

VLBI observations of seven BL Lacertae objects from RGB sample[★]

Zhongzu Wu^{1,2,3}, D. R. Jiang^{1,2}, Minfeng Gu^{1,2}, and Yi Liu^{1,2}

¹ Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, PR China
e-mail: zzwu@shao.ac.cn

² Joint Institute for Galaxy and Cosmology (JOINGC) of SHAO and USTC

³ Graduate School of the Chinese Academy of Sciences, Beijing 100039, PR China

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ABSTRACT

We present EVN observations of seven BL Lac objects selected from the RGB sample. To investigate the intrinsic radiation property of BL Lac objects, we estimated the Doppler factor with the VLA or MERLIN core and the total 408 MHz luminosity for a sample of 170 BL Lac objects. The intrinsic (comoving) synchrotron peak frequency was then calculated by using the estimated Doppler factor. Assuming a Lorentz factor of 5, the viewing angle of jets was constrained. The high-resolution VLBI images of seven sources all show a core-jet structure. We estimated the proper motions of three sources with the VLBI archive data, and find that the apparent speed increases with the distance of components to the core for all of them. In our BL Lacs sample, the Doppler factor of LBLs is systematically larger than that of IBLs and HBLs. We find a significant anti-correlation between the total 408 MHz luminosity and the intrinsic synchrotron peak frequency. However, the scatter is much larger than for the blazar sequence. Moreover, we find a significant positive correlation between the viewing angle and the intrinsic synchrotron peak frequency. The BL Lac objects show a continuous distribution on the viewing angle. While LBLs have a smaller viewing angle than that of IBLs and HBLs, IBLs are comparable to HBLs. We conclude that the intrinsic synchrotron peak frequency is not only related to the intrinsic radio power (though with a large scatter), but also to the viewing angle for the present sample.

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

1. Introduction

BL Lac objects are a subclass of radio loud active galactic nuclei (AGNs) with no emission lines or less of them, but they have a strong continuum ranging from radio to γ -ray bands. Their spectral energy distribution (SED) consists of a synchrotron component at lower frequencies and an inverse Compton component at higher frequencies. Historically, BL Lac objects have been separately discovered through radio or X-ray surveys and have been divided into two classes, namely, radio-selected BL Lacs (RBLs) and X-ray selected BL Lacs (XBLs). However, this classification is based on the observing band rather than on the intrinsic physical properties. As a matter of fact, some BL Lac objects can be classified as both RBL and XBL, such as Mrk 501. Padovani & Giommi (1995) have suggested dividing RBL-like and XBL-like objects into low-energy peaked BL Lacs (LBLs) and high-energy peaked BL Lacs (HBLs) according to the location of the peak of the synchrotron emission ν_{peak} (Urry & Padovani 1995). Generally, RBLs tend to be LBLs, and XBLs tend to be HBLs. The synchrotron peak frequency of RBLs is usually in the radio/IR band, while UV/X-ray band for XBLs (Giommi et al. 1995). In recent years, samples including intermediate BL Lac objects (IBLs) have been found in surveys that combine X-ray and radio observations (Laurent-Muehleisen et al. 1999; Perlman et al. 1998; Landt et al. 2001; Caccianiga et al. 1999). Their discovery has shown that BL Lac objects most likely form one class with a continuous distribution of

synchrotron emission peak energies, while RBLs and XBLs represent the opposite ends of the continuum (Nieppola et al. 2006).

The so-called “blazar sequence” was proposed to link the shape of the SED and the synchrotron peak frequency to the source luminosity for blazars, which consists of more luminous flat-spectrum radio quasars (FSRQs) and BL Lac objects (Fossati et al. 1998; Ghisellini et al. 1998). The most powerful sources have relatively small synchrotron peak frequencies, and the least powerful ones have the highest ν_{peak} values. This anti-correlation can be theoretically explained by the cooling processes. In more powerful sources, the energy density is higher and the emitting particles have a higher probability of losing energy so are subjected to more cooling, resulting in a lower value for ν_{peak} . However, this sequence is based on the absence of high-luminosity HBLs and low-luminosity LBLs, therefore at least part of this systematic trend can result from selection effects (Antón & Browne 2005). Indeed, the evidence of low-power LBLs has been recently discovered (Padovani et al. 2003; Caccianiga & Marchã 2004; Antón & Browne 2005), and the possible discovery of high luminosity HBLs is also reported in the Sedentary survey (Giommi et al. 2005). In addition, the high-power-high- ν_{peak} FSRQs were found in the Deep X-ray Radio Blazar Survey (DXRBS), which is both X-ray and radio-selected, though they do not reach the extreme ν_{peak} values of HBLs. From all these discoveries, it seems that the blazar sequence in its simplest form cannot be valid (Padovani 2006).

Instead of focusing on one or two limited surveys, Nieppola et al. (2006) have examined the properties of BL Lacs through constructing the SEDs for a large, heterogeneous sample of BL

[★] Tables 1–4 are only available in electronic form at <http://www.aanda.org>

Lacs taken from the Veron-Cetty & Veron BL Lac catalogue and visible from the Metsähovi radio observatory. To our knowledge, this is the largest BL Lacs sample to revisit the blazar sequence up to now, though it is heterogeneous. The authors have found an anti-correlation between the radio power and ν_{peak} , with a huge scatter, reaching 5 orders of magnitude in power, and many outliers were also found, especially in the low-power-low- ν_{peak} region. However, it is well known that the radio power of BL Lacs is affected by the beaming effect of radio jets, since BL Lacs are generally believed to have a relativistic jet aligned close to the line of sight (Urry & Padovani 1995). As the blazar sequence was originally proposed as the anti-correlation between the intrinsic luminosity and peak frequency, it nevertheless might be important to revisit the correlation using the intrinsic radio power. Moreover, the peak frequency $\nu_{\text{peak}} \propto B\delta\gamma_{\text{peak}}^2$, where B is the magnetic field, δ the Doppler factor, and γ_{peak} a characteristic electron energy that is determined by a competition between accelerating and cooling processes. While blazars as a whole population suffer the Doppler boosting, the difference in Doppler factor can exist between various subsets, which implies the importance of investigating the intrinsic peak frequency after excluding the Doppler factor. As Kollgaard et al. (1996b) find, the average angles of radio jets to the line of sight is approximately 20° for XBLs, but 10° for RBLs. When the BL Lac objects show a continuous distribution of synchrotron emission-peak energies and most recent works focus on the correlation between the power and peak frequency, it is not clear whether they also show a continuous distribution for the angle to the line of sight, and HBLs and LBLs occupy the opposite ends of this distribution.

