the CRATES catalog has been compiled using the GB6 in the above range of declination, a comparison to it is nested within the following analysis.

The total number of LORCAT sources within the GB6 footprint is 15,814. Assuming the difference $\Delta \alpha$ (i.e., 0.3+3323 J000238+334008 00:02:38.41 +33:40:08.3 6.27 0.18 0.12 WENSS
0000.0+4449 J000237+450554 00:02:37.65 +45:05:54.1 10.98 0.38 0.1 WENSS
0000.0+5008 J000236+502220 00:02:36.82 +50:22:20.3 6.78 −0.28 0.12 WENSS
0000.0+6737 J000235+675422 00:02:35.79 +67:54:22.7 2.78 0.33 0.07 WENSS
0000.0−1838 J000239−182128 00:02:39.71 −18:21:28.8 29.83 0.28 0.16 WISH
0000.1+4452 J000240+450928 00:02:40.17 +45:09:28.5 4.39 0.07 0.08 WENSS
0000.1+4628 J000242+464509 00:02:42.71 +46:45:09.0 10.26 0.0 0.09 WENSS
0000.2−2131 J000249−211419 00:02:49.81 −21:14:19.3 4.43 −0.15 0.03 WISH
0000.2−2251 J000250−223437 00:02:50.77 −22:34:37.7 9.52 0.29 0.14 WISH
0000.3+2926 J000252+294253 00:02:52.36 +29:42:53.2 3.15 0.22 0.06 WENSS

| Name | NVSS Name | R.A. (NVSS) (J2000) | Decl. (NVSS) (J2000) | $R$ (arcsec) | $\alpha_{\text{low}}$ | $\sigma_{\text{low}}$ | Survey |
|------|-----------|---------------------|----------------------|-------------|----------------|----------------|--------|
| J000238+334008 | J000238+334008 | 00:02:38.41 | +33:40:08.3 | 6.27 | 0.18 | 0.12 | WENSS |
| J000237+450554 | J000237+450554 | 00:02:37.65 | +45:05:54.1 | 10.98 | 0.38 | 0.1 | WENSS |
| J000236+502220 | J000236+502220 | 00:02:36.82 | +50:22:20.3 | 6.78 | −0.28 | 0.12 | WENSS |
| J000235+675422 | J000235+675422 | 00:02:35.79 | +67:54:22.7 | 2.78 | 0.33 | 0.07 | WENSS |
| J000239−182128 | J000239−182128 | 00:02:39.71 | −18:21:28.8 | 29.83 | 0.28 | 0.16 | WISH |
| J000240+450928 | J000240+450928 | 00:02:40.17 | +45:09:28.5 | 4.39 | 0.07 | 0.08 | WENSS |
| J000242+464509 | J000242+464509 | 00:02:42.71 | +46:45:09.0 | 10.26 | 0.0 | 0.09 | WENSS |
| J000249−211419 | J000249−211419 | 00:02:49.81 | −21:14:19.3 | 4.43 | −0.15 | 0.03 | WISH |
| J000250−223437 | J000250−223437 | 00:02:50.77 | −22:34:37.7 | 9.52 | 0.29 | 0.14 | WISH |
| J000252+294253 | J000252+294253 | 00:02:52.36 | +29:42:53.2 | 3.15 | 0.22 | 0.06 | WENSS |

Notes. Column 1: WSRT name. Column 2: NVSS counterpart of the WSRT source. Column 3: R.A. from the NVSS catalog. Column 4: decl. from the NVSS catalog. Column 5: angular separation between the WSRT and the NVSS position: $R$. Column 6: low-frequency radio spectral index $\alpha_{\text{low}}$. Column 7: uncertainty on the $\alpha_{\text{low}}$. Column 8: WSRT original survey: WENSS or WISH.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

![Flux density scatterplot. LORCAT sources (magenta circles) are shown in comparison to those associated in the whole WSRT–NVSS cross-match (black circles). The dashed black line marks the radio spectral index $\alpha_{\text{low}} = 0$.](image)
\[ \Delta \alpha = \alpha_{\text{high}} - \alpha_{\text{low}} \] between the low- (i.e., \( \alpha_{\text{low}} \)) and the high-frequency (i.e., \( \alpha_{\text{high}} \)) spectral indices equal to zero with \( \alpha_{\text{high}} \) defined as 

\[ -1.85 \log \left( \frac{S_{4850}}{S_{1400}} \right) \]

we computed the extrapolated flux density at 4.85 GHz \( S_{\text{ex},4850} \) for the LORCAT sources to determine those expected to be detected in the GB6. We found that above the completeness threshold of the GB6, there are 3219 LORCAT sources with \( S_{\text{ex},4850} > 50 \) mJy.

