

Intermediate BL Lac objects

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Accepted 2001 March 16. Received 2001 March 16; in original form 2000 August 10

ABSTRACT

The 200-mJy sample, defined by Marchã et al., contains about 60 nearby, northern, flat-spectrum radio sources. In particular, the sample has proved effective at finding nearby radio-selected BL Lac objects with radio luminosities comparable to those of X-ray-selected objects, and low-luminosity flat-spectrum weak emission-line radio galaxies (WLRGs). The 200-mJy sample contains 23 BL Lac objects (including 6 BL Lac candidates) and 19 WLRGs. We will refer to these subsamples as the 200-mJy BL Lac sample and the 200-mJy WLRG sample, respectively. We have started a systematic analysis of the morphological pc-scale properties of the 200-mJy radio sources using VLBI observations.

This paper presents VLBI observations at 5 and 1.6 GHz of 14 BL Lac objects and WLRGs selected from the 200-mJy sample. The pc-scale morphology of these objects is briefly discussed. We derive the radio beaming parameters of the 200-mJy BL Lac objects and WLRGs and compare them with those of other BL Lac samples and with a sample of FR I radio galaxies. The overall broad-band radio, optical and X-ray properties of the 200-mJy BL Lac sample are discussed and compared with those of other BL Lac samples, radio- and X-ray-selected. We find that the 200-mJy BL Lac objects fill the gap between HBL and LBL objects in the colour–colour plot, and have intermediate α_{XOX} as expected in the spectral energy distribution unification scenario. Finally, we briefly discuss the role of the WLRGs.

Key words: galaxies: active – BL Lacertae objects: general – radio continuum: galaxies.

1 INTRODUCTION

BL Lac objects are an enigmatic class of active galactic nuclei (AGN). They are characterized by high luminosity, a flat radio spectrum that steepens in the optical–IR bands, relatively high optical and radio polarization, rapid variability in at least one of the radio, optical or X-ray bands, and weak or absent emission lines (see Kollgaard 1994 and Urry & Padovani 1995 for extensive reviews on BL Lac objects). The observational properties of BL Lac objects have been interpreted in terms of a relativistic jet aligned within a small angle to the line of sight (Blandford & Rees 1978). This model, known as the beaming model, implies that there must be a so called ‘parent population’ of radio sources intrinsically identical to BL Lac objects, but with the jets oriented at large angles to the line of sight. Browne (1983) and Wardle, Moore & Angel (1984) were the first to propose the low-luminosity edge-darkened FR I radio galaxies (Fanaroff & Riley 1974) as the most likely candidate for the ‘parent population’ of the core-dominated BL Lac objects.

This hypothesis has been investigated further by a number of authors comparing the extended radio luminosity and morphology (Antonucci & Ulvestad 1985; Kollgaard et al. 1992; Laurent-Muehleisen et al. 1993; Murphy, Browne & Perley 1993; Perlman & Stocke 1993; Cassaro et al. 1999), the radio polarization properties (Gabuzda et al. 1994; Gabuzda & Cawthorne 1996; Stanghellini et al. 1997), the properties of the host galaxies (Ulrich 1989; Abraham, Crawford & McHardy 1991; Falomo 1996; Wurtz, Stocke & Yee 1996) and the space densities and luminosity functions of the parent and beamed population (Padovani & Urry 1990, 1991; Urry, Padovani & Stickel 1991).

All these studies have concentrated on only a few samples: one selected in the radio frequency range of the spectrum – the 1-Jy sample of BL Lacs (Stickel et al. 1991) – and the others selected in the X-ray – the *HEAO-1* Large Area Sky Survey BL Lac sample (Wood et al. 1984; Kollgaard et al. 1996), the *Einstein* Extended Medium Sensitivity Survey (EMSS) BL Lac sample (Gioia et al. 1990; Stocke et al. 1991; Maccacaro et al. 1994), and the *Einstein* Slew Survey sample of BL Lac objects (Perlman et al. 1996a).

Radio-selected and X-ray-selected BL Lac objects (respectively RBLs and XBLs) have slightly different observational properties.

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The XBLs show less extreme properties than the RBLs, such as lower radio core dominance, larger starlight fraction and lower optical polarization (Laurent-Muehleisen et al. 1993; Perlman & Stocke 1993; Jannuzzi, Smith, & Elston 1994). Furthermore, RBLs and XBLs have different overall spectral energy distributions (SED) and therefore occupy different regions in the X-ray–optical and radio–optical spectral index space (e.g. Brinkmann et al. 1996).

On the basis of the broad-band spectral energy distribution, BL Lac objects have been re-classified as high-energy peaked BL Lacs (HBL), when the peak of the synchrotron emission falls in the UV/X-ray bands, and low-energy peaked BL Lacs (LBL), for objects with the peak in the IR/optical bands (Giommi & Padovani 1994; Padovani & Giommi 1995). Generally, the XBLs are HBLs and the RBLs are LBLs, but the importance of the new classification scheme is that it is based on a physical difference between the two subclasses and not on the selection band: in the HBLs the X-ray emission is produced by the synchrotron peak, while in the LBLs the X-ray is dominated by the inverse Compton component.

Many of these properties are consistent with the FR I – BL Lac unification hypothesis if XBLs are objects oriented at larger angles from the line of sight than RBLs. However, the standard unified scheme is probably too simplistic and intrinsic differences must be present between the two subclasses. For example, the difference in the SED peak frequency between LBLs and HBLs is too large (about 5 orders of magnitude) to be explained as different jet speed and/or orientation (Sambruna, Maraschi & Urry 1996), and the highest redshift radio-selected BL Lac objects have optical and radio properties more consistent with being FR II radio galaxies viewed edge on (Kollgaard et al. 1992; Cassaro et al. 1999) or, in a few cases, gravitationally lensed quasars (Stocke & Rector 1997).

Two models have been recently proposed that explain and unify HBL and LBL spectral energy distributions as produced by a combination of kinetic jet luminosity and viewing angle (Georganopoulos & Marscher 1998), or peak frequency of the synchrotron component and total luminosity (Ghisellini et al. 1998). Both these models imply there must be a single population of BL Lac objects with a continuous range of viewing angle, peak frequency and/or kinetic jet luminosity. The clear-cut distinction between HBLs and LBLs would be the effect of the shallow surveys from which the first BL Lac samples were selected. In the present work we will use the term intermediate BL Lac objects to refer to objects with overall properties intermediate between HBL and LBL objects.

In recent years a lot of effort has been made to select larger and deeper samples of BL Lac objects in the radio and X-ray wavebands (the *ROSAT* Green Bank Sample of Intermediate BL Lacs, Laurent-Muehleisen et al. 1999; the Deep X-Ray Radio Blazar Survey, Perlman et al. 1998; the REX survey, Caccianiga et al. 1999). These large samples can allow the study of the whole BL Lac population and not only the extreme tails of HBLs and LBLs. Furthermore, they should provide the opportunity to study transitional objects between BL Lacs and FR I radio galaxies.

With these same goals we are engaged in a study of the pc-scale radio morphology and polarization properties of a sample of flat-spectrum radio sources that have radio fluxes intermediate between HBLs and LBLs, the 200-mJy sample defined by Marchã et al. (1996). In the current paper we will discuss the pc-scale properties of 14 objects selected from the 200-mJy sample, the radio beaming of the BL Lac object and weak-line radio galaxy samples, and the overall broad-band spectral properties of the

200-mJy BL Lac sample, comparing them with other BL Lac samples. The polarization properties and a comprehensive discussion of the pc-scale morphology of all the 200-mJy BL Lac objects and radio galaxies will be presented in a forthcoming paper.

We assume a Hubble constant $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2 THE 200-mJy SAMPLE

Marchã et al. (1996) selected a sample of 55 flat-spectrum radio sources (hereafter the 200-mJy sample) from the 8.4-GHz VLA Survey (Patnaik et al. 1992), with the following key criteria:

- (i) radio flux density at 5 GHz $\geq 200 \text{ mJy}$;
- (ii) declination $> 20^\circ$;
- (iii) flat-spectrum objects between 6 and 20 cm ($\alpha \leq 0.5$, $S \propto \nu^{-\alpha}$);
- (iv) $z \leq 0.2$ if the object had a known redshift;
- (v) Palomar Observatory Sky Survey identifications with $V \leq 17 \text{ mag}$;
- (vi) $|b| > 12^\circ$.

The sample was selected with two main purposes in mind: (i) to find nearby low-luminosity BL Lac objects with radio luminosities comparable to those of X-ray selected BL Lacs; (ii) to investigate the differences between BL Lacs and other flat-spectrum radio galaxies.

Spectroscopy and optical polarimetry of the 200-mJy sample have been obtained for nearly all the sources (Marchã et al. 1996). These observations allowed the determination of the equivalent width of the observed emission lines, the Ca II break, and the optical polarization. Based on these observations the flat-spectrum radio galaxies have been classified as BL Lac objects, BL Lac candidates, weak-line radio galaxies and radio galaxies with Seyfert-type spectra. The classification as BL Lac candidates refers to objects that although not fulfilling the standard definition of BL Lacs, i.e. Ca II break < 0.25 and EW $< 5 \text{ \AA}$ (Stickel et al. 1991; Stocke et al. 1991), show evidence for non-thermal nuclear emission, namely by showing Ca II break < 0.4 , and/or strong optical polarization. This point deserves some comments. The measurement of Ca II break contrast in a well-studied sample of giant ellipticals (Dressler & Shectman 1987) yielded a value around 0.5 for these sources. Hence, a measured Ca II break below this value (in particular below 0.4, which less than 5 per cent of galaxies showed) can be interpreted as evidence for an extra source of optical continuum. In principle a sample of BL Lacs should show a continuous range of values for the break contrast from 0 to 0.4, indicative of different relative strengths between BL Lac nucleus and host galaxy.

The flat-spectrum weak-line radio galaxies (WLRGs) show optical spectra typical of an elliptical galaxy with weak or absent emission lines and Ca II break > 0.4 . Many WLRGs in the 200-mJy sample are borderline objects with the BL Lac candidates and there is clearly a continuity in the spectroscopic and polarimetric properties of BL Lac objects, candidates and WLRGs. An intriguing possibility in the framework of the unified model is that the BL Lac candidates and the flat-spectrum radio galaxies could be the transitional objects between the BL Lacs and steep-spectrum FR I radio galaxies.

The 200-mJy sample has been recently updated, bringing the number of sources in the sample to 61 (Marchã private

communication). The above criteria have proved very effective in selecting BL Lac objects and BL Lac candidates. The 200-mJy sample contains 17 BL Lacs, 6 BL Lac candidates, 19 WLRGs, 13 Seyfert-like objects, and 6 objects that lack adequate spectral information for a proper classification or that do not fit in any of the previous classes. Redshifts are known for 16 of the 23 BL Lac objects and candidates. The median redshift of the whole sample is 0.06, and this is also the median redshift for the BL Lac objects, while the WLRGs have a slightly lower median redshift of 0.05.