Apart from investigating the SED of BL Lac objects, the high-resolution radio observation is an important way to explore the radio structure of BL Lacs, from which we can obtain the physical information, such as the viewing angle, Lorentz factor and magnetic field. From the VLBI observations, the different subsets of BL Lacs can be compared based on the compact radio structure. In particular, it enables us to explore the jet orientation for BL Lac objects, because the properties of the parsec scale structure are strongly dependent on jet orientation. Kollgaard et al. (1996a) show that the jets in XBLs fade more quickly than in RBLs. The VLBI observations show that most of LBLs display the rapid superluminal apparent motions (Jorstad et al. 2001), while the TEV blazar sources (most are HBLs) display subluminal or mildly relativistic (Giroletti et al. 2004b, 2006; Piner & Edwards 2004). Rector et al. (2003) have observed 15 HBLs and 3 BL Lacs from the RGB sample and find that the HBLs, like most LBLs, show parsec-scale core-jet morphologies with complex kilo-parsec scale morphologies. Moreover, the jets in HBLs are more well-aligned, suggesting that the jets of HBLs are either intrinsically straighter or are seen further off-axis than LBLs. Giroletti et al. (2004a) selected 30 low-redshift BL Lac objects and confirmed that parsec and kilo-parsec scale jets are oriented at the same P.A. in a large fraction of HBLs. The HBLs show less distortion and therefore are expected to be oriented at larger angles than the LBL sources.

Laurent-Muehleisen et al. (1999) present a sample of 127 BL Lac objects from the ROSAT ALL-Sky Survey-Green Bank catalogue (RGB), which exhibits properties intermediate between high- and low-energy-peaked BL Lac objects. In this paper, we present EVN observations of seven BL Lac objects selected from the RGB sample. Our goal is to investigate their compact radio structure. In combination with the previous observations and the archive data, we aim to explore the possible structure variation and measure the proper motion for our sources. Moreover, to

explore BL Lac objects as a whole population, we investigated the distribution of the intrinsic radio power, the Doppler factor, and the viewing angle along the intrinsic synchrotron peak frequency for a sample of BL Lac objects selected from Nieppola et al. (2006).

The layout of this paper is as follows. In Sect. 2, the observations and data reduction for our seven sources are given. The compact radio structure are investigated in Sect. 3, where the proper motion are estimated for three sources as well. In Sect. 4, the intrinsic radio low-frequency luminosity, the Doppler factor, and the viewing angle are estimated for a sample of BL Lacs selected from Nieppola et al. (2006), and their distribution with the intrinsic synchrotron peak frequency is also explored. The discussions are shown in Sect. 5, while the conclusions are drawn in Sect. 6. Throughout this work, we adopt the following values for the cosmological parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, except an otherwise stated. The spectral index α is defined as $f_\nu \propto \nu^{-\alpha}$.

2. VLBI observations and data reduction

All seven BL Lac objects were observed with EVN at 5 GHz on 22 November 1999. The raw data were obtained with the MKIII VLBI recording system, with an effective bandwidth of 28 MHz, and correlated in Bonn at the Max-Planck-Institute. To study the structure and proper motion of these sources, we collected EVN and VLBA archive data. All seven sources are listed in Table 1: Col. (1) Source name, Col. (2) redshift, Cols. (3) the observational date and (4) the half-power beamwidth (*HPBW*) of the weighted beam, Col. (5) the noise of the image, Col. (6) the peak flux of the image, Col. (7) VLBI array. All the data were reduced using the NRAO Astronomical Image Processing System (AIPS) package. The system temperatures and gains were obtained from the VLBA website. After the initial reduction (including editing, amplitude calibration, instrumental phase corrections, and antenna-based fringe-fitting), we imported the calibrated data into DIFMAP package (Shepherd et al. 1994, 1995) to make images and fit the sources with a number of discrete circular Gaussian components. The fitting was done directly on the final, self-calibrated visibility data. The modelfit parameters are listed in Table 2.

3. Results

The VLBI images show core-jet structure for all sources we selected, and some of them are in good agreement with previous observations. The MERLIN archive images and available VLA images also show that these sources possess very straight jets. Model fitting of the radio structures in each image was performed, using the MODELFIT of Caltech DIFMAP package (*uvweight* = 0, -1). The modelfit parameters are presented in Table 2. To determine the uncertainty of the component position, we used the Difwrap package (Lovell 2000). The errors were estimated by perturbing the fit parameters until the resulting residual maps were unacceptable and taking the most extreme accepted points. A visual inspection was done to determine the goodness of the fit, and we used the best-fit total χ^2 as the upper limit for every fit of the components.

In our seven BL Lac objects, previous VLBI observations at 6 cm are available for five of them. Combining our observations with the archive data, we got at least four-epoch observations for three sources: 1727+502, 1133+704, and 1741+196. The weighted linear fits to the component distances from the

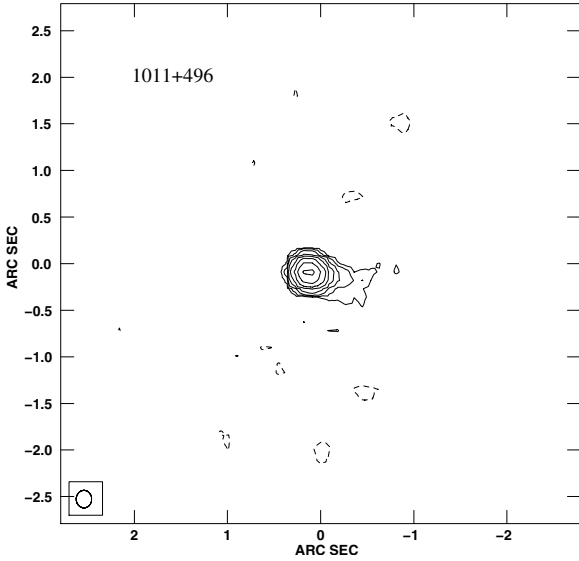


Fig. 1. The MERLIN archive image of 1011+496 at 1.6 GHz on May 6, 1999. The contour levels are $-1, 1, 2, 4, 8, 16, 32, 64\dots$ times $0.001742 \text{ Jy beam}^{-1} (3\sigma)$.

core as a function of the observing time were used to estimate the proper motion of the components. The results are given in Table 3, in which Col. (1) is the source name, (2) the components label, (3) the proper motion, and (4) the apparent speed. From Table 3, we find that all three sources have superluminal motion, and the apparent speed increases with distance from the core. For 1011+496 and 1424+240, only three-epoch data are available, therefore we do not measure their proper motion and only present their images in this work. For 4C+37.46 and 1542+614, there are no previous VLBI images and archive data available, so we present their first image.

3.1. Comments on individual sources

1011+496 – Snapshot VLA observations have found hints of extended structure around a bright core (Machalski & Condon 1983). This was confirmed by Kollgaard et al. (1996b), who found diffuse emission extending around 10° to the north from their VLA B-configuration data. Augusto et al. (1998) have modeled this source with three components, which clearly showed that the jet of this source extends to about a few hundreds mas of the core with position angle -99° . The MERLIN archive image (see Fig. 1) shows that the jet extends in nearly the same direction with our EVN and VLBA images (see Fig. 2), which show a jet in the opposite direction on the parsec scale. As the jet direction is similar in MERLIN, EVN, and VLBA images, this source is well-aligned.

