Parsec scale properties of nearby BL Lacs

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ABSTRACT

We present new radio data completing the imaging for a sample of 30 nearby ($z < 0.2$) BL Lac objects on parsec and kiloparsec scale. The sample is composed of both high and low luminosity sources and it is therefore an ideal test bed for unified schemes in the low power regime. VLBI and VLA data are used, thus providing information on both extended and inner, beamed components. We find morphologies and jet parameters consistent with a parent population composed of FR I radio galaxies, i.e. in agreement with the unified scheme. We also present a comparison to high quality HST data; we find a correlation between the radio and optical core luminosities, and speculate about the accretion rates for the central black holes.

1. INTRODUCTION

BL Lac objects are a class of radio loud AGN possessing extreme and variable properties at all wavelengths (Giroletti 2004). In the radio, they are usually dominated by a compact core, showing high variability and polarization. When investigated in detail with Very Long Baseline Interferometry (VLBI), the main component is typically resolved into a core+one sided jet morphology, the core having high brightness temperature and the jet possibly displaying proper motion of components. No less interesting are the properties at other frequencies: optical radiation is also variable and strongly polarized, usually lacking significant spectral features, highly variable X-ray emission is also a characteristic of BL Lacs, and extremely energetic TeV photons have been detected in a few cases, contributing a major amount of the total emitted energy.

BL Lacs properties and spectral energy distribution (SED) are usually explained in terms of synchrotron plus inverse compton emission from a couple of relativistic jets. In the unified model of radio loud AGN, a BL Lac object is observed when the angle between the jets axis and our line of sight is small, and the intrinsic properties of the source are similar to those of a low power radio galaxy (FR I). As often happens, the
real situation is more complicated: for example, there are a few BL Lac objects showing a large total radio power, more easily comparable to that of FR II than of FR I; on the other hand, there are objects of very low total power, whose properties are still poorly known; finally, the synchrotron component of the SED of a BL Lac can peak anywhere between the infrared and the soft X-rays, leading to the well-known dichotomy between Low- and High- frequency peaked BL Lacs (LBL and HBL, respectively).

In the present work, we will present radio observations on parsec and kiloparsec scale and discuss the properties of a sample of nearby BL Lacs, trying to shed light on some of their properties. The selection of a sample of nearby objects bears consequences that are actually as important as they may seem trivial.

First, at low redshift, the angular resolution of modern observing facilities turns into extraordinary linear resolution. In the optical, the Hubble Space Telescope is able to resolve and separate the contribution of the central core and of the host galaxy; in the radio, VLBI arrays are able to image the relativistic jet on pc and even sub-pc scale.

Second, all measured flux densities correspond to intrinsic low luminosity; this means that we have low power objects that are weak in the radio, typically peaking at high $\nu_{\text{peak}}$. They are then mostly HBL, and some of them are TeV emitters in their high energy spectral component. In contrast, their radio power is extremely low, which would make them comparable to radio quiet objects, if de-beaming were taken into account.

Thus, we can use the VLBI technique to test the current unification schemes. Its high resolution imaging capability allows us to derive pc scale properties (e.g. Doppler factor), which we can afterwards compare to different class of objects, such as radio galaxies. Furthermore, thanks to multi-wavelength data, we can discuss physical implications on the origin of the energy and physical properties of the jets and of the ISM, for objects belonging to a frontier population. More detail on the present work can also be found in Giroletti et al. (2004b).

2. THE SAMPLE

Scarpa et al. (2000) have undertaken a large project to investigate the host galaxies of 110 BL Lacs with the Hubble Space Telescope. The study of the host galaxy is a crucial test bed for unified schemes. Orientation is irrelevant to the host properties; their investigation provides therefore an useful check for the comparison of a population with its possible misaligned counterparts. Furthermore, several years of ground based observations did not help in solving the question whether BL Lacs could be hosted in disk galaxies.