The low-frequency radio power is a reliable indicator of the intrinsic radio power as it is only marginally affected by Doppler-boosted compact components. We collected low-frequency radio measurements for 56 objects of the 200-mJy sample from the Westerbork Northern Sky Survey (Rengelink et al. 1997) and the TEXAS survey (Douglas et al. 1996). Fig. 1 shows the distribution of the 327-MHz radio power of the 200-mJy sample. The median of the distribution is $\log P = 24.3 \text{ W Hz}^{-1}$ which is comparable with that of the low-luminosity FR I radio galaxies.

3 VLBI OBSERVATIONS

With the aim of starting a systematic study of the pc-scale properties of the 200-mJy sample, we selected a subset of the 200-mJy sample for Very Long Baseline (VLBI) observations with the Very Large Baseline Array (VLBA) and the European VLBI

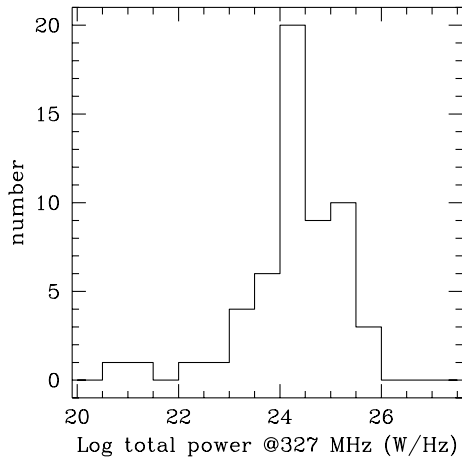


Figure 1. 327-MHz radio power distribution of the 200-mJy sample.

Network (EVN) among those without available pc-scale resolution observations. We observed also three objects that fulfil the selection criteria of the 200-mJy sample but have Galactic latitude $|b| < 12^\circ$ (two of them were originally included in the list of the 200-mJy sample). In Table 1 we list, for each source, the optical classification as BL Lac object (BLO), candidate (BLC), weak-line radio galaxy (WLRG) or hybrid object (HYB) based on the data of Marchã et al. (1996), together with the restoring beam, the peak brightness, and the rms noise of the images.

3.1 VLBA 5-GHz observations

Observations at 5 GHz with the full VLBA array were carried out in 1995 October. Each source was observed in snapshot mode for a total of about 90 min, recording with 32-MHz bandwidth, left circular polarization. Data reduction was done using the National Radio Astronomy Observatory (NRAO) AIPS package. The data sets were edited to remove bad data using the editing information supplied with the calibration files. First-order amplitude calibration was performed using the system temperatures and gains provided by the VLBA stations. A refinement of this calibration was obtained by observing two point-like sources (0016+731, 1739+522) and deriving the antenna-based amplitude corrections from them. The antenna-based corrections were found to be ≤ 5 per cent and consistent between the two unresolved sources. The standard procedure for removing residual delays, rates and phases and for hybrid mapping was applied. Fig. 2 shows the images obtained from the 5-GHz observations.

3.2 EVN 1.6-GHz observations

In 1995 May we observed 11 of the 14 objects selected for the VLBA observations with the European VLBI Network at 18 cm. The observations were carried out by an array of five telescopes (Effelsberg, Medicina, Noto, Onsala and Westerbork). Each source was observed in snapshot mode for a total time of about 90 min in left circular polarization with a total bandwidth of 28 MHz. Data reduction was done using the National Radio Astronomy Observatory (NRAO) AIPS package. The data sets were edited to remove bad data using the editing information supplied with the calibration files. First-order amplitude calibration was performed using the system temperatures and the gain curves provided by the EVN stations. To improve this calibration we observed three strong point-like sources (0059+581, 0955+476 and 1739+522), to

Table 1. Image parameters.

IAU Name B1950	class	4.9-GHz mas	beam size "	$S_{\text{peak}}^{4.9 \text{ GHz}}$ mJy beam $^{-1}$	$\sigma_{\text{r}}^{4.9 \text{ GHz}}$ mJy beam $^{-1}$	1.6-GHz beamsize mas	$S_{\text{peak}}^{1.6 \text{ GHz}}$ mJy beam $^{-1}$	$\sigma_{\text{r}}^{1.6 \text{ GHz}}$ mJy beam $^{-1}$
0109+224	BLO	3.2×1.6	−5	337	0.08	26×11	335	0.62
0125+487	HYB	2.2×1.7	−25	58	0.19	11×11	146	0.13
0149+710	BLC	2.2×1.5	−83	202	0.09			
0210+515	BLO	2.0×1.8	−25	98	0.06	13×13	114	0.18
0651+428	BLC	2.5×1.5	−4	72	0.06	11×11	72	0.33
0729+562	WLRG	4.3×3.9	+67	27	0.09	13×13	112	0.18
1055+567	BLO	2.2×1.6	+38	120	0.07	11×11	201	0.12
1215+303	BLO	2.5×1.6	0	266	0.06			
1241+735	WLRG	2.2×2.1	+33	81	0.08			
1558+595	WLRG	2.3×1.6	+19	63	0.07	13×13	151	0.11
1646+499	HYB	2.8×1.7	−4	114	0.09	12×12	86	0.11
1959+650	BLO	2.6×1.9	+21	176	0.09	13×13	167	0.21
2202+363	WLRG	2.5×1.6	−12	120	0.08	11×11	163	0.29
2344+514	BLO	2.9×2.1	−6	102	0.06	14×14	97	0.14

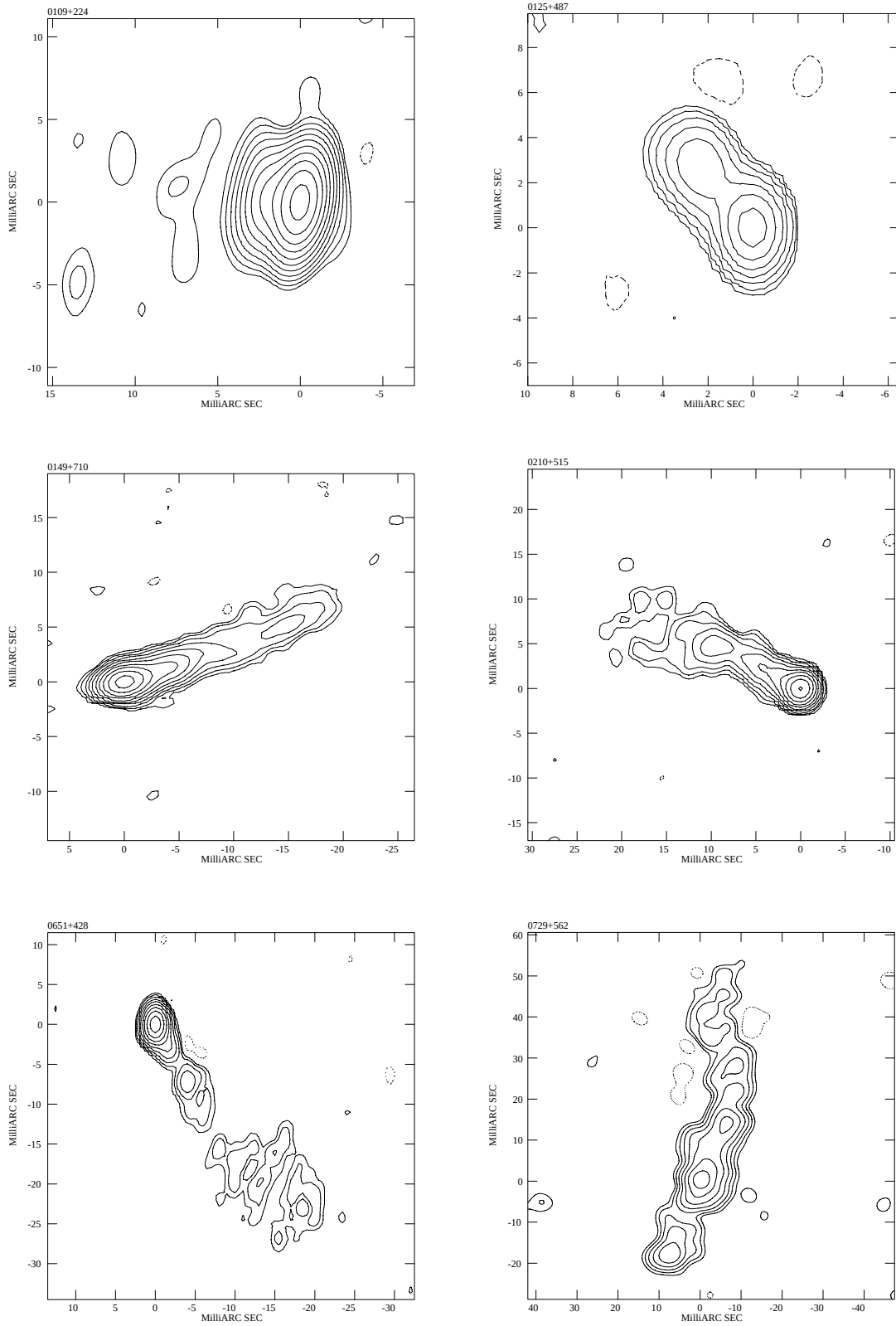


Figure 2. Contour maps of sources observed at 4.9 GHz with the VLBA. The minimum contour level is 3 times the rms noise given in Table 1. The contour levels are multiples (−1, 1, 2, 4, 8, 16, 32, 64, ...) of the minimum contour level.