1133+704 – The images from three epochs (see Fig. 3) all show that the jet extends at a structural position angle of $\sim 110^\circ$, and the outer components extend to the northeast around 75° . These features are similar to the parsec scale jet found by Kollgaard et al. (1996a) and are well-aligned with the kiloparsec scale halo and short inner jet presented by Giroletti et al. (2004a) and Giroletti et al. (2006). It can be seen from Fig. 3 that five components are detected in 1133+704, which is labeled as M0, M1, M2, M3, and M4, respectively. The weighted linear fits of components M1, M2, and M3 are presented in Fig. 4. As expected from the fitted line, M3 can be close to M2 at epoch 1991.433; however, it is not detected in the archive data. As M4 is only detected at two epochs, we do not perform the fit to this

component. It can be seen from Table 3 that the inner components move more slowly, and the outer ones move faster.

The variability of this source has been investigated on other wavebands. Xie et al. (2004) show that the source did not show any noticeable variability, and it was quiet in the optical band during their observations. Albert et al. (2006) have detected very high-energy γ -Rays from this source, and an optical outburst in 2006 March was also observed but no evidence of flaring was detected by the University of Michigan Radio Observatory (UMRAO).

1424+240 – From the images of three epoch VLBI observations (Fig. 2), the component can not be well-resolved; however, the jet clearly extends to the southeast with position angle of about $PA = 150^\circ$. This result is similar with Fey & Charlot (2000), who modeled this source with two components at 2.3 GHz and 8.5 GHz, all with jets extending in the nearly same direction. However, this direction is a little misaligned with the VLA map found by Rector et al. (2003), which shows a compact structure consisting of a core and either a halo or roughly collinear jets extending north $PA = -10^\circ$ and south $PA = -175^\circ$. The MERLIN archive data (see Fig. 5) shows a very compact structure, and the jet direction is not evident.

1542+614 – There have no previous observations and archive data for this source. The redshift is unknown. We present our observations in Fig. 2. The source shows a compact core and straight jet extending to $PA = 110^\circ$ on a parsec scale.

4C+37.46 – We present our image in Fig. 2, in which the source clearly shows one jet towards the northeast $PA = 55^\circ$. The MERLIN archive image (see Fig. 6) also shows a jet in the same direction. The jet direction is consistent with Marecki et al. (2006), in which this source could be core-jet-lobe source, either with a steep spectrum or some diffuse structure. This source may also be a well aligned source.

1727+502 – The large amplitude variability of this source has been detected on several occasions. A violent variation of 2.1 mag in the optical band was reported by Scott et al. (1976). Fan et al. (1999) detected the variations of $\Delta H = 0.57$ mag and $\Delta K = 0.82$ mag. This source was observed by Kollgaard et al. (1996a) in 1991 at 6 cm and showed a core-jet morphology. Giroletti et al. (2004a) and Giroletti et al. (2006) show that this source displays a remarkable alignment from the parsec to the kilo-parsec scale. The multi-epoch images in Fig. 7 show a core and a jet extending to northeast with a position angle of about -55° . The model fit parameters of this source were presented in Table 2. It can be seen from Fig. 7 that six components were detected, which are labeled with C0, C1, C2, C3, C4, and C5. The weighted linear fit of components C1, C2, C3, C4, and C5 are shown in Fig. 8, and their measured proper motion and apparent speed are listed in Table 3. Interestingly, the component C5 was not detected at epoch 1991.433 (data from Kollgaard et al. 1996a) and 2002.403. From the fitted line for C5, the position of C5 at epoch 1991.433 is expected to be close to that of component C4; therefore, it is possible that these components are mixed together, causing difficulty in detection. At 2002.403, C5 very likely moved far away from the core and became very weak, so it was not detected. Due to the poor uv-coverage of our data and the fact that the beam size at this epoch is larger than other observations, we did not detect component C1 at 1999.893 (see Fig. 8). It is apparent that C3 and C4 at epoch 1998.493 was closer to the core than the expected distance from the fit. Actually, it seems that these two components move slowly (or were even stationary) before 1998.493, but move quickly afterwards, with the proper motion of C4 comparable to that of C5. However, the present data do not allow us to investigate this

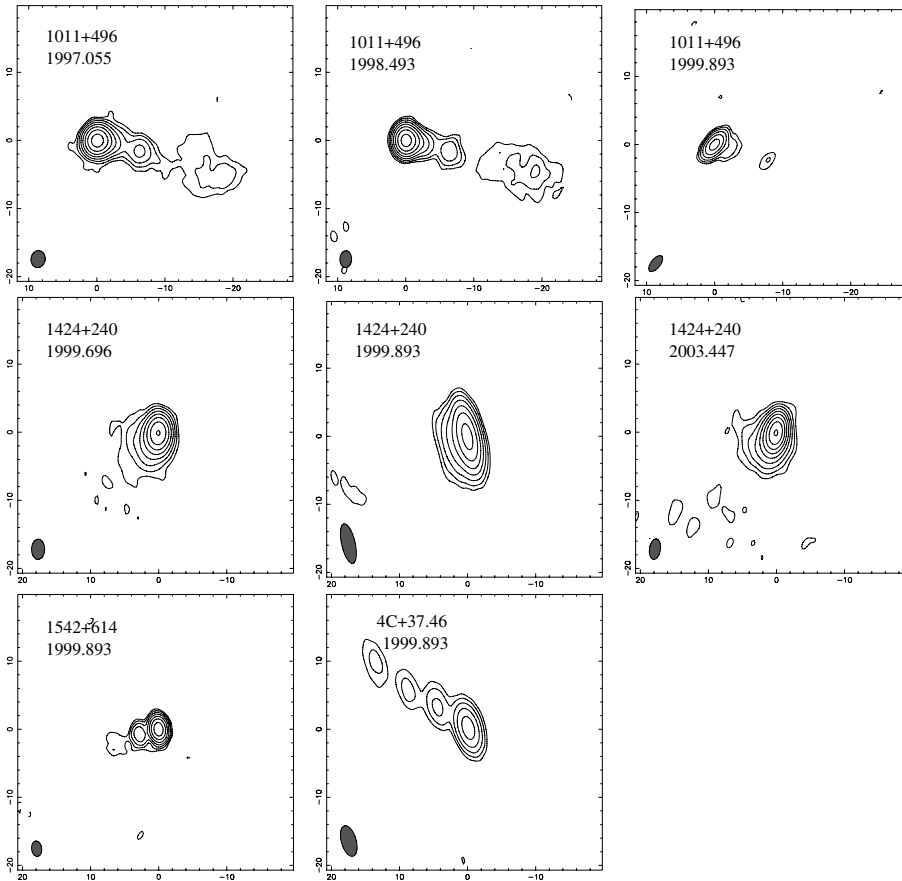


Fig. 2. Multi-epoch EVN and VLBA images at 5 GHz. The minimum contour level is 3 times the rms noise given in Table 1. The contour levels are multiples ($-1, 1, 2, 4, 8, 16, 32, 64, \dots$) of the minimum contour level and the axes are labeled in milliarcseconds. The top three panels are for 1011+496 at 1997.055, 1998.493, and 1999.893 (from left to right); the middle for 1424+240 at 1999.696, 1999.893, and 2003.447 (from left to right); while the bottom for 1542+614 and 4C+37.46 at 1999.893.