Then, searching the correspondences between the LORCAT and the GB6 catalogs, we found that 1942 out of the 3219 (i.e., \( \sim 60\% \)) are detected at 6 cm within their positional uncertainty regions at a 1\( \sigma \) level of confidence, computed between the NVSS and the GB6 positions. In particular, only 875 out of these 1942 radio sources show a flux density, \( S_{4850} \), above the completeness limit of the GB6 survey. The distribution of the high-frequency spectral index \( \alpha_{\text{high}} \) computed with the observed \( S_{4850} \) in the GB6 for the 2834 LORCAT–GB6 associations is reported in Figure 9 together with their \( \Delta \alpha \) histograms. More than \( \sim 75\% \) of the 1942 LORCAT sources detected in the GB6 still have a “flat” radio spectrum at frequencies above \( \sim 1 \) GHz (see Figure 9), according to the canonical, widely accepted definition of flat-spectrum radio sources (i.e., \( \alpha_{\text{high}} < 0.5 \)) (e.g., Kellermann 1974; Condon 1989, and references therein). This strongly supports our definition of low-frequency “flat” radio spectra (see Section 4.1). However, a significant fraction (i.e., \( \sim 60\% \)) of these GB6–LORCAT sources appear to have radio spectra that steepen toward higher frequencies (i.e., \( \Delta \alpha > 0 \)).

It is worth mentioning that the subclass of blazars indicated as flat-spectrum radio quasars and labeled as BZQs (e.g., Massaro et al. 2009) generally show flat high-frequency spectra, thus LORCAT sources with steep high-frequency spectra may not actually be BZQs (e.g., Condon et al. 1983). However, \( \Delta \alpha > 0 \) is occurring for a small fraction (i.e., \( \sim 5\% \)) of the known blazars listed in the ROMA-BZCAT and these are all classified as BL Lac objects. In Figure 10, we also report the radio spectral index, \( \alpha_{1400} \), evaluated for all the ROMA-BZCAT blazars that have radio observations in the NVSS and in the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003) at 843 MHz. It is evident that blazars show a clear steepening at higher frequencies in agreement with that...
Figure 8. LogN–log S distributions of the LORCAT sample calculated with the WSRT flux density, $S_{\text{low}}$, (black circles) and with that of the NVSS at 1.4 GHz (red squares). Similar shapes for the two logN–log S distributions of the LORCAT sample are expected since the $S_{\text{low}}$ and $S_{1400}$ flux densities are correlated (see Figure 5). The magenta line indicates the $N \propto S^{-1.5}$ relation expected from a uniform source distribution, while the vertical dashed black line marks the completeness limit of the WSRT survey at 30 mJy. (A color version of this figure is available in the online journal.)

Figure 9. Left panel: the distribution of the high-frequency spectral index $\alpha_{\text{high}}$ computed for all the LORCAT sources with a counterpart in the GB6 survey within their radio positional uncertainties (see Section 5 for more details). It is worth noting that a significant fraction of sources, having flat spectra at low frequencies between $\sim 300$ MHz and $\sim 1$ GHz (i.e., $-1 < \alpha_{\text{low}} < 0.4$), appear to be relatively flat, according to the general definition (i.e., $\alpha_{\text{high}} < 0.5$ marked by the vertical black line), at high frequencies between $\sim 1$ GHz and $\sim 5$ GHz. Right panel: the distribution of the $\Delta \alpha = \alpha_{\text{high}} - \alpha_{\text{low}}$ for the LORCAT–GB6 radio correspondences. Radio sources with flatter high-frequency spectrum, with respect to the low-energy one, have $\Delta \alpha < 0$, while those steepening at high frequencies show $\Delta \alpha > 0$. The vertical dashed line marks the threshold, $\Delta \alpha = 0$. (A color version of this figure is available in the online journal.)

found for the LORCAT sources. In addition, there is also the possibility that these radio spectra are intrinsically mildly curved (e.g., Howard et al. 1965; Kellermann et al. 1969; Pauliny-Toth et al. 1972). It is known that spectral curvature appears at higher frequencies in the submillimeter data (e.g., Giommi et al. 2007, 2012). Finally, we note that the presence of radio sources with $\Delta \alpha < 0$ in the LORCAT sources might indicate that the low-frequency emission could be contaminated by that of extended components. These cannot be resolved with the large beam of the low-frequency survey and, in general, present steep spectra (see, e.g., Massaro et al. 2013b, for a recent discussion).
6. SUMMARY AND CONCLUSIONS