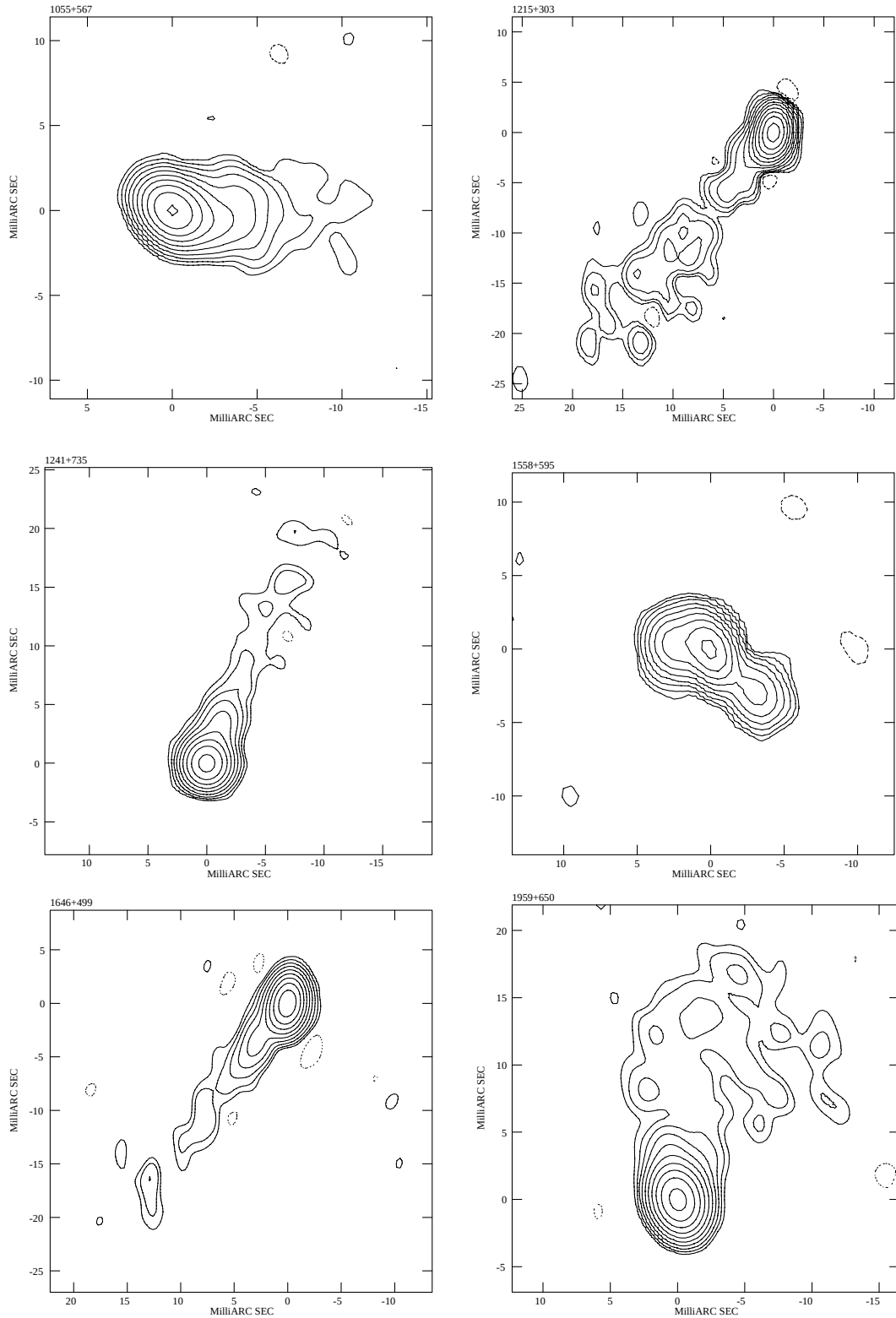


Figure 2 – continued

derive the antenna-based amplitude corrections. We found consistent results from the three point-like sources with corrections $\lesssim 10$ per cent. The standard procedure for removing residual delays, rates and phases and for hybrid mapping was applied. The images were all restored with a circular beam

except for 0109+224. Fig. 3 shows the images obtained from the 1.6-GHz observations for sources with extended emission; images for the three sources (0109+224, 1959+650 and 2202+363) which appeared point-like or barely resolved at 18 cm are not shown.

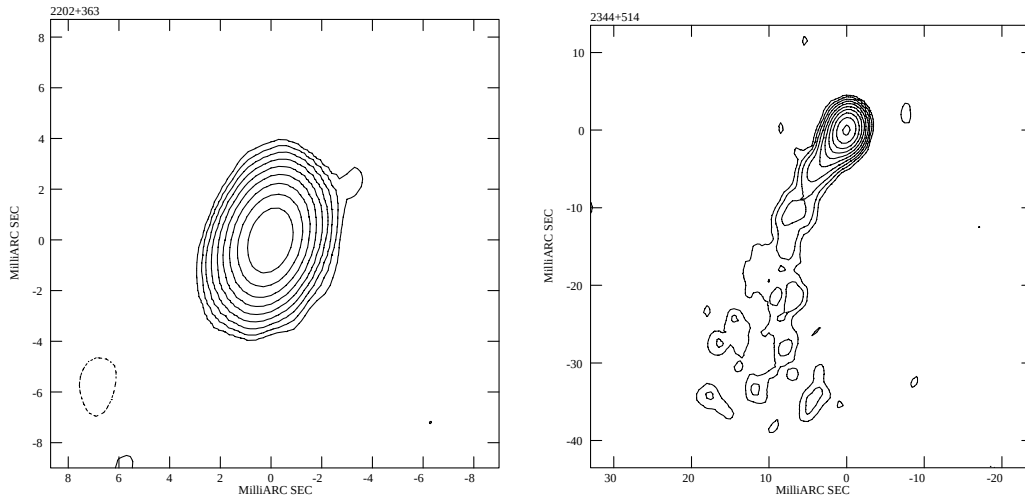


Figure 2 – continued

4 COMMENTS ON INDIVIDUAL SOURCES

0109+224: this is a BL Lac object with featureless optical spectrum and unknown redshift. The host galaxy is unresolved in *Hubble Space Telescope* (*HST*) observations (Falomo 1996) and IRCAM *K*-band images (Wright et al. 1998). A lower limit to the redshift can be set to 0.4 based on the optical host appearance (Falomo 1996). At 5 GHz we detect a compact core with a secondary component at about 3 mas at position angle $\approx 85^\circ$. There are hints of additional diffuse extended emission resolved out by our observations at 5 GHz, but the 1.6-GHz EVN observations do not detect any extended emission. On the arcsec scale, 0109+224 shows a faint collimated radio jet about 2 arcsec long in the south-western direction (Wilkinson et al. 1998). The inner region of the VLA radio jet has a position angle $\approx 225^\circ$, implying a misalignment between the mas and arcsec scale of about 130° .

0125+487: we name this object, together with 1646+499, as hybrid because it is a low-radio-luminosity object showing all the properties of classical BL Lacs, except that it displays significant broad emission lines (Marchã et al. 1996; Jackson & Marchã 1999). The optical galaxy is at $z = 0.067$, and at this distance 1 mas corresponds to about 0.86 pc. On the pc scale, the radio source displays a core–short jet morphology at 5 GHz. The 1.6-GHz observations make it possible to image the jet to a distance of about 100 mas from the core at about the same position angle as the inner jet detected in the 5-GHz observations. VLA observations show weak and extended emission elongated in the same direction as the pc-scale structure to a distance of about 5 arcsec from the core (Stanghellini, private communication).

0149+710: this is classified as a BL Lac object candidate following the Marchã criterion (Marchã et al. 1996; Laurent-Meuheisen et al. 1999). The redshift of the host galaxy is 0.022, and 1 mas corresponds to about 0.31 pc.

The 5-GHz VLBA image shows a bright core and a collimated, straight jet. The jet extends to about 20 mas from the core at a position angle of -70° . The core seems to be slightly extended also in the direction opposite to the main jet. Deeper observations are needed to clarify whether this faint emission is the base of the counter-jet or is just caused by residual errors in the self-calibration procedure. A 1.6-GHz VLBI image is not available because the radio source was not observed. The B array configuration VLA

image (Marchã 1994) shows a highly collimated jet up to about 40 arcsec from the core. At this distance the jet flares and changes direction ($\Delta\theta \approx 25^\circ$). A very short counter-jet is detected in this image. The main jet on the pc scale is well aligned with the inner region of the kpc-scale jet. At the resolution of the NRAO VLA Sky Survey (NVSS, Condon et al. 1998),¹ 45 arcsec, the radio source shows an asymmetric core–jet structure. The jet extends up to a projected distance of 6 arcmin from the core in north-western direction, and produces a faint lobe which bends to the south. No counter-jet is detected on the opposite side at this resolution.

0210+515: this is identified with a BL Lac object at $z = 0.049$. At this distance 1 mas corresponds to about 0.65 pc. The VLBA 5-GHz image shows a core–jet morphology. The jet extends to about 20 mas from the core at position angle 62° , and it bends slightly towards the east with increasing distance. The 1.6-GHz image traces the radio emission to a much longer distance from the core: the jet extends up to 100 mas from the core at position angle 90° , showing several wiggles along its path, and terminates in a rather compact knot. A similar knot is detected on the opposite side as well at a distance of about 50 mas from the core. At a resolution of a few arcsec, the structure is dominated by a compact core and a region of extended emission at a position angle about 90° ; weaker extended emission is also detected on the opposite side (Marchã 1994; Stanghellini et al., private communication). The NVSS image shows that the diffuse emission on the eastern side of the core extends up to about 1 arcmin from the nucleus, and there is a lobe of diffuse emission at a position angle about -40° which extends to several arcmin from the nucleus. It is not clear whether this is really a radio lobe related to the BL Lac object or just an effect of confusion produced by a background or foreground radio source.

0651+428: this is identified with a BL Lac candidate at $z = 0.126$. At this distance 1 mas is roughly 1.4 pc. The radio emission is unresolved on the arcsec scale (Patnaik et al. 1992). The lower resolution 1.6-GHz image (Fig. 3) shows a core–jet structure. The jet extends to about 40 mas from the core at position angle -146° . At 5 GHz (Fig. 2) we see that the jet is well collimated up to 15 mas from the core, where it suddenly flares.

0729+562: this is identified with a WLRG at $z = 0.104$ (1 mas corresponds to 1.2 pc). A large number of features are displayed by