From this large dataset, Falomo et al. (2000) extracted a sub-sample of 30 low redshift ($z < 0.2$) objects for which it was possible to perform a detailed study of the properties of the host galaxy. We concentrated our attention on this work, since the redshift limit presents all the characteristics that suit our goals:

- it effectively reduces the bias toward brightest, unrepresentative objects,
- conversely, it includes the weakest, least studied objects,
- all the objects detected at TeV energy so far are at $z < 0.2$, including 5 of them belonging to this sample,
- all host galaxies have been resolved, separating the contribution of the host and of the non-thermal continuum; the hosts are all "normal" elliptical galaxies, and in three cases (0521−36, 3C 371, 2201+044) an optical jet is detected,
- in this redshift range, the high angular resolution of VLBI techniques allows observers to investigate the very innermost regions (1 mas $\sim$ 1.7 pc at $z = 0.1$). \(^1\)

\(^1\) We assume $H_0 = 71\text{ km s}^{-1}\text{ Mpc}^{-1}$ and $q_0 = 0.5$. 

Giroletti et al. (2004b).
We actually discarded three objects from the original sample: 1853+671 and 2326+174, which have a redshift slightly larger than 0.2 (\(z = 0.212\) and 0.213, respectively), and 2005−489, which is too far south for our observations. Conversely, we add three more objects, which also have \(z < 0.2\) and high quality HST observations available. The objects are 1215+303 (\(z = 0.130\)), 2254+074 (\(z = 0.190\)), and 1652+398 (Mkn 501, \(z = 0.034\)).

HBLs are clearly dominant, and most objects have been originally selected at X-ray energies. This selection is significantly different from most previous studies at radio frequencies. We note that HBLs have lower total luminosities and are particularly weak in the radio. If we compare the distributions of total power at 1.4 GHz for objects in the present sample and in the 1 Jy sample, we find them to be significantly different, being that \(<\log P_{1.4\text{GHz}}\rangle = 24.7 \pm 0.6 \text{ W Hz}^{-1}\) and 26.7 \(\pm 0.9 \text{ W Hz}^{-1}\), respectively (some objects in the 1 Jy sample lack redshift information and were not considered). This result is largely due to the large flux limit of the 1 Jy sample; furthermore, with no cut in redshift, it contains a number of high-\(z\) BL Lacs that bias the sample toward more powerful objects.

### 3. OBSERVATIONS AND IMAGES

After collecting information from the literature for well known sources, we obtained observing time with the VLA, the VLBA, the EVN, and the MERLIN to complete the imaging for all objects in the sample on both kiloparsec and parsec scale.

Observations at 1.4 GHz with the VLA were performed on 2002 Feb 22 and May 3 in A configuration (10 hrs/19 sources) and on 2002 Oct 8 in C configuration (5 hrs/9 sources). The A array observation provided a resolution of \(\sim 1.9'' \times 1.2''\) (HPBW), while the more compact C configuration yielded a HPBW of \(\sim 15'' \times 11''\).

VLBA and EVN observations have provided the information about the milliarcsecond structure. VLBA observations at 5 GHz have been performed on 2002 February (15 hrs/15 sources), with a resolution of 3.8 mas \(\times 1.5\) mas and a noise level of \(\sim 0.15\) mJy beam\(^{-1}\). EVN observations at 1.6 GHz have taken place in June 2002, for a total of 12 hrs for 8 sources. The typical beam is 10.1 mas \(\times 4.5\) mas, and the noise varies between 0.5 and 1 mJy/beam.

Finally, 12 hours of joint EVN+MERLIN observing time at 5 GHz have been obtained to investigate the properties of two peculiar sources (1215+303 and 1728+502), with
Fig. 2. Parsec scale images, left to right: 0706+591 (VLBA @5 GHz, l.c. 0.38 mJy/beam, peak 33 mJy/beam), 1212+078 (VLBA @5 GHz, l.c. 0.36 mJy/beam, peak 33 mJy/beam), and 1215+303 (EVN+MERLIN @5 GHz, l.c. 0.40 mJy/beam, peak 294 mJy/beam).

resolution ranging between 50 mas (HPBW, MERLIN data only) and ~2 mas (HPBW, EVN data).

Sample images at kiloparsec and parsec scale are presented in Figs. 1 and 2, respectively. Fig. 1 presents one core+halo source (e.g. 0706+591, 4 in total), one core+jet source (e.g. 1959+650, 8 in total), and one source with more than a single compact component and some diffuse emission (e.g. 2344+514, 7 in total). Besides these morphologies, we find 9 unresolved sources, and two wide-angle tails. The pc scale images (Fig. 2) are less varied, and except for 9 unresolved objects, we find always a core and an one-sided jet.