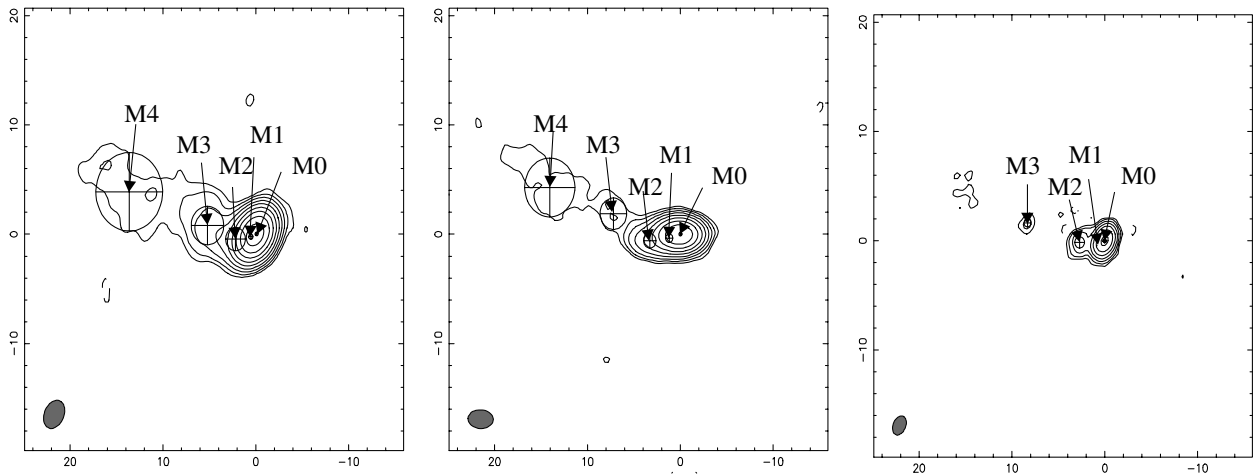


Fig. 3. EVN and VLBA images of 1133+704 at 5 GHz. The epoch of observation from left to right are: epoch 1997.055, epoch 1998.493, epoch 1999.893. The axes are labeled in milliarcseconds. Contours are drawn at $-1, 1, 2, 4, 8, 16, \dots$ times the noise level. Numerical parameters of the images are given in Table 1.

possibility further. From Table 3, we find that the apparent speed of components increases with the distance from the core. When looking in detail, components C4 and C5 show superluminal motion, while C1, C2 and C3 show subluminal motions. C1 is the closest component to the core, and it also shows the smallest proper motion. Actually, the error in the proper motion of C1 is larger than its proper motion. Therefore, it is possible that this component is stationary within the available observations.

1741+196 – The six-epoch images of this source in Fig. 9 all show a very straight jet extending to the east with $PA = 80^\circ$. This

is similar to the result in Rector et al. (2003), in which one epoch VLBA map was presented, and the jet direction is nearly aligned with the VLA snapshot in Perlman et al. (1996) with $\Delta PA = 5^\circ$. Five components are detected in Fig. 9, which are labeled as E0, E1, E2, E3, and E4. The weighted linear fit of E1, E2, E3, and E4 are shown in Fig. 10, and their measured proper motion and apparent speed are listed in Table 3. When we perform fits to the components, we exclude the data at epoch 2002.400, because the beam size of this epoch is much larger than others. While E4 shows a superluminal motion, E1, E2, E3 all show a rather small

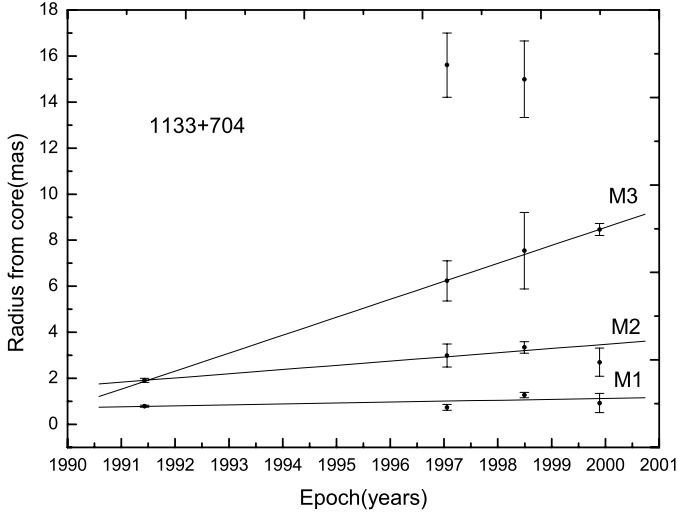


Fig. 4. Positions of components with respect to the core at different epochs from model fitting for 1133+704. The data point at 1991.433 is taken from Kollgaard et al. (1996a). All the other epochs are those presented in this paper, and the lines represent the linear fitting of the motion for each jet component.

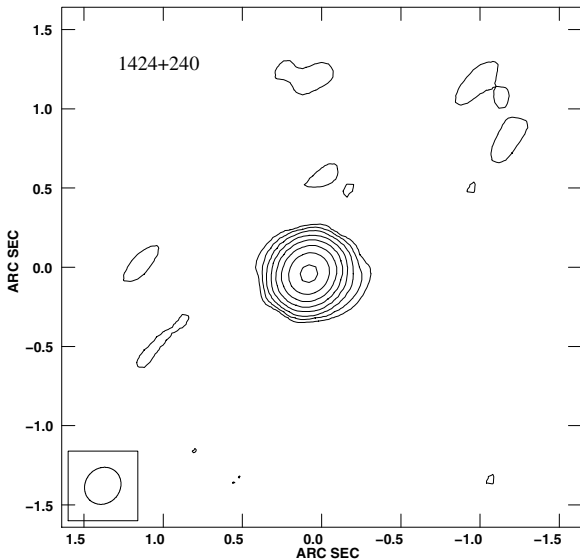


Fig. 5. The MERLIN archive image of 1424+240 at 1.6 GHz observed on 1993 Apr. 1. The contour levels are $-1, 1, 2, 4, 8, 16, 32, 64, \dots$ times $0.001745 \text{ Jy beam}^{-1} (3\sigma)$.

apparent speed. For components E2 and E3, the error in proper motion is actually larger than their proper motion. In view of this fact and the rather low value of proper motion, E2 and E3 could be stationary (within the error) in the time duration covered by the presenting available observations.

4. Properties of a sample of BL Lac objects

Nieppola et al. (2006) collected a large amount of multi-frequency data for the objects in the Metsähovi radio observatory BL Lac sample. The Metsähovi BL Lac sample includes 381 objects selected from the Veron-Cetty & Veron BL Lac Catalogue (Veron-Cetty & Veron 2000, hereafter VCV2000), and 17 objects from the literature, of which many sources are from the well-known BL Lac samples like 1Jy, S4, S5, Einstein Medium Sensitivity Survey (EMSS), Einstein Slew Survey, and DXRBS.