¹<http://www.cv.nrao.edu/~jcondon/nvss.html>

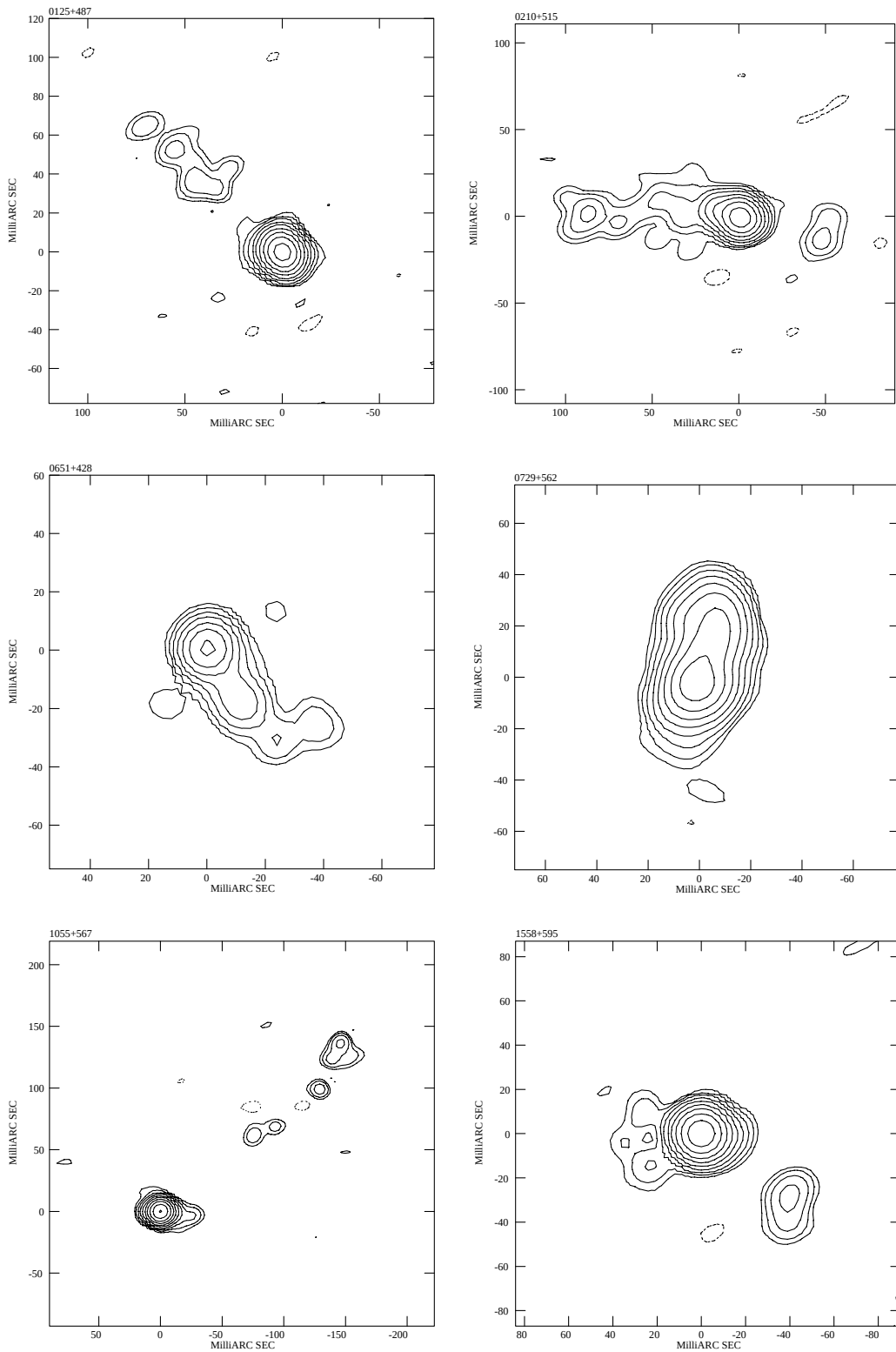
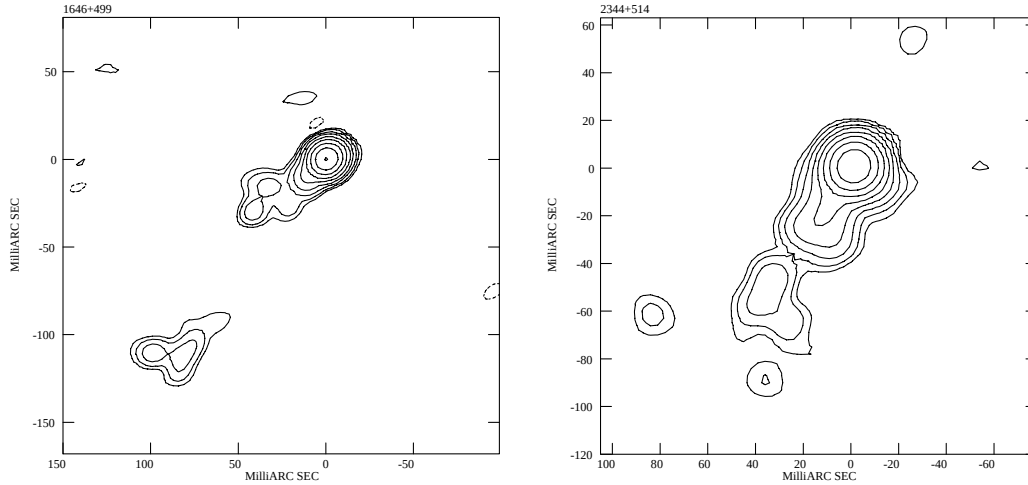


Figure 3. Contour maps of extended sources from 1.6-GHz EVN observations. The minimum contour level is 3 times the rms noise given in Table 1. The contour levels are multiples $(-1, 1, 2, 4, 8, 16, 32, 64, \dots)$ of the minimum contour level.

the 5-GHz VLBA image (Fig. 2): the source is rather collimated and presents a series of bright and relatively compact knots. From these images it is not straightforward to see which component is the core and whether the source is one-sided or two-sided. The lower

resolution 1.6-GHz EVN image (Fig. 3) shows a resolved radio source with an elongated structure approximately in the north–south direction. The total angular size of the source is about 80 mas. We used the 5-GHz data set to produce an image with the

Figure 3 – *continued*

same restoring beam as the 1.6-GHz map and combined the two to obtain a spectral index map. This suggested that the southernmost component has an inverted spectrum and is therefore the best candidate for the core, although uncertainties in the alignment of the maps could affect this result. VLA observations have found this source unresolved down to a resolution of about 0.2 arcsec (Patnaik et al. 1992).

1055+567: this is identified with a BL Lac object with an uncertain redshift. Marchã et al. (1996) estimated a redshift of 0.410 based on a [O III] emission line at 7000 Å, but this identification is probably incorrect, as subsequent observations (Bade et al. 1998; Laurent-Muehleisen 1998) have not detected emission lines, but only absorption features at a redshift of 0.144. On the arcsec scale 1055+567 is unresolved (Patnaik et al. 1992). The 5-GHz VLBA image (Fig. 2) shows a strong and compact core with a short jet extending westward to a distance of about 10 mas from the nucleus. At 1.6 GHz (Fig. 3) the jet can be traced up to about 40 mas from the nucleus, some knots of emission are also detected at larger distances from the core (between 100 and 200 mas at position angle $\approx -41^\circ$) suggesting a bending jet on larger scales.

1215+303: this is a BL Lac object at $z = 0.130$ (Perlman et al. 1998). At this redshift, 1 mas corresponds to about 1.5 pc. The 5-GHz image (Fig. 2) detects a one-sided jet extending to about 30 mas from the bright core. In the inner 8 mas the jet is highly collimated, unresolved transversally, and shows wiggles that suddenly change the jet direction. Beyond this point, the jet expands. On the kpc scale, the FIRST (Faint Images of the Radio Sky at Twenty cm, Becker, White & Helfand 1995)² image shows a bright compact component within a low surface brightness halo with a total extension of about 45 arcsec.

1241+735: this is classified as a WLRG at $z = 0.075$ (1 mas corresponds to 0.94 pc). The radio source has an unusual radio morphology for a radio galaxy: the pc-scale morphology (Fig. 2) resembles those for the BL Lac objects in the sample, with a bright, compact core and a one-sided jet extending up to about 15 mas from the nucleus with a position angle of about -20° . The radio jet has the same position angle up to 10 arcsec where it starts bending to the south-western direction and appears to end in a compact component at about 30 arcsec from the nucleus at position angle

-95° (Marchã 1994). There is no hint of a counter-jet or of any extended emission on the side opposite to the main radio jet.

1558+595: this is another WLRG at $z = 0.057$ (1 mas corresponds to 0.74 pc). The 5-GHz VLBA image (Fig. 2) shows a compact triple component morphology. A similar structure, but on a scale ten times larger, is detected by the 1.6-GHz EVN observations (Fig. 3). We can not derive spectral information for the three components detected at the higher frequency given that they are blended inside the beam of the 1.6-GHz image. For this reason it is not clear which component is the core. On the kpc scale the source is unresolved (Stanghellini, private communication).

1646+499: this is another hybrid object at $z = 0.045$ (1 mas corresponds to 0.60 pc). Again the mas-scale structure is that of a bright core and a collimated one-sided jet. The jet is detected for about 20 mas on the 5-GHz image (Fig. 2). The lower frequency EVN observations (Fig. 3) trace the jet to about 50 mas from the nucleus and detect also other radio emission aligned with the inner jet at a distance of about 130 mas. On the kpc scale the source shows a one-sided jet aligned with the pc-scale jet, extending to about 33 arcsec from the nucleus (Stanghellini, private communication).

1959+650: this is a BL Lac object at $z = 0.047$ (1 mas corresponds to 0.62 pc). On the mas scale (Fig. 2) the source displays a bright core and a transversally resolved jet which bends and flares at about 16 mas from the nucleus. The source is only slightly resolved in the 1.6-GHz EVN observations. No extended emission is detected on the arcsec scale.

2202+363: this is classified as a WLRG galaxy at $z = 0.073$ (1 mas corresponds to 0.92 pc). The 5-GHz VLBA observations (Fig. 2) show a single component barely resolved with no hints of extended emission. The source is unresolved in the 1.6-GHz EVN observations and also on the arcsec scale.

2344+514: this is a BL Lac object at $z = 0.039$ (1 mas corresponds to 0.51 pc). This BL Lac does not belong to the 200-mJy sample because of the Galactic latitude limit. The 5-GHz VLBA image (Fig. 2) shows a narrow one-sided jet which extends to about 20 mas from the compact core at position angle 150° , and then suddenly flares and bends to the south. More extended emission is detected in the 1.6-GHz EVN image (Fig. 3). On the kpc scale the BL Lac appears as a strong core-dominated radio source with a faint halo of extended emission, which extends for a few arcsec around the core (Stanghellini, private communication).

²<http://sundog.stsci.edu/top.html>

5 PC-SCALE STRUCTURE

In this section we will briefly discuss the pc-scale properties of the objects listed in Table 1 in relation to their larger scale radio structure and optical classification. A comprehensive discussion of the radio morphology and polarization properties of the whole 200-mJy BL Lac and WLRG samples will be presented in a future paper. The source list comprises six BL Lac objects, two BL Lac candidates, four WLRGs, and two hybrid objects chosen from the 200-mJy sample among those without previous VLBI observations.

All the objects were found to be resolved at 5 GHz and, with the only exception of 2202+363, they show extended structure, mostly jet-like features from a few to tens of mas. In many cases, the 1.6-GHz EVN observations made it possible to detect further extended emission at larger distances. All the BL Lac objects, the BL Lac candidates and the two hybrid objects show one-sided jets. One possible exception is the BL Lac 0210+515, in which the 1.6-GHz EVN observations detected an extended blob of emission on the counter-jet side at a distance of about 50 mas. Owing to the faintness of the extended feature and the limited $u-v$ coverage of the 1.6-GHz data this detection needs to be confirmed by longer and more sensitive observations but it is certainly intriguing, considering that a VLA snapshot image also shows two-sided extended emission. The four WLRGs show a more varied morphology. One object (2202+363) is a single resolved component without extended emission, another one (1241+735) has an asymmetric core–jet structure reminiscent of that seen in BL Lac objects, and the remaining two have complex radio morphologies indicative of possibly symmetric emission. Eight of the 14 objects observed with VLBI have extended emission on the kpc scale. Of the four WLRGs only one (1241+735) has kpc scale extended emission, compared with seven of the remaining 10 sources. In two cases (1215+303 and 2344+514) the extended emission is in form of a low-surface-brightness spherical halo and so we can not relate it to the direction of the pc scale jet. In all the other cases the kpc-scale emission is in form of a radio jet. The misalignment angle between the pc and kpc jet is usually very small. Out of the six objects with a detectable jet on both pc and kpc scales, only one, 0109+224, has a misalignment angle exceeding 30° .