We have assembled a low-frequency radio catalog of flat-spectrum sources (LORCAT) built by combining the radio observations of the two main WSRT surveys (i.e., WENSS and WISH) at 325 MHz and 352 MHz, respectively, with those of the NVSS at 1.4 GHz. The main goals underlying the creation of this catalog are similar to those of the CRATES (Healey et al. 2007) since both can be used to search for new, unknown blazar-like counterparts of the $\gamma$-ray sources in the future.\footnote{The LORCAT catalog has already been used for $\gamma$-ray source associations that will be released with the next Fermi catalog currently in preparation.}

We defined a new criterion for associating WSRT and NVSS sources, improving our previous analyses (Massaro et al. 2013a; Nori et al. 2014), and we provided a new definition of flat-spectrum radio sources at low frequencies based on the distribution of the spectral index, $\alpha_{\text{low}}$, between 325 MHz and 1.4 GHz found for blazars in the ROMA-BZCAT. Sources with radio analysis flags, as well as double matches between the radio surveys, have been excluded from our final list. Thus, the LORCAT sample comprises 28,358 radio sources, including $\sim$667 known blazars having $-1 < \alpha_{\text{low}} < 0.4$.

We also compared our LORCAT catalog with the GB6 radio catalog since it is the most recent radio survey covering the largest fraction of the LORCAT footprint at higher frequency (i.e., $\sim$5 GHz). We found that a significant fraction of the LORCAT sources with extrapolated flux densities at $\sim$5 GHz above the completeness threshold of the GB6 are detected (i.e., $\sim$86%). In addition, they appear to be “flat”-spectrum radio sources above $\sim$1 GHz, according to the canonical definition (i.e., $\alpha_{\text{high}} < 0.5$) (e.g., Condon 1989, and references therein). The lack of detections for a small fraction of the LORCAT sources in the GB6 footprint could be explained in terms of a spectral steepening toward high frequencies (i.e., a mild curvature) as already observed in blazars.

Finally, we highlight that to investigate the nature of the LORCAT sources, aiming to identify the fraction of $\gamma$-ray blazar candidates asscociable to Fermi sources, a detailed analysis of the IR and optical properties is necessary (see, e.g., D’Abrusco et al. 2012; Massaro et al. 2012, 2013d). This will be presented in a separate, forthcoming paper (Massaro et al. 2014).

We thank the anonymous referee for many helpful comments and for all of the checks performed on our tables. This work is supported by NASA grants NNX12AO97G and NNX13AP20G.

R. D’Abrusco gratefully acknowledges the financial support of the US Virtual Astronomical Observatory, which is sponsored by the National Science Foundation and the National Aeronautics and Space Administration. The work by G. Tosti is supported by the ASI/INAF contract I/005/12/0. P.S.C. is grateful for support from the NSF through the NSF Graduate Research Fellowships Program Grant DGE1144152. The WENSS project was a collaboration between the Netherlands Foundation for Research in Astronomy and the Leiden Observatory. We acknowledge the WENSS team, including Ger de Bruyn, Yuan Tang, Roeland Rengelink, George Miley, Huub Rottgering, Malcolm Bremer, Martin Bremer, Wim Brouw, Ernst Raimond, and David Fullagar, for extensive work aimed at producing the WENSS catalog. Part of this work is based on archival data, software, or online services provided by the ASI Science Data Center. This research has made use of data obtained from the high-energy Astrophysics Science Archive Research Center (HEASARC) provided by NASA’s Goddard Space Flight Center; the SIMBAD database operated at CDS, Strasbourg, France; the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Part of this work is based on the NRAO VLA Sky Survey (NVSS). The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. TOPCAT\footnote{http://www.star.bris.ac.uk/~mbt/topcat/} (Taylor 2005) for the preparation and manipulation of the tabular data and the images.

Facilities: WSRT, VLA, GBT

Figure 10. Distribution of the radio spectral index, $\alpha_{\text{1400}}$, for all the known blazars that lie within the NVSS and in the SUMSS footprints (left panel). The cumulative distribution is shown on the right panel where the red dashed line marks the $\alpha_{\text{1400}} = 0.5$, according to the canonical definition of flat-spectrum radio sources.