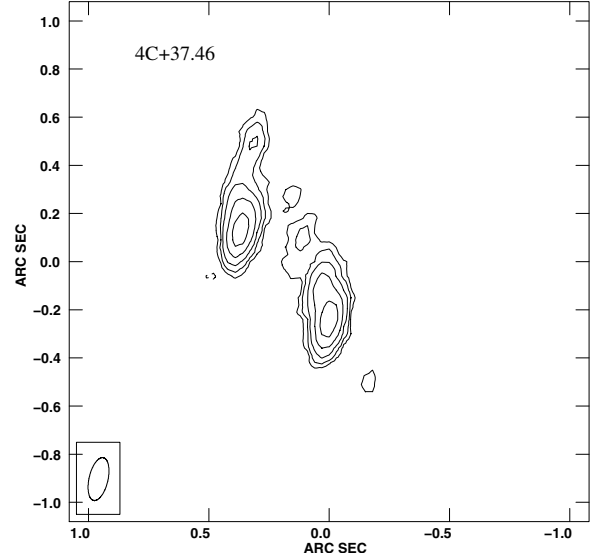


Fig. 6. The MERLIN archive image of 4C+37.46 at 5 GHz observed on 1999 May 6. The contour levels are $-1, 1, 2, 4, 8, 16, 32, 64, \dots$ times $0.001745 \text{ Jy beam}^{-1} (3\sigma)$.

The authors argue that this sample is supposed to have no selection criteria (other than declination) in addition to the ones in the original surveys. Based on the multi-frequency data, the SED of each source were constructed in the $\log \nu - \log \nu F_\nu$ representation. The synchrotron component of the SED was fitted with a parabolic function

$$y = Ax^2 + Bx + C \quad (1)$$

in order to determine the synchrotron peak frequency $\nu_{\text{peak}} = -B/2A$. The objects were assigned an LBL/IBL/HBL classification according to ν_{peak} : for LBLs $\log \nu_{\text{peak}} < 14.5$, for IBLs $14.5 < \log \nu_{\text{peak}} < 16.5$, and for HBLs $\log \nu_{\text{peak}} > 16.5$.

We collected the available data at 330 MHz, 360 MHz, 408 MHz, and 1.4 GHz from the Astrophysical Catalogues Support System (CATs)¹ maintained by the Special Astrophysical Observatory, Russia, and also the available VLA or MERLIN core and extended flux for their sample, resulting in a sample of 170 BL Lac objects. The redshift is known for most of the sources from NED and the literature. For the sources without redshift, we adopt the average redshift of 0.473, 0.302, 0.271 for LBLs, IBLs, and HBLs, respectively. The sample of BL Lac objects is listed in Table 4: Col. 1 the source IAU name (J2000); Col. 2 the source alias name; Col. 3 the redshift; Col. 4 the intrinsic synchrotron peak frequency (see Sect. 4.4); Col. 5 the total 408 MHz radio power; Col. 6 the 5 GHz core luminosity; Col. 7 the 5 GHz or 1.4 GHz extended flux density; Col. 8 the references; Col. 9 the Doppler factor (see Sect. 4.4); Cols. 10–12 the viewing angle estimated assuming $\Gamma = 3, 5, \text{ and } 10$, respectively (see Sect. 4.5). In the following sections, we investigate the various properties, e.g. the Doppler factor, viewing angle for this sample.

4.1. Method of estimating Doppler factor

A reliable determination of the Doppler factor, δ , is a key step in studying the origins of the physical process in the compact emission regions of AGNs (Lähteenmäki & Valtaoja 1999). There are several methods available from the literature that can be used

¹ <http://cats.sao.ru/>

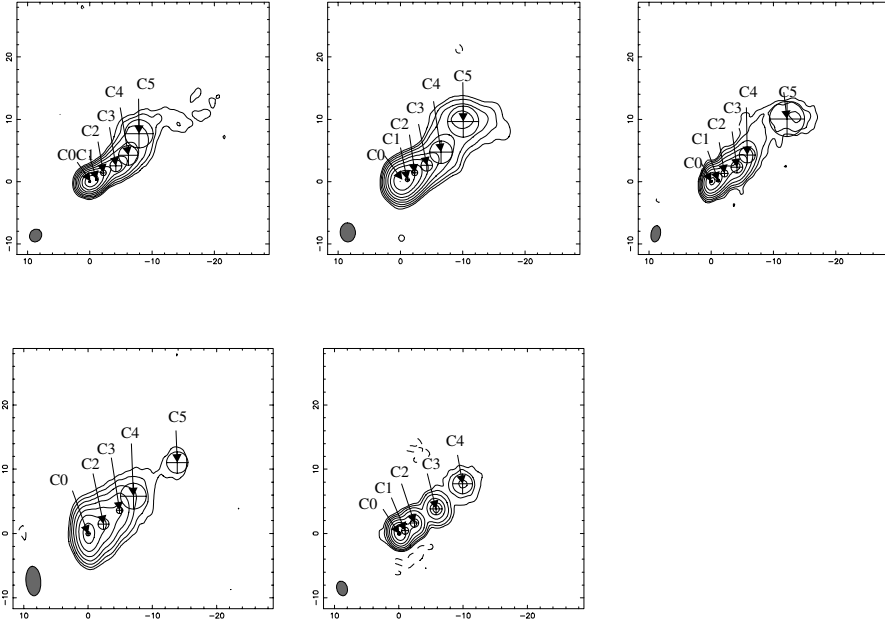


Fig. 7. EVN and VLBA images of 1727+502 at 5 GHz. The top from left to right are: epoch 1995.534, epoch 1997.055, epoch 1998.493. The bottom from left to right are: epoch 1999.893, epoch 2002.403. The axes are labeled in milliarcseconds. Contours are drawn at $-1, 1, 2, 4, 8, 16, \dots$ times the noise level. Numerical parameters of the images are given in Table 1.