6 DISCUSSION

The 200-mJy samples of BL Lac objects and WLRGs are presented in Tables 2 and 3, respectively. BL Lac objects originally selected in the 1-Jy sample or in the Slew Survey sample are identified with a ‘L’ or ‘H’, and BL Lac candidates are identified with a ‘C’ in columns 3 and 6 of Table 2. In order to investigate the characteristics of the 200-mJy BL Lac sample we carried out a comparison with other BL Lac samples and with a FR I radio galaxy sample selected from Zirbel & Baum (1995). The other samples of BL Lac objects used in this comparison are the 1-Jy sample of radio-selected BL Lac objects (Stickel et al. 1991), an X-ray-selected sample containing the BL Lac objects from the *HEAO-I* Large Area Sky Survey (Kollgaard et al. 1996) and the *Einstein* Medium Sensitivity Survey (Morris et al. 1991), or alternatively the Slew Survey Sample of BL Lac objects (Perlman et al. 1996a), and finally the *ROSAT* Green Bank sample of BL Lac objects (Laurent-Muehleisen et al. 1999). From the large sample of FR I and FR II radio galaxies compiled by Zirbel & Baum (1995) we selected a subsample of 67 FR I radio galaxies characteristic of

Table 2. The 200-mJy sample of BL Lac objects.

IAU Name B1950	z	Note	IAU Name B1950	z	Note
0109+224			1147+245		L
0651+428	0.126	C	1215+303	0.130	H
0652+426	0.059	C	1219+285	0.102	H
0716+714		L	1246+586		
0806+350	0.082		1418+546	0.151	L
0912+297			1424+240		
0925+504			1645+292	0.132	C
1055+567	0.144		1652+398	0.033	L,H
1101+384	0.031	H	1703+233	0.049	C
1123+203	0.133	C	1807+698	0.046	L,H
1133+704	0.046	H	1959+650	0.047	H
1144+352	0.063	C			

Table 3. The 200-mJy sample of WLRGs.

IAU Name B1950	z	IAU Name B1950	z
0035+227	0.096	1217+295	0.002
0055+300	0.015	1241+736	0.075
0116+319	0.060	1245+676	0.103
0651+410	0.021	1551+239	0.115
0729+562	0.104	1558+595	0.057
0733+597	0.041	1658+302	0.036
0836+290	0.079	1755+626	0.024
0848+686	0.039	2202+363	0.073
0902+468	0.084	2320+203	0.038
1146+596	0.009		

the parent population of BL Lac objects. There is appreciable overlap in membership between the various BL Lac samples we consider. The 200-mJy BL Lac sample contains previously identified HBLs, LBLs and objects found in the recent deep surveys (e.g. RGB sample). In the following analysis, objects belonging to different samples will be counted in all the samples. The only exception to this rule are Figs 6–9 where, to avoid an excessive crowding of points and symbols, objects belonging to different samples are plotted only once. In particular, we adopted the following priority for plotting symbols of objects belonging to different samples: 200-mJy sample, 1-Jy sample, Slew Survey sample and RGB sample.

6.1 Radio beaming: the R parameter

It is likely that the extended kpc-scale radio emission is nonrelativistic and therefore the radio core-to-extended emission ratio, $R = S_{\text{core}}/S_{\text{ext}}$, also called the core dominance parameter, is often taken as a relative measure of orientation. The proper way to derive R would be to use radio images with resolution high enough to separate the core from the isotropic emission and with enough sensitivity to detect all the extended radio structure. These high-quality images are not always available for large samples and in these cases it is necessary to resort to lower resolution surveys to estimate the total flux density. However, snapshot observations at 1.4 GHz are available for a subsample of the 200-mJy sample and we used these data together with the FIRST and NVSS radio surveys to obtain estimates of the core and extended radio flux densities at 1.4 GHz for the 200 mJy radio sources.

Deep observations at 1.4 GHz of the 1 Jy, *HEAO-I* and EMSS

Table 4. Median properties.

Property	RBL 1 Jy	XBL <i>HEAO</i> + EMSS	RGB BL Lacs	200 mJy BL Lacs	200 mJy WLRGs	FR I
z	0.50	0.20	0.16	0.06	0.05	0.04
R	10.2	1.7	1.1	1.9	0.73	0.017
$\log S_X/S_R$	-6.9	-4.8	-5.6	-6.1		

samples are available (Laurent-Muehleisen et al. 1993; Kollgaard et al. 1996; Cassaro et al. 1999), and we used these data to derive the core dominance parameter at 1.4 GHz. The RGB sample of BL Lac objects consists of 127 sources, most of them without high-sensitivity interferometric radio images. Laurent-Muehleisen et al. (1997) used the core flux densities derived from snapshot VLA observations at 5-GHz and total fluxes from the Green Bank 5-GHz radio survey (Gregory & Condon 1991; Gregory et al. 1996) to derive the core dominance parameter for the whole RGB sample of AGNs. To be consistent with the previous samples, where R is calculated at 1.4 GHz, we assume a core spectral index $\alpha_{\text{core}} = 0$ between 5 and 1.4 GHz and then we use the FIRST and/or NVSS total flux to derive the extended flux for the RGB BL Lacs. The core dominance parameters were K corrected assuming a core spectral index $\alpha_{\text{core}} = 0$ and an extended spectral index $\alpha_{\text{ext}} = 0.75$; when a redshift was not available for an object, the median redshift of the sample was used.

Table 4 lists the median of the redshift and core dominance parameter distributions for the various BL Lac samples and the WLRG sample. We used the Astronomy SURVival (ASURV) data analysis software (LaValley et al. 1992) to compute the Kaplan–Meier estimator of the distributions. The histograms of the core dominance parameter distribution for the various samples are shown in Fig. 4. The values for the 200-mJy sample in Fig. 4 are given for all the objects, regardless of their optical identification. The R value for the WLRGs must be taken with caution, as it is not clear whether these objects belong to a homogeneous and well-defined class and also because of the poor statistic. It is clear from the medians and the histograms that the BL Lac objects of the 200-mJy sample are less core-dominated than the RBLs of the 1-Jy sample and are similar to the XBLs of the EMSS and *HEAO* surveys. On the other hand, the RGB BL Lac sample, which has a radio flux density limit ten times lower than the 200-mJy sample, is less core-dominated than the other BL Lac samples previously mentioned, but still a factor of 65 more core-dominated than the FR I radio galaxies. Even if this result is based on relatively few objects, it is interesting to note that the flat-spectrum weak-line radio galaxies are less core-dominated than any of the BL Lac samples but still significantly more than the FR I radio galaxies. This is consistent with the selection criteria: the flat spectrum of the 200-mJy sources naturally favours core-dominated sources.

The 200-mJy BL Lac sample has a restriction in redshift while the other samples do not. In flux-limited samples a selection in redshift implies a limit in power. Higher redshift objects are those which appear more powerful and where the beaming is more extreme. What happens to the core dominance parameter of the RBL and XBL samples if we consider only BL Lacs with redshift less than 0.2? Within redshift 0.2 we have 18 XBLs and six RBLs for which R can be calculated. The 18 XBLs give a median R of 1.6, not significantly different from the value of the whole sample. The six RBLs are too few for a statistical analysis but we can still say something. Three of these six objects are also in the 200-mJy sample and the other three objects have not been selected by the

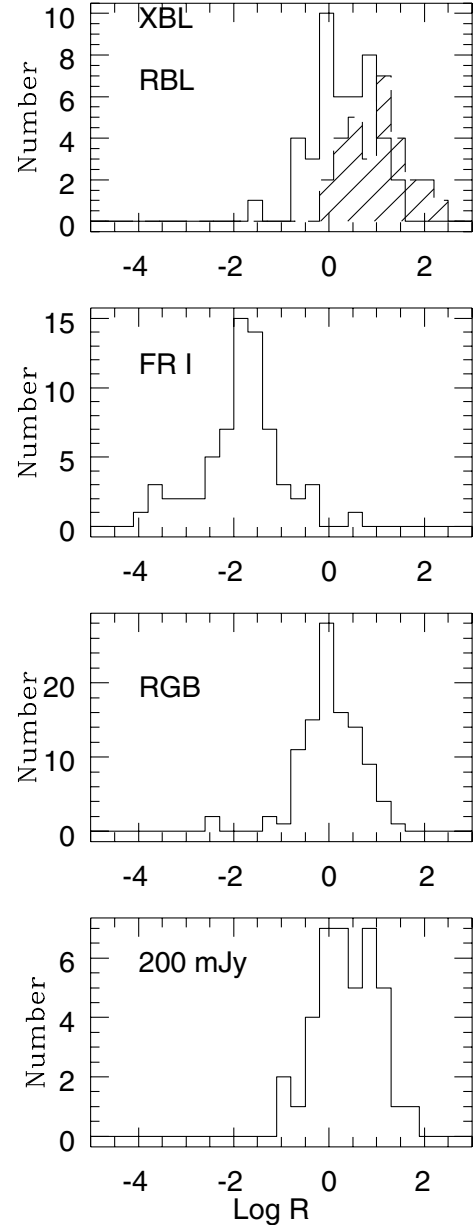


Figure 4. Distribution of R , the core dominance parameter, for, from top to bottom, (a) radio-selected (hatched region) and X-ray-selected BL Lac objects; (b) FR I radio galaxies; (c) RGB sample of BL Lac objects; (d) the 200-mJy sample excluding the Seyfert-type objects.

200-mJy sample only because they are outside the declination or Galactic latitude limits. So all these objects could be considered intermediate BL Lacs, but this does not mean that they are representative of the whole class. In fact, only one out of the six has $R < 5$, typical of the 200-mJy BL Lac objects. In conclusion, we can say that the 1-Jy sample BL Lac objects with redshift less than

0.2 can be considered the higher power tail of the intermediate BL Lac objects.