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

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJS, 188, 405

Ackermann, M., Ajello, M., Allafort, A., et al. 2011a, ApJ, 743, 171

Ackermann, M., Ajello, M., Allafort, A., et al. 2011b, ApJ, 741, 30

Artyukh, V. S., & Vetukhnovskaya, Y. N. 1981, SvA, 25, 397

Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071

Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559

Cohen, A. S., Lane, W. M., Cotton, W. D., et al. 2007, AJ, 134, 1245

Condon, J. J., Balonek, T. J., & Jauncey, D. L. 1975, AJ, 80, 887

Condon, J. J., Condon, M. A., Broderick, J. J., & Davis, M. M. 1983, AJ, 88, 20

Condon, J. J. 1984a, ApJ, 287, 461

Condon, J. J. 1984b, ApJ, 284, 44

Condon, J. J. 1988, Galactic and Extragalactic Radio Astronomy (2nd ed.), ed. G. L. Verschuur & K. I. Kellermann

Condon, J. J. 1989, ApJ, 338, 13

Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693

D'Abrusco, R., Massaro, F., Ajello, M., et al. 2012, ApJ, 748, 68

D'Abrusco, R., Massaro, F., Paggi, A., et al. 2013, ApJS, 206, 12

De Breuck, C., Tang, Y., de Bruyn, A. G., et al. 2002, A&A, 394, 59

Ghirlanda, G., Ghisellini, G., Tavecchio, F., & Foschini, L. 2010, MNRAS, 407, 791

Giommi, P., Capalbi, M., Cavazzuti, E., et al. 2007, A&A, 468, 571

Giommi, P., Polenta, G., Lähteenmäki, A., et al. 2012, A&A, 541, 160

Gregory, P. C., Scott, W. K., Douglas, K., & Condon, J. J. 1996, ApJS, 103, 427

Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79

Healey, S. E., Romanis, R. W., Taylor, G. B., et al. 2007, ApJS, 171, 61

Hermens, W., Swanenburg, B. N., Bignami, G. F., et al. 1977, Natur, 269, 494

Howard, W. E., Dennis, T. R., III, Maran, S. P., & Aller, H. D. 1965, ApJS, 10, 331

Ivezić, Z., Menou, K., Knapp, G. R., et al. 2002, AJ, 124, 2364

Kellermann, K. I. 1964, ApJ, 140, 969

Keller, K. I. 1974, ApJ, 194, 518

Kellermann, K. I., Pauliny-Toth, I. I. K., & Williams, P. J. S. 1969, ApJ, 157, 1

Kovalev, Y. Y. 2009, ApJL, 707, L56

Kovalev, Y. Y., Aller, H. D., Aller, M. F., et al. 2009, ApJL, 696, L17

Mahoney, E. K., Sadler, E. M., Murphy, T., et al. 2010, ApJ, 718, 587

Maselli, A., Massaro, E., Nesci, R., et al. 2010, A&A, 512, 74

Massaro, E., Giommi, P., Leto, C., et al. 2009, A&A, 495, 691

Massaro, E., Giommi, P., Leto, C., et al. 2011a, Multifrequency Catalogue of Blazars (3rd ed.), ARACNE Editrice, Rome, Italy

Massaro, F., D’Abrusco, R., Ajello, M., Grindlay, J. E., & Smith, H. A. 2011b, ApJL, 740, L48

Massaro, F., D’Abrusco, R., Tosti, G., et al. 2012, ApJ, 752, 61

Massaro, F., D’Abrusco, R., Giroletti, M., et al. 2013a, ApJS, 207, 4

Massaro, F., Giroletti, M., Paggi, A., et al. 2013b, ApJS, 208, 15

Massaro, F., D’Abrusco, R., Paggi, A., et al. 2013c, ApJS, 206, 13

Massaro, F., D’Abrusco, R., Paggi, A., et al. 2013d, ApJ, 709, 10

Massaro, F., D’Abrusco, R., Paggi, A., et al. 2014, ApJS, in prep.

Mattox, J. R., Schachter, J., Molnar, L., et al. 1997, ApJ, 481, 95

Mauch, T., Murphy, T., Buttery, H. J., et al. 2003, MNRAS, 342, 1117

Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31

Nori, M., Giroletti, M., Massaro, F., et al. 2014, ApJS, 212, 3

Owen, F. N., Condon, J. J., & Ledden, J. E. 1983, AJ, 88, 1

Pauliny-Toth, I. I. K., Kellermann, K. I., Davis, M. M., et al. 1972, AJ, 77, 265

Petrov, L., Mahony, E. K., Edwards, P. G., et al. 2013, MNRAS, 432, 1294

Rengelink, R., Tang, Y., de Bruyn, A. G., et al. 1997, A&A, 124, 259

Taylor, M. B. 2005, ASPC, 347, 29

Urry, C. M., & Shaffer, R. A. 1984, ApJ, 280, 569

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479

Witzel, A., Pauliny-Toth, I. I. K., Nauber, U., & Schmidt, J. 1979, AJ, 84, 942