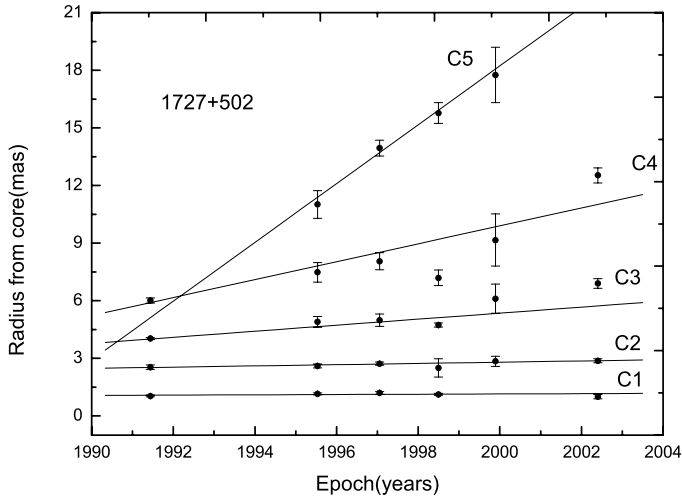


Fig. 8. Positions of components with respect to the core at different epochs from model fitting for 1727+502. The data point at 1991.433 is taken from Kollgaard et al. (1996a). All the other epochs are those presented in this paper, and the lines represent the linear fitting of the motion for each jet component.

to estimate the Doppler factor. Ghisellini et al. (1993) estimated the Doppler factor for a sample of AGNs, based on the synchrotron self-Compton model. This method needs the angular size of the core from high-resolution VLBI observation and assumes that the X-ray flux originates from the self-Compton components. However, this method is limited in practice for the case of BL Lac objects. On the one hand, the detailed VLBI studies on BL Lac objects are only available for bright objects and a few other outstanding sources (Giroletti et al. 2006). On the other hand, while both the soft and the hard X-ray bands are dominated by the inverse Compton process in FSRQs, they are dominated by the synchrotron process in HBL, and the synchrotron flux dominates in the soft band and the flatter Compton component appears at higher X-ray energies in LBL (Donato et al. 2001).

In this work, we use the method suggested by Giovannini et al. (2001) and Giroletti et al. (2004a). Generally, 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 (Bondi et al. 2001), while the relativistic boosting at the base of the jet affects the observed radio power of the core. Giovannini et al. (1988) and Giovannini et al. (2001) find a general correlation between the intrinsic core radio power and total radio power for a sample of radio galaxies

$$\log P_{\text{ci}5} = 0.62 \log P_{\text{t}} + 8.41 \quad (2)$$

where $P_{\text{ci}5}$ is the intrinsic core 5 GHz radio power derived assuming $\Gamma = 5$ (see Giovannini et al. 2001 for details), and P_{t} is the total radio power at 408 MHz. From the measured total 408 MHz radio power, we can derive the intrinsic core radio power. Thus, the Doppler factor can be derived if we know the observed radio core luminosity. As it is currently believed that most BL Lac objects are beamed FR I radio galaxies, Giroletti et al. (2004a) have applied this correlation to 30 BL Lac objects and find that the distribution of either the total radio power or the intrinsic core radio power derived from this correlation is similar with the FR I sample in Giovannini et al. (2001). This indicates that Eq. (2) is applicable to our large sample of BL Lac objects, although this relation was made from a sample of mainly radio galaxies, and only few BL Lac objects were included.

4.2. Low-frequency radio power

The anti-correlation between the synchrotron peak frequency and the intrinsic power was first suggested by Fossati et al. (1998) and Ghisellini et al. (1998) for samples of blazars. Nieppola et al. (2006) find an anti-correlation between the luminosity at 5 GHz and 37 GHz with ν_{peak} for a large sample of BL Lac objects. However, the 5 GHz and 37 GHz luminosity can be severely affected by the beaming effect from the radio jets and can't be used to indicate of the intrinsic radio power. Bondi et al. (2001) and Giroletti et al. (2004a) suggest that the low-frequency radio luminosity of BL Lac objects can indicate the intrinsic power from the radio jet. However, most of the objects in their works are HBLs and IBLs. For LBLs, especially

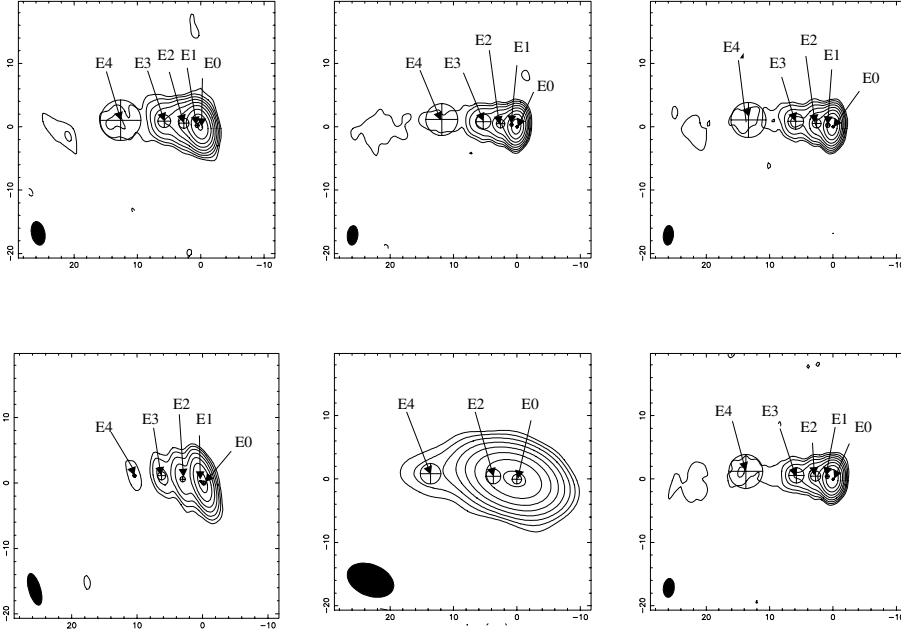


Fig. 9. EVN and VLBA images of 1741+196 at 5 GHz. The top from left to right are: epoch 1997.055, epoch 1997.378, epoch 1998.493. The bottom from left to right are: epoch 1999.893, epoch 2002.400, epoch 2003.447. The axes are labeled in milliarcseconds. Contours are drawn at $-1, 1, 2, 4, 8, 16, \dots$ times the noise level. Numerical parameters of the images are given in Table 1.

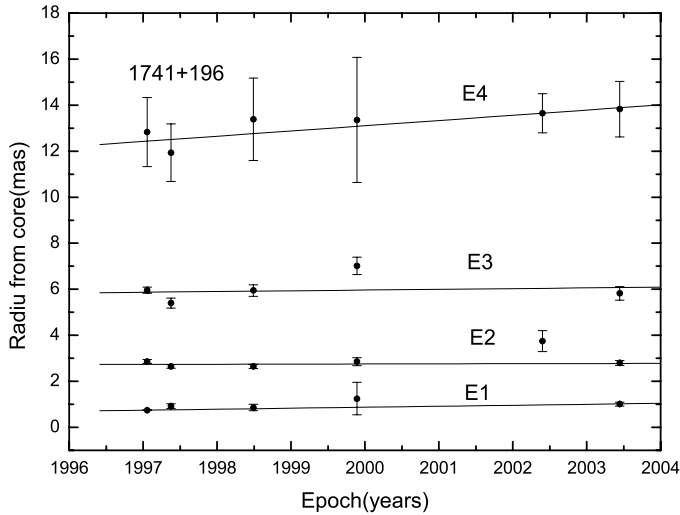


Fig. 10. Positions of components with respect to the core at different epochs from model fitting for 1741+196. All the data points are presented in this paper, the lines represent the linear fitting of the motion for each jet component except the data point at 2002.400, as the baseline of this epoch is much shorter than the others.

those in the 1 Jy sample, as there is a selection criterion of the radio spectral index being less than 0.5 ($\alpha_r \leq 0.5$; $S_\nu \propto \nu^{-\alpha_r}$), the low-frequency radio emission may still be Doppler boosted (Cao et al. 2003). Indeed, Liu et al. (2006) find that the low-frequency radio emission of sources with a flat spectrum are likely to be Doppler-boosted, although only radio-loud quasars are considered in their work.