The starting hypothesis of the low-luminosity unified scheme scenario is that BL Lac objects are FR I radio galaxies seen roughly along the line of sight (e.g. Urry & Padovani 1995). It is possible to use a simplified beaming model and the R parameter distribution to constrain the jet Lorentz factor or orientation for the different samples. The relation between the core dominance parameter and the jet velocity and orientation is

$$R = \frac{S_{\text{core}}}{S_{\text{ext}}} (1+z)^{\alpha_{\text{core}} - \alpha_{\text{ext}}} = f \delta^p,$$

where f is the intrinsic core-to-lobe ratio and δ is the Doppler factor. The beaming index, p , is $p = 3 + \alpha$ or $p = 2 + \alpha$ for a single sphere or a continuous jet, respectively (e.g. Pearson & Zensus 1987), where α is the observed integrated spectrum rather than the spectral index of the local emission (Cawthorne 1991). The beaming index will be modified by the lifetimes of emitting electrons, the radial dependence of the emissivities and the presence of relativistic shocks (Lind & Blandford 1985; Urry & Padovani 1995). Reasonable values for the beaming index are in the range $p = 2-4$. We assume that the sample of FR I radio galaxies selected from Zirbel & Baum (1995) is characteristic of the parent population of BL Lac objects and is oriented at an average angle to the line of sight of $\theta = 60^\circ$. As a first step we can also assume that there is a single velocity for the population of FR I radio galaxies and BL Lac objects with $\Gamma \approx 6$ (Urry & Padovani 1995; Kollgaard et al. 1996; Laurent-Muehleisen et al. 1997). With these assumptions, using the median R values in Table 4 and allowing p to lie in the range 2–4, the average angle to the line of sight is in the range $11^\circ-20^\circ$ for the 1-Jy RBLs, $20^\circ-26^\circ$ for the XBLs and 200-mJy BL Lacs, and $23^\circ-27^\circ$ for the RGB BL Lac sample. If we allow Γ to vary in the range $3 \leq \Gamma \leq 20$ then the average angle to the line of sight for the 200-mJy sample BL Lac objects is constrained within a fairly small range $15^\circ \leq \theta \leq 24^\circ$ as shown in Fig. 5, where we have used $p = 2.7$ and the horizontal line is the observed mean R between the 200-mJy BL Lac objects and FR I radio galaxies. Using the same range for Γ and $p = 2.7$,

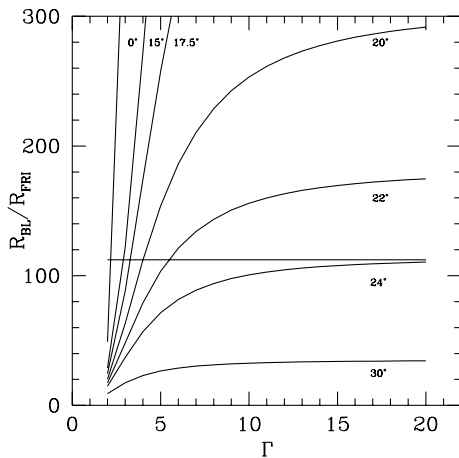


Figure 5. Predicted ratio between the median core-to-lobe ratios of the 200-mJy BL Lac objects and FR I radio galaxy samples versus the jet Lorentz factor with different line-of-sight orientation for the BL Lac sample. It is assumed that the FR I radio galaxies have an average $\theta_{\text{FR1}} = 60^\circ$ and the same Lorentz factor as the BL Lac objects. The horizontal line is the observed ratio.

the RBLs are found to have $\theta \leq 17^\circ$ and the RGB BL Lacs have $20^\circ \leq \theta \leq 27^\circ$.

6.2 X-ray to radio flux density ratios

As shown by Laurent-Muehleisen et al. (1999), the bimodality in the ratio of the X-ray to radio flux densities of HBLs and LBLs was produced by selection effects in the previous X-ray and radio-selected BL Lac samples. The RGB BL Lac sample, obtained by cross-correlating deep X-ray and radio surveys, contains large numbers of intermediate BL Lac objects with a median of $\log S_X/S_R \approx -5.5$, the value previously identified as a threshold between LBL and HBL objects (Padovani & Giommi 1995; Brinkmann et al. 1996; Perlman et al. 1996b).

The 200-mJy sample is radio and optically selected with a radio flux limit a factor of 5 lower than the 1-Jy sample and an order of magnitude higher than the RGB sample. For this reason it is interesting to compare the distribution of $\log S_X/S_R$ for the 200-mJy sample with other BL Lac samples. Following Laurent-Muehleisen et al. (1999), in calculating the $\log S_X/S_R$ we consider only the arcsec-scale core flux densities. The limited angular resolution of X-ray observations makes it problematic to disentangle the nuclear non-thermal component from any thermal component associated with the galaxy or cluster of galaxies, but for the BL Lac objects any thermal unbeamed contribution can be considered negligible compared with the beamed non-thermal nuclear component. From the *ROSAT* All Sky Survey Database, we obtained the X-ray flux densities for 19 of the 23 BL Lac objects and candidates in the 200-mJy sample. From the X-ray flux we evaluated the unabsorbed monochromatic flux density at 2 keV, assuming the absorption produced by a galactic hydrogen column density taken from Stark et al. (1992). If no X-ray spectral index is available in the literature we use the median value $\alpha_X = 1.4$ derived from those with known α_X . The same α_X is used to K -correct the X-ray flux densities. The radio flux density used to calculate the $\log S_X/S_R$ is the core radio flux density at 5 GHz taken from VLA arcsec-scale resolution observations available in the literature. When a 5-GHz measure was not available, we used the 8.4-GHz flux density from Patnaik et al. (1992). The radio core flux densities were K -corrected assuming $\alpha_R = 0.0$. The median value for the 200-mJy BL Lac sample is listed in Table 4 together with the values for the other BL Lac samples taken from Laurent-Muehleisen et al. (1999). The ratio between the X-ray and radio flux in the 200-mJy sample BL Lacs is intermediate between the 1-Jy and RGB BL Lacs. Consistent with the selection criteria adopted in defining the 200-mJy sample, we find a continuity in the ratio between X-ray and radio flux densities among different BL Lac samples, but with a significant difference. The LBL and HBL objects from the 1-Jy, EMSS, *HEAO* and *SLEW* samples share approximately the same X-ray luminosity, and the clearcut difference in the S_X/S_R distribution is caused by the great difference in the radio band. On the other hand, the 200-mJy BL Lac objects are intermediate in the S_X/S_R ratio mainly because they have lower X-ray luminosity than the HBL samples, while the radio core flux density is comparable with that of HBLs. We will return to this point in the following section.

6.3 Broad-band spectral properties: the colour–colour diagram

The spectral energy distribution of blazars, and in particular of BL Lac objects, is characterised by two peaks. The frequency of the

peaks is anticorrelated with the source luminosity. The first peak (resulting from synchrotron emission) moves from $\sim 10^{16}$ – 10^{17} Hz for less luminous sources to $\sim 10^{13}$ – 10^{14} Hz for the most luminous ones, and the second peak (resulting from inverse Compton emission) also moves from $\sim 10^{24}$ – 10^{25} Hz for less luminous sources to $\sim 10^{21}$ – 10^{22} for the most luminous ones (Fossati et al. 1998).

The shift of the synchrotron peak frequency with luminosity naturally explains the different loci occupied in the colour–colour $\alpha_{\text{ox}}-\alpha_{\text{ro}}$ diagram by LBL and HBL objects. Roughly speaking, in the colour–colour diagram the HBLs occupy a horizontal stripe with $0.2 < \alpha_{\text{ro}} < 0.6$ and $\alpha_{\text{ox}} \leq 1.2$, while the LBLs have $\alpha_{\text{ro}} > 0.5$ and $0.9 < \alpha_{\text{ox}} < 1.6$ with lower α_{ox} corresponding to higher α_{ro} (e.g. Brinkmann et al. 1996).

It is worth noting that to derive the broad-band spectral index only the flux of the AGN compact component should be used. As we have said in the previous subsection, the X-ray and VLA radio observations at 5 GHz supply a robust determination of the core flux densities in these bands, with minimal contamination from the galaxy. On the other hand, in the optical band the total magnitude of the galaxy overestimates the AGN flux. To disentangle the AGN optical magnitude from that of the host galaxy it is necessary to have high-resolution optical imaging (e.g. *HST*) or to use the measure of the Ca II break contrast to estimate the non-thermal contribution resulting from the AGN (Laurent-Muehleisen et al. 1998; Dennett-Thorpe & Marchã 2000). Scarpa et al. (2000) provide a list of nuclear and host optical magnitudes derived from *HST* observations for a list of BL Lacs including the 1-Jy and Slew Survey samples.

Fig. 6 shows the colour–colour diagram of the AGN component for LBL objects from the 1-Jy catalogue (circles), HBL objects from the Slew Survey BL Lac sample (triangles), the 200-mJy BL Lacs (squares), and a subsample of 19 BL Lacs from the RGB sample for which an estimate of the AGN optical magnitude is available (stars). In Figs 6–9, objects belonging to more than one sample are plotted only once; in particular, all the 200-mJy BL Lacs are plotted with the same symbol. The optical magnitudes for the AGN component are taken from Scarpa et al. (2000) for the 1-Jy LBLs, the Slew Survey Sample HBLs objects and a few 200-mJy BL Lac objects, from Dennett-Thorpe & Marchã (2000)

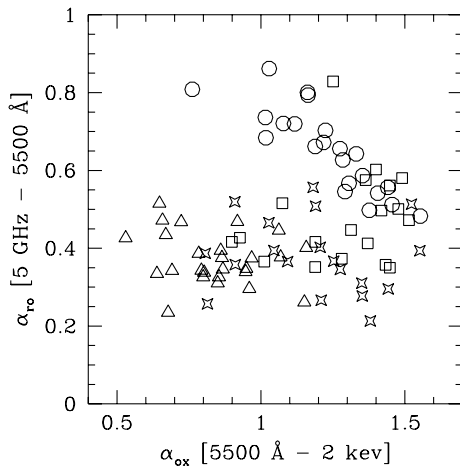


Figure 6. $\alpha_{\text{ro}} - \alpha_{\text{ox}}$ colour–colour diagram for the AGN component: the rest-frame broad-band spectral indices are calculated between 5 GHz, 5500 Å and 2 keV for LBL (circles), HBL (triangles), 200-mJy BL Lacs (squares) and a subsample of the RGB BL Lacs (stars).

for the rest of the 200-mJy BL Lacs and from Laurent-Muehleisen et al. (1999) for the RGB BL Lacs. In the latter two cases the AGN optical magnitudes are estimated from the Ca II break contrast. The rest frame broad-band spectral indices are calculated at 5 GHz, 5500 Å and 2 keV. Optical fluxes at different wavelengths were transformed to 5500 Å assuming $\alpha_{\text{O}} = 1.0$, and X-ray fluxes at 1 keV were transformed to 2 keV using the quoted X-ray spectral index or the median value for the sample. The same spectral indices were used to apply the *K* correction.

Fig. 6 shows how the 200-mJy BL Lacs, together with the 19 BL Lacs from the RGB sample, fill the gap between the HBL and LBL populations, overlapping somewhat with both. In particular the intermediate BL Lac objects have about the same α_{ro} as the HBL but a steeper α_{ox} . Among the 200-mJy BL Lacs plotted in Fig. 6 there are three BL Lac candidates. Two of them occupy the same region as the intermediate BL Lacs, in particular they have $\alpha_{\text{ox}} > 1.3$. The third one is the object with the steepest α_{ro} , but in this case a revised determination of the contrast indicates that this object should be classified as a WLRG (Dennett-Thorpe & Marchã 2000). The distribution of BL Lac objects (HBL, intermediate, and LBL) in the colour–colour plot confirms that there is a continuity in the SED of BL Lacs going from HBL to LBL, and that new BL Lac samples are filling the gap between HBLs and LBLs, adding intermediate objects (Perlman et al. 1998; Caccianiga et al. 1999; Laurent-Muehleisen et al. 1999).