4. RESULTS AND DISCUSSION

4.1. Radio data

The BL Lacs of the present low redshift sample are strongly core dominated objects. Although we found 10/30 objects where the core flux density is < 50% the total flux density (at 1.4 GHz), it is in general true that the core is the strongest component in the source. The value of the core dominance parameter \( R = \frac{S_{\text{core}}}{S_{\text{ext}}} \) in our sample is \( \langle R \rangle = 4.5 \), assuming that the three sources (1418+546, 1514−241, and 2254+074) in which the flux density of the core is larger than the total have \( R \) equal to the highest found in the sample; this behaviour has to be ascribed to variability, and reminds us that the whole result needs to be considered with caution. However, this is true also for other samples and we do not expect it to affect the average properties of the sources in our sample. In comparison to other BL Lac samples, such as the EMSS (Rector et al. 2000) and the 1 Jy (Rector & Stocke 2001), the present low redshift BL Lac sample is similar to the EMSS (\( \langle R \rangle \geq 4.2 \)), while much larger values are observed in the bright, core-dominated 1 Jy BL Lacs.

Beaming effects at the base of the jet are likely responsible of the enhanced observed radio power of the core, and the discrepancy to the expected value allows us to estimate the amount of beaming for each object. In the left panel of Fig. 3 we plot the core vs. total power for the objects in the sample, together with the literature correlation (Giovannini et al. 2001). As can be seen, all the objects have core luminosities far greater...
than expected from the correlation. Assuming that the viewing angle \( \theta \) and the jet Lorentz factor \( \Gamma \) are related by \( \Gamma \sim 1/\theta \), the resulting distributions are shown in the middle (angles) and right (Lorentz factor) panels, where the shaded parts refer to LBL only. The average viewing angle is \( \langle \theta \rangle = 18^\circ \pm 5^\circ \), without any significant difference between LBL and HBL. On the other hand, the distribution of Lorentz factor is bimodal, with the majority of objects, including all HBL, distributed around \( \Gamma = 3 \) and four sources, all LBL, which have \( \Gamma > 5 \). Thus, it seems that the bulk velocity of jets in the radio-emitting region is larger in LBLs than in HBLs (including TeV sources). As a speculation, the emission of TeV taking place on even smaller scales may be responsible for energetic losses resulting in slower jets on radio scales.

**FR I radio galaxies are the best candidate to be the parent population of objects in the present sample.** From our estimate of the jet velocity and orientation, we can derive the intrinsic core radio power. In Fig. 4 we present the distribution of the core and low frequency total radio power for the present sample and the sample of FR I and low power compact radio galaxies studied by Giovannini et al. (2001). The two samples cover the same range in low frequency total radio power (Fig. 4 left), as expected if FR IIs are the parent population of BL Lacs. We note that the total radio power at 325 MHz should be an intrinsic source property since the core is self-absorbed and extended lobe emission dominates at low frequency. In the right panels, the shaded histograms represent the intrinsic core radio power distribution, while the overlaid dashed histograms refer to the observed power of the radio core. Despite a significant difference in the observed values, the distribution of the intrinsic core radio power is similar and in the same range, confirming that the intrinsic properties of the two populations are the same.

Therefore, we conclude that in our sample the parent population is composed of FR I radio galaxies alone and that the fraction of FR IIIs in the parent population of BL Lacs must be very small, if any. FR IIIs that may be present in the 1 Jy sample must therefore be ascribed to the very large volume considered. In any case, their incidence may not be negligible only among the most powerful LBL, which could therefore have different properties.

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**Fig. 3.** Left: \( P_{\text{tot}}/P_{\text{core}} \) diagram for the sources in the sample; empty circles represent HBL, filled circles are for LBL; the dashed line is the correlation found by Giovannini et al. (2001). Middle and right: distribution of the resulting viewing angle \( \theta \) (left) and Lorentz factor \( \Gamma \) (right); the shaded parts correspond to LBL only.
Fig. 4. Distribution of total and intrinsic core power for objects in the present sample and FRI and LPC radio galaxies in a sample of radio galaxies [Giovannini et al. 2001]. The dashed histograms overlayed to the intrinsic core power show the distribution of the observed values.