To test whether the low-frequency radio emission is Doppler-boosted, we selected 61 BL Lac objects from Nieppola et al. (2006), which have VLA observations and extended flux. These sources are listed in Table 4, including all powerful sources of the 1 Jy sample, and some other type of BL Lac objects. After extrapolating from the 1.4 GHz extended flux using $\alpha = 1.0$ for 15 sources without 5 GHz extended flux, we plot the 5 GHz extended flux with the total 408 MHz flux in Fig. 11, which is directly from the available measurements, or extrapolated from

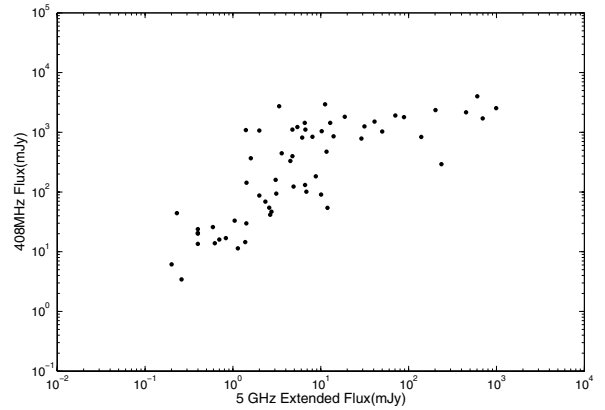


Fig. 11. The relationship between the radio 5 GHz extended flux and the radio low-frequency 408 MHz flux.

330 MHz, 360 MHz, or the total 1.4 GHz radio flux (see below). We find a generally good correlation. However, the scatter is obviously seen. This can be caused by the difference in the spectral index of two bands between sources, while both emissions are not influenced by the beaming effect. However, the possibility that the low-frequency radio emission in some sources is indeed Doppler boosted can't be excluded completely with present data. Nevertheless, we believe that the low-frequency radio emission is intrinsic, as most of the sources follow the correlation.

To calculate the Doppler factor using the method in Sect. 4.2, we had to obtain the total 408 MHz luminosity. Unfortunately, not all sources in our sample had an observed 408 MHz flux. We adopted three methods of calculating 408 MHz luminosity according to the available data. For BL lac objects with the extended flux available, we estimated the 408 MHz luminosity by extrapolating from the 5 GHz or 1.4 GHz extended flux assuming a spectral index of $\alpha = 1.0$. For the sources with observed low-frequency radio flux, we estimated the total 408 MHz luminosity after a K-correction using spectral index $\alpha = 1.0$. For the remaining sources, neither the extended flux nor the low-frequency flux was available, so we extrapolated from the total

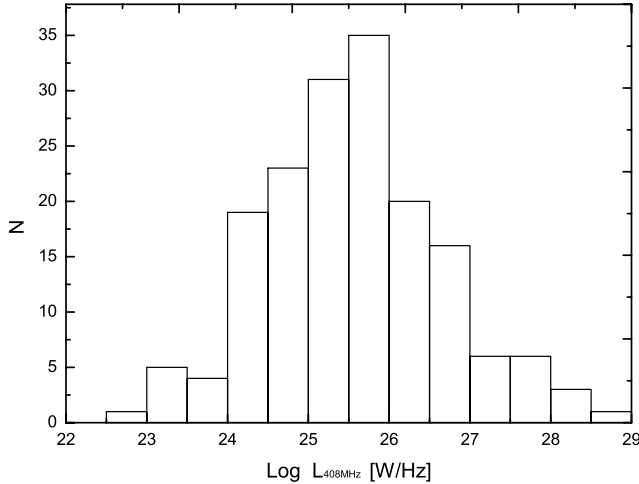


Fig. 12. The distribution of 408 MHz luminosity for BL Lac objects selected from Nieppola et al. (2006).

1.4 GHz flux density with a spectral index of $\alpha = 0.207$, which is the average spectral index between 408 MHz and 1.4 GHz of the BL Lac objects in our sample. The estimated total 408 MHz radio power is listed in Col. 5 of Table 4. To compare with the FR I radio galaxies sample of Zirbel & Baum (1995), we converted the total 408 MHz radio luminosity into the same cosmological frame ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$), as used in their calculation. The distribution of this total 408 MHz radio power is shown in Fig. 12. Although our sample contains about two thirds of the BL Lac objects from the 1Jy sample, we find that the mean and median values of the 408 MHz radio power (mean = 25.56 W Hz^{-1} and median = 25.52 W Hz^{-1}) are consistent with those of the low-luminosity FR I radio galaxies in Zirbel & Baum (1995), which is mean = $25.50 \pm 0.12 \text{ W Hz}^{-1}$ and median = 25.38 W Hz^{-1} . This, on one hand, supports the scenario that FR I radio galaxies are the parent population of BL Lac objects; and on the other hand, it indicates that the estimated total 408 MHz radio power of our BL Lac objects is intrinsic, as it is comparable to FR I radio galaxies.

4.3. Doppler factor of BL Lac objects

According to the unified schemes, classes of apparently different AGN might actually be intrinsically similar, when only viewed at different angles with respect to the line of sight. It was suggested that BL Lac objects are FR I radio sources viewed at relatively small angles to the line of sight and that the relativistic beaming has an enormous effect on the observed luminosities, so determining the Doppler factor is important in studying the properties of BL Lac objects, especially the differences between different types of BL Lac objects. To estimate the Doppler factor using the method described in Sect. 4.1, we collected 5 GHz VLA or MERLIN core flux of 170 BL Lac objects (see Table 4). The 5 GHz core luminosity was calculated with a K-correction assuming a spectral index of $\alpha = 0$. The Doppler factor is then estimated by using the 5 GHz core luminosity, the estimated radio power at 408 MHz (see Sect. 4.3), and Eq. (2). In this work, we adopt $P_{c,0} = P_{c,i} \delta^{2+\alpha}$ (corresponding to a continuous jet), assuming $\alpha = 0$, where $P_{c,0}$ is the observed 5 GHz core luminosity and $P_{c,i}$ the intrinsic one calculated from Eq. (2).