The path in the colour–colour plot from HBL through intermediate BL Lacs to LBL can be reproduced by the SED unification scheme proposed by Fossati et al. (1998). According to this scenario a single parameter, related to the radio luminosity, should determine the frequencies of the two peaks in the SED. This implies that the radio luminosity should increase moving along the horizontal branch in the $\alpha_{\text{ox}}-\alpha_{\text{ro}}$ plot from the HBLs to the intermediate BL Lacs and then rising through the diagonal branch of the LBLs. This trend is reproduced in Fig. 7, which plots the total radio luminosity at 5 GHz versus the optical–X-ray spectral index for HBLs, LBLs and the 200-mJy BL Lacs. It could be argued that the increase in the total radio luminosity at 5 GHz going from HBLs through intermediate objects to LBLs is simply the result of an increase of the beaming, as expected from the unification paradigm. Actually this is not the whole story: the same trend is observed even considering the 327-MHz, instead of the 5-GHz, radio luminosity.

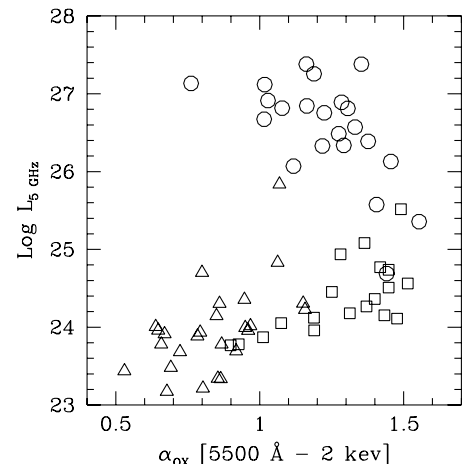


Figure 7. 5-GHz total radio luminosity versus α_{ox} . Symbols are the same as in Fig. 6.

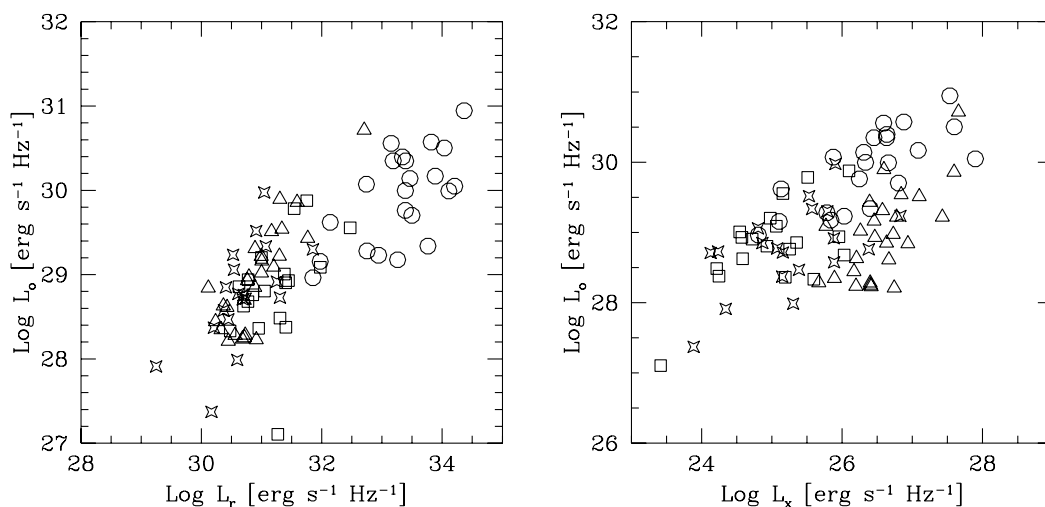


Figure 8. (a) Optical luminosity (5500 Å) versus radio (5-GHz) and (b) optical luminosity (5500 Å) versus X-ray (2-keV) luminosities, for LBL (circles), HBL (triangles), 200-mJy BL Lacs (squares) and a subsample from the RGB BL Lacs (stars). All the luminosities are AGN component only.

The position of the intermediate BL Lacs in the knee of the colour–colour distribution has other implications. In Fig. 8 we plot the optical versus radio and optical versus X-ray luminosity of the AGN component for the same objects shown in Fig. 6. While the nuclear radio and optical luminosities of the 200-mJy BL Lacs are consistent with those of the Slew Survey BL Lac sample, the X-ray luminosities at 2 keV are systematically lower (median is $\log L_X = 25.1 \text{ erg s}^{-1} \text{ Hz}^{-1}$ for the 200-mJy BL Lacs compared with $\log L_X = 26.5 \text{ erg s}^{-1} \text{ Hz}^{-1}$ for the median X-ray luminosity of the Slew Survey Sample BL Lacs). The lower X-ray luminosity of intermediate BL Lacs compared with both HBLs and LBLs is confirmed by the subsample of 19 RGB BL Lacs plotted in Fig. 8, and can be explained in the scenario of the SED unification of BL Lac objects. The X-ray flux at about 2 keV in the LBLs is produced by the flat rise of the inverse Compton component, while in the HBLs the X-ray emission originates from the decreasing tail of the synchrotron emission. This means that in the intermediate objects the X-ray band should overlap with the steepest tail of the synchrotron component and the minimum of the SED where the synchrotron and inverse Compton components are connected. This fact, combined with the shift of the peaks in the SED, will produce lower X-ray fluxes for the intermediate BL Lacs. This characteristic of the X-ray band in the intermediate BL Lacs has been directly measured in the intermediate object ON 231 (Tagliaferri et al. 2000).

6.4 Broad-band spectral properties: α_{XOX}

Another way to confirm that the 200-mJy BL Lacs are intermediate BL Lacs is to derive the composite X-ray/optical spectral index defined as $\alpha_{\text{XOX}} = \alpha_{\text{OX}} - \alpha_X$. This parameter measures changes in the spectral energy distribution between the optical and soft X-ray bands by distinguishing the relative importance of inverse Compton and synchrotron emission processes. Values of $\alpha_{\text{XOX}} < 0$ mean that the X-rays lie along the steep power-law synchrotron continuum, and then the object is an HBL. In contrast, $\alpha_{\text{XOX}} > 0$ is indicative of a concave spectrum likely caused by a hard inverse Compton component, typical of a LBL. For these reasons, intermediate BL Lac objects should have $\alpha_{\text{XOX}} \approx 0$. Median values of α_{XOX} for different BL Lac samples are found in the literature. These values have been calculated using the total

optical magnitude of the BL Lac objects. To allow a direct comparison with these data we use the same method. The median of the α_{XOX} distribution for the 200-mJy sample of BL Lac objects is -0.10 . Laurent-Muehleisen et al. (1999) found median values of -0.14 for the RGB BL Lac sample, -0.23 for the Slew Survey Sample and $+0.23$ for the 1-Jy sample of BL Lac objects. This result strengthens the hypothesis that the 200-mJy sample is selecting intermediate BL Lac objects, i.e. BL Lacs with broad-band spectral properties intermediate between HBLs and LBLs.

6.5 The role of the 200-mJy weak line radio galaxies

So far we have discussed the properties of the BL Lac objects selected in the 200-mJy sample, but the flat-spectrum weak-line radio galaxies deserve some comments too. One of the goals in selecting the 200-mJy sample was to pick up radio sources transitional between the beamed (BL Lac) and unbeamed (FR I) populations. In this context the WLRGs seemed to be good candidates because they have properties of both the populations. Indeed, together with an optical spectrum dominated by the emission from the galaxy, they show a flat radio spectrum indicative of compact radio emission as supported by the VLBI observations. Actually we cannot state that the WLRGs in the 200-mJy sample represent a homogeneous class. For instance, a rather flat or inverted spectral index can be observed if the turnover falls between the 6- and 20-cm wavelengths used for the selection, or even at higher frequencies. In this case, the flat spectral index is not related to beaming, and the compactness of the radio source is not the result of projection effects. The radio galaxy OQ208, a GHz peaked radio source, was selected in the 200-mJy sample for this reason.

To compare the nuclear properties of the WLRGs with those of BL Lac objects and FR I radio galaxies, we added FR I and flat-spectrum weak-line radio galaxies to Fig. 8(a). In Fig. 9 the AGN optical and radio luminosities for BL Lacs (symbols are the same as in Fig. 8), FR I radio galaxies (filled hexagons) from Chiaberge et al. (2000) and WLRGs from the 200-mJy sample (empty hexagons) are plotted. The AGN optical luminosity for the 200 mJy WLRGs is taken from Dennett-Thorpe & Marchã (2000), and it should be considered as an upper limit. Fig. 9 clearly shows that the nuclear properties of the WLRGs are consistent with those of the

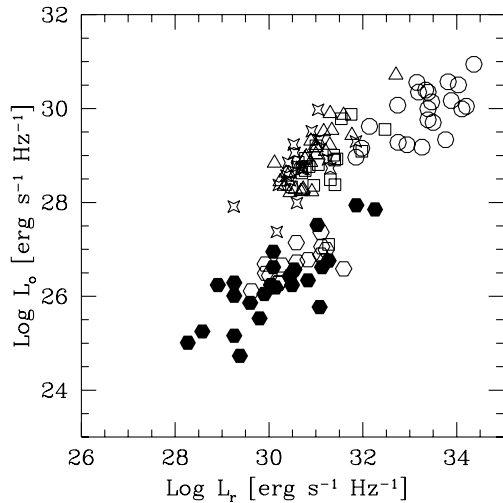


Figure 9. Nuclear optical luminosity (5500 Å) versus radio (5 GHz) luminosities for LBL (circles), HBL (triangles), 200-mJy BL Lacs (squares), a subsample from the RGB BL Lacs (stars), FR I radio galaxies (filled hexagons) and WLRGs from the 200-mJy sample (empty hexagons).

FR I radio galaxies, and are not intermediate between the FR I and the BL Lac objects.

7 CONCLUSIONS

We have presented and discussed VLBA and EVN images of BL Lac objects, BL Lac candidates, and flat-spectrum weak-line radio galaxies selected from the 200-mJy sample (Marchã et al. 1996). We found that the pc-scale morphology of BL Lac objects and candidates is the same, i.e. a strong unresolved core and a one-sided jet. The four WLRGs we observed have a more varied pc-scale structure: two objects show indications of possible symmetric emission (though we do not have enough spectral information to confirm the core as the central component), one has a one-sided jet, and the last is only marginally resolved. For BL Lacs and candidates the radio jet on the kpc scale is within 30° of the direction of the pc-scale jet, with the only exception being 0109+224. Large misalignments between pc and kpc scales are frequent in high-luminosity BL Lac objects, e.g. the 1-Jy BL Lacs, and can be interpreted as arising from intrinsically small variations in the direction of a relativistic jet closely aligned with the line of sight. This is consistent with the fact that the BL Lac objects, the maps of which are presented here, are less luminous and/or less beamed than the 1-Jy BL Lacs. The smaller amount of beaming could be produced either by a larger angle of the relativistic jet to the line of sight, or by an intrinsically slower flow in the jet.

Furthermore, we checked the hypothesis that the BL Lac objects from the 200-mJy sample are intermediate BL Lacs, i.e. objects with spectral and beaming properties intermediate between the HBLs and LBLs. We did this by calculating the core dominance parameter, R , for the 200-mJy sample of BL Lac objects and comparing it with those of HBL and LBL objects, and FR I radio galaxies. We found that the 200-mJy BL Lacs are compatible with being slightly more beamed than the HBL samples of BL Lac objects and clearly less beamed than the other sample of radio-selected BL Lacs, the 1-Jy sample.