4.2. Radio/Optical

Multiwavelength data provide a tool to investigate the mechanisms involved in the nuclear activity. For the present sample, a wealth of information is available thanks to the optical observations performed with the Hubble Space Telescope. In particular, for all the objects it has been possible to separate the contribution of a central compact core and of the host galaxy. Both quantities have significant impact on our understanding of the BL Lac phenomenon: the central compact core is a clear signature of the nuclear activity and gives clues on the emission process; the host galaxy luminosity is a tool to estimate the mass of the central black hole, and therefore to study the accretion onto it.
Chiaberge et al. (1999) have previously exploited Hubble Space Telescope and radio data to discuss the physical properties of nuclei of radio galaxies, finding a linear correlation between optical and radio luminosity. This correlation is interpreted in terms of a common non-thermal origin. Our high quality radio data and the optical HST results (Urry et al. 2000; Falomo et al. 2000) allow us to perform the same study on the sources of our low redshift sample of BL Lacs. We present in Fig. 5 (left panel) the comparison between optical and radio core luminosity for BL Lacs, together with the correlation found by Chiaberge et al. (1999) for FR I nuclei.

The objects in the present sample span almost three orders of magnitude in radio core luminosity (at 1.4 GHz) and the optical core luminosity increases linearly with it over this interval. As in FR I radio galaxies, the emission in the two wavebands is ascribed to the same non-thermal process, with negligible contribution from, e.g., a thermal disk. However, the optical cores of BL Lacs are about two magnitudes brighter than those of FR I galaxies with the same core radio luminosity. Notice that we are plotting observed values, i.e., quantities that are affected by beaming. While it is interesting to note that this keeps the correlation tight, we argue that this may be responsible for the optical offset observed for BL Lacs. Chiaberge et al. (2000) obtained a similar result from the BL Lacs in the Slew survey, while the LBL of the 1 Jy sample are less displaced from the correlation than our objects. They put forward an explanation based on de-beaming trails for the broadband SED and conclude that a single emitting region can not account for this observational behaviour. Interestingly, a two velocity jet (fast spine and slower external layer) is a plausible solution that accounts also for other observational properties, such as limb brightening of jets (Giroletti et al. 2004a).

Exploiting the well known correlation between $M_{BH}$ and the host galaxies bulge luminosity (Magorrian et al. 1998; Kormendy & Gebhardt 2001), HST data can be used also to derive the black hole mass for the present sample (Falomo et al. 2003). We show in Fig. 5 (middle panel) the plot of black hole mass vs. core radio power. Neither the core nor the total (not shown) radio power seem to be good indicator of the black hole mass, although in both cases there is a weak trend of larger $M_{BH}$ for more powerful radio sources (the correlation coefficients are $r = 0.47$ and 0.45, respectively).
The right panel in Fig. 5 shows the distribution of objects belonging to the present sample in the Ledlow & Owen diagram (Ledlow & Owen 1996); in such diagram, the optical magnitude of the host galaxy and the radio power are plotted on the $x$- and $y$-axis, respectively, and the dashed line corresponds to the division between FR I and FR II. All our HBL are situated below this line, i.e. in the FR I region. Only two LBL (0521−365 and 0829+046) lie above the dashed line, and 2200+420 intercepts it. However, if we consider the de-beamed intrinsic radio power, they all move below the line, where FR I are placed, yielding further evidence that low power radio galaxies are the parent population of our BL Lacs.

Furthermore, as discussed above, the optical magnitude of the host in $R$-band is related to the BH mass. Similarly, Willott et al. (1999) have discussed the relationship between radio power and accretion generated power, showing that the total radio power is related to the narrow emission line luminosity, which is directly produced by photoionization from the nuclear accreting radiation. Therefore, the radio power is a measure of the accretion luminosity and the division between FR I and FR II can be attributed to a critical ratio between accretion luminosity and black hole mass.

Ghisellini & Celotti (2001) have estimated the accretion rate for radio galaxies and proposed that FR Is and FR IIs have $\dot{m}$ below and above $10^{-2} - 10^{-3}$, respectively; thus, some value in between could be the critical one above which an ADAF (advection dominated accretion flows) can not be maintained (Narayan & Yi 1995). Then, a different state for the central engine would be at the base of the difference between the two classes. BL Lacs in the present sample are all situated below this threshold; they are sub-Eddington systems with sub-critical accretion rates.

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