We derived information on the spectral energy distribution of the 200-mJy sample BL Lacs, calculating the broad-band spectral indices α_{OX} , α_{RO} and the composite optical/X-ray spectral index

α_{OX} . We found that the 200-mJy BL Lac objects fill the gap between HBLs and LBLs in the colour–colour plot, and have intermediate α_{OX} , as expected in the SED unification scenario proposed by Fossati et al. (1997). According to the SED unification scenario, intermediate BL Lacs are expected to have the synchrotron peak in the optical band. This implies that selecting optically bright BL Lacs, as the 200-mJy sample does, is a favourable criterion to pick up intermediate objects. The hypothesis that the total radio luminosity is linked to the frequency shift in the SED (Fossati et al. 1998) is, at least qualitatively, confirmed by the intermediate BL Lacs of the 200-mJy sample. Not only the 5-GHz radio luminosity increases from HBL objects to intermediate and LBL objects, but also the 327 MHz radio luminosity, which is not affected by the beaming. A convincing physical interpretation of the different SEDs in BL Lac objects has been given by Ghisellini et al. (1998). Intrinsically lower luminosity objects (e.g. HBLs) suffer less cooling and the particles can be accelerated to energies high enough to produce synchrotron emission in the X-ray band. On the other hand, intrinsically more luminous objects (e.g. LBLs) are affected by a stronger cooling, implying a synchrotron peak at lower frequencies (Ghisellini et al. 1998).

The 200-mJy sample also selected flat-spectrum weak-emission line radio galaxies, named WLRGs. The possibility that all the WLRGs are transitional objects between the BL Lacs and the steep-spectrum FR Is is not supported. On the contrary, the WLRGs occupy the same region in the radio and optical core luminosity plane as the FR I radio galaxies (Fig. 9), arguing for roughly the same beaming in both classes. This does not necessarily imply that some WLRGs, of which 1241+735 is the best candidate, could turn out to be transitional objects or BL Lac object in a state of low optical activity.

In summary, the intermediate BL Lacs discussed here and in other papers (e.g. Perlman et al. 1998; Caccianiga et al. 1999; Laurent-Muehleisen et al. 1999) support the scenario of a single population of BL Lac objects with a common spectral energy distribution.

ACKNOWLEDGMENTS

The authors thank all the staff at the EVN and VLBA radio telescopes and correlators. DD acknowledges support by the Italian Ministry for University and Research (MURST) under grant Cofin98-02-32. The National Radio Astronomy Observatory is operated by Associated Universities Inc., under co-operative agreement with the National Science Foundation. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Finally, we thank the anonymous referee for a careful reading of this paper and many suggestions for improving it.

REFERENCES

- Abraham R. G., Crawford C. S., McHardy I. M., 1991, MNRAS, 252, 482
- Antonucci R. R. J., Ulvestad J. S., 1985, ApJ, 294, 158
- Bade N. et al., 1998, A&AS, 127, 145
- Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
- Blandford R., Rees M. J., 1978, in Wolfe A. N., ed., Proc. Pittsburgh Conf. on BL Lac Objects. Univ. Pittsburgh, Pittsburgh, p. 328

- Brinkmann W., Siebert J., Kollgaard R. I., Thomas H.-C., 1996, *A&A*, 313, 356
- Browne I. W. A., 1983, *MNRAS*, 204, 23
- Caccianiga A., Maccacaro R., Wolter A., Della Ceca R., Gioia I. M., 1999, *ApJ*, 513, 51
- Cassaro P., Stanghellini C., Bondi M., Dallacasa D., Della Ceca R., Zappalà R. A., 1999, *A&AS*, 139, 601
- Cawthorne T. V., 1991, in Hughes P. A., ed., *Beams and Jets in Astrophysics*. Cambridge Univ. Press, Cambridge, p. 187
- Chiaberge M., Celotti A., Capetti A., Ghisellini G., 2000, *A&A*, 358, 104
- Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, *AJ*, 115, 1693
- Dennett-Thorpe J., Marchã M. J. M., 2001, *A&A*, 361, 480
- Douglas J. N., Bash F. N., Bozayan F. A., Torrence G. W., Wolfe C., 1996, *AJ*, 111, 1945
- Dressler A., Shectman S., 1987, *AJ*, 94, 899
- Falomo R., 1996, *MNRAS*, 283, 241
- Fanaroff B. L., Riley J. M., 1974, *MNRAS*, 167, 31
- Fossati G., Celotti A., Ghisellini G., Maraschi L., 1997, *MNRAS*, 289, 136
- Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G., 1998, *MNRAS*, 299, 433
- Gabuzda D. C., Cawthorne T. V., 1996, *MNRAS*, 283, 759
- Gabuzda D. C., Mullan C. M., Cawthorne T. V., Wardlaw J. F. C., Roberts D. H., 1994, *ApJ*, 435, 140
- Georganopoulos M., Marscher A. P., 1998, *ApJ*, 340, 181
- Ghisellini G., Celotti A., Fossati G., Maraschi L., Comastri A., 1998, *MNRAS*, 301, 451
- Gioia I. M., Maccacaro T., Schild R., Wolter A., Stocke J. T., Morris S., Henry J. P., 1990, *ApJS*, 72, 567
- Giommi P., Padovani P., 1994, *MNRAS*, 268, L51
- Gregory P. C., Condon J. J., 1991, *ApJS*, 75, 1011
- Gregory P. C., Scott W. K., Douglas K., Condon J. J., 1996, *ApJS*, 103, 427
- Jackson N., Marchã M. J. M., 1999, *MNRAS*, 309, 153
- Jannuzi B. T., Smith P. S., Elston R., 1994, *ApJ*, 428, 130
- Kollgaard R. I., 1994, *Vistas in Astronomy*, 38, 29
- Kollgaard R. I., Wardle J. F. C., Roberts D. H., Gabuzda D. C., 1992, *AJ*, 104, 5
- Kollgaard R. I., Palma C., Laurent-Muehleisen S. A., Feigelson E. D., 1996, *ApJ*, 465, 115
- Laurent-Muehleisen S. A., Kollgaard R. I., Moellenbrock G. A., Feigelson E. D., 1993, *AJ*, 106, 876
- Laurent-Muehleisen S. A., Kollgaard R. I., Ryan P. J., Feigelson E. D., Brinkmann W., Siebert J., 1997, *A&AS*, 122, 235
- Laurent-Muehleisen S. A., Kollgaard R. I., Ciardullo R., Feigelson E. D., Brinkmann W., Siebert J., 1998, *ApJS*, 118, 127
- Laurent-Muehleisen S. A., Kollgaard R. I., Feigelson E. D., Brinkmann W., Siebert J., 1999, *ApJ*, 525, 127
- LaValley M., Isobe T., Feigelson E. D., 1992, *BAAS*, 24, 839
- Lind K. R., Blandford R. D., 1985, *ApJ*, 295, 358
- Maccacaro T., Wolter A., McLean B., Gioia I. M., Stocke J. T., Della Ceca R., Burg R., Faccini R., 1994, *Astrophys. Lett. Commun.*, 29, 267
- Marchã M. J. M., 1994, PhD thesis, Univ. Manchester
- Marchã M. J. M., Browne I. W. A., Impey C. D., Smith P. S., 1996, *MNRAS*, 281, 425
- Morris S. L., Stocke J. T., Gioia I. M., Schild R. E., Wolter A., Maccacaro T., Della Ceca R., 1991, *ApJ*, 380, 49
- Murphy D. W., Browne I. W. A., Perley R. A., 1993, *MNRAS*, 264, 298
- Padovani P., Giommi P., 1995, *ApJ*, 444, 567
- Padovani P., Urry C. M., 1990, *ApJ*, 356, 75
- Padovani P., Urry C. M., 1991, *ApJ*, 368, 373
- Patnaik A. R., Browne I. W. A., Wilkinson P. W., Wrobel J. M., 1992, *MNRAS*, 254, 655
- Perlman E. S., Stocke J. T., 1993, *ApJ*, 406, 430
- Perlman E. S. et al., 1996a, *ApJS*, 104, 251
- Perlman E. S., Stocke J. T., Wang Q. D., Morris S. L., 1996b, *ApJ*, 456, 451
- Perlman E. S., Padovani P., Giommi P., Sambruna R. M., Jones R. L., Tzioumis A., Reynolds J., 1998, *AJ*, 115, 1253
- Pearson T. J., Zensus J. A., 1987, in Zensus J. A., Pearson T. J., eds, *Superluminal Radio Sources*. Cambridge Univ. Press, Cambridge, p. 1
- Rengelink R. B., Tang Y., de Bruyn A. G., Miley G. K., Bremer M. N., Röttgering H. J. A., Bremer M. A. R., 1997, *A&AS*, 124, 259
- Sambruna R. M., Maraschi L., Urry C. M., 1996, *ApJ*, 463, 444
- Scarpa R., Urry C. M., Falomo R., Pesce J. P., Treves A., 2000, *ApJ*, 532, 740
- Stanghellini C., Dallacasa D., Bondi M., Della Ceca R., 1997, *A&A*, 318, 376
- Stark A. A., Gammie C. F., Wilson R. W., Bally J., Linke R. A., Heiles C., Hurwitz M., 1992, *ApJS*, 79, 77
- Stickel M., Padovani P., Urry C. M., Fried J. W., Kuhur H., 1991, *ApJ*, 374, 431
- Stocke J. T., Rector T. A., 1997, *ApJ*, 489, 17
- Stocke J. T., Morris S. L., Gioia I. M., Maccacaro T., Schild R. E., Wolter A., Fleming T. A., Henry J. P., 1991, *ApJS*, 76, 813
- Tagliaferri G. et al., 2000, *A&A*, 354, 431
- Ulrich M. H., 1989, in Maraschi L., Maccacaro T., Ulrich M. H., eds, *BL Lac Objects*. Springer-Verlag, Berlin, p. 45
- Urry C. M., Padovani P., 1995, *PASP*, 107, 715
- Urry C. M., Padovani P., Stickel M., 1991, *ApJ*, 382, 501
- Urry C. M., Sambruna R. M., Worrall D. M., Kollgaard R. I., Feigelson E. D., Perlman E. S., Stocke J. T., 1996, *ApJ*, 463, 424
- Wardle J. F. C., Moore R. L., Angel J. R. P., 1984, *ApJ*, 279, 93
- Wilkinson P. N., Browne I. W. A., Patnaik A. R., Wrobel J. M., Sorathia B., 1998, *MNRAS*, 300, 790
- Wood K. S. et al., 1984, *ApJS*, 56, 507
- Wright S. C., McHardy I. M., Abraham R. G., Crawford C. S., 1998, *MNRAS*, 296, 961
- Wurtz R., Stocke J. T., Yee H. K. C., 1996, *ApJS*, 103, 109
- Zirbel E. L., Baum S. A., 1995, *ApJ*, 448, 521

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