The synchrotron peak frequency $\nu_{\text{peak}} \propto B \delta \gamma_{\text{peak}}^2$, therefore it may not be intrinsic since the Doppler factor can vary between sources in our sample. Once the Doppler factor can be estimated,

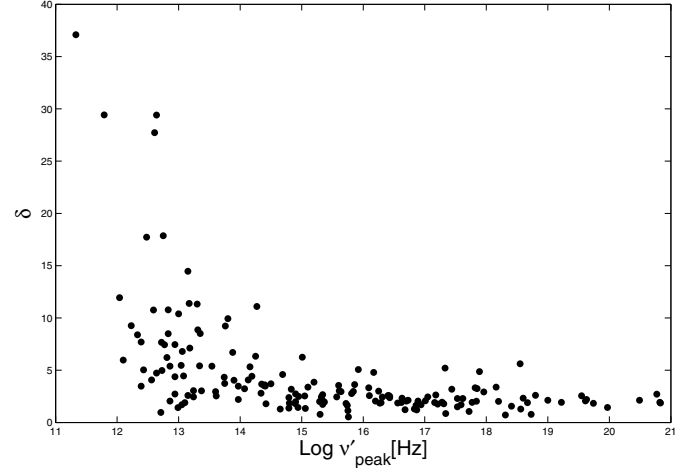


Fig. 13. The Doppler factor versus the intrinsic synchrotron peak frequency ν'_{peak} (see text for details).

it would be fundamental in calculating the intrinsic peak frequency. In this work, we calculate the intrinsic synchrotron peak frequency $\nu'_{\text{peak}} = \nu_{\text{peak}}(1+z)/\delta$, where ν_{peak} is from Nieppola et al. (2006). The factor $(1+z)$ is included since the ν_{peak} of Nieppola et al. (2006) is determined from the $\log \nu - \log \nu f_{\nu}$ panel in the observer's frame. The distribution of the Doppler factor and the intrinsic peak frequency is shown in Fig. 13. While all IBLs and HBLs have a Doppler factor below 10, LBLs have a wide spread for the Doppler factor, with most sources below 20, and it can be over 30 in a few cases. It seems that the Doppler factor systematically decreases with increasing peak frequency; however, it is similar for IBLs and HBLs. Indeed, the Spearman rank correlation analysis shows an anti-correlation between the Doppler factor and ν'_{peak} at $\gg 99.99$ per cent significance level. This may indicate that the Doppler boosting is systematically more pronounced in LBLs than in IBLs and HBLs, although a fraction of LBLs are comparable to IBLs and HBLs.

The estimation of Doppler factor enables us to investigate the relationship between the intrinsic radio power and the intrinsic synchrotron peak frequency. The relationship between the intrinsic peak frequency and 408 MHz radio power is shown in Fig. 14. It can be seen that LBLs are statistically more powerful than other BL Lac objects. There is a significant anti-correlation between luminosity and ν'_{peak} at $\gg 99.99\%$ confidence level from the Spearman Rank Correlation analysis. Although we used the low-frequency radio emission to indicate the intrinsic radio power and correct the peak frequency for Doppler factor, our results in Fig. 14 are very similar to those of radio power at 5 GHz in Nieppola et al. (2006). Several low-luminosity LBLs are apparently seen, and they even reach lower luminosities than any of the HBLs.

We note that the 408 MHz radio power in our sample is calculated in inhomogenous ways, and the redshift of some sources is actually unknown and tentatively taken as the average value of subclasses. To verify how the correlation depends on the data, we check with a sample that has the measured 408 MHz flux and known redshift. Still, these twenty-one sources (Fig. 14) show a strong anti-correlation at about a 98 per cent confidence level. However, due to the small number of these sources, we add the sources with known redshift and 408 MHz radio power extrapolated from either 330 MHz or 360 MHz radio flux (Fig. 14), resulting in a sample of 56 sources, of which the uncertainty from extrapolation is minimized. It is clearly seen that these sources

follow the general trend of whole sample. The Spearman rank correlation analysis shows a significant anti-correlation at about a 99.9 per cent confidence level. We are thus confident that the inhomogenous data derivation does not influence our results.

Despite much more scatter in our figure than in the corresponding one of Fossati et al. (1998), the anti-correlation between luminosity and ν'_{peak} is still significant and possibly caused by the intrinsic physical differences (such as magnetic fields, electron energies), as suggested by Sambruna et al. (1996). As jet formation is closely connected with the central engine (Liu et al. 2006), this correlation can also be caused by the common relationship between both the radio luminosity and peak frequency and the central engine, as suggested by Wang et al. (2002) that the peak frequency is significantly correlated with the accretion rate. Although our sample is relatively large, still only a small fraction of low-luminosity LBLs are included in the sample. As a matter of fact, there is no evidence of very high-luminosity HBLs in the sample of Nieppola et al. (2006), which is our parent sample.

4.4. Viewing angle

There have been several models trying to explain the differences in different types of BL Lac objects. It was originally explained as the orientation effects, with HBLs being observed at larger inclination to the jet axis (Urry & Padovani 1995). However, Sambruna et al. (1996) argue that it is difficult to model the detailed transition from an HBL to an LBL SED only in terms of orientation only and instead suggest a continuous change in the physical parameters of the jet. To study the viewing angle distribution for our sample of BL Lac objects, we estimated the viewing angle for each object assuming a Lorentz factor of $\Gamma = 5$, in combination with the estimated Doppler factor in Sect. 4.3. The difference between this angle and that of $\Gamma = 3$ and $\Gamma = 10$ are taken as the uncertainty. The distribution of the viewing angle and intrinsic synchrotron peak frequency $\nu'_{\text{peak}} = \nu_{\text{peak}}(1+z)/\delta$ is shown in Fig. 15, in which the errorbar are indicated with the viewing angle from $\Gamma = 3$ and $\Gamma = 10$. It can be seen that most of LBLs are in the range of angles (0° , 20°), while most of IBLs and HBLs are in (15° , 30°). As an intermediate subclass between the LBLs and HBLs, the IBLs' viewing angles are larger than that of LBLs; however, it is indistinguishable from those of HBLs. Moreover, BL Lac objects, as a whole, mostly have viewing angle smaller than 30° . This is consistent with the unified scheme in which BL Lac objects are the aligned version of FR I radio galaxies (Urry & Padovani 1995). It clearly shows that there is a significant positive correlation between viewing angle and ν'_{peak} at $\gg 99.99$ per cent significance level. Actually, this can be expected simply from the relationship between the Doppler factor and ν'_{peak} , if a uniform Lorentz factor is adopted for all sources. Therefore, it is not surprising that LBLs have smaller viewing angles compared to IBLs and HBLs, since their Doppler factor is systematically larger.

Usually, the viewing angles can be estimated by using the Doppler factor and the measurements of proper motion, however, the latter are not available for most of sources. Using the measured proper motion and the Doppler factor, we calculated the Lorentz factor for the three sources we observed. We find that the estimated Lorentz factor is generally consistent with the assumption of $\Gamma = 5$, and the range of Γ between 3 and 10 (see Table 3). This indicates that the angle got by assuming a Lorentz factor of 5 can be reasonable for our sample. Certainly, the adoption of a Lorentz factor of 5 only makes sense for our

statistical sample investigation and can't be used for an individual source. We believe that the exact value of Lorentz factor will not change our results significantly. From Fig. 15, it seems that the BL Lac objects as a single population possess a continuous range of viewing angle and a positive correlation between the viewing angle and the ν'_{peak} . Similar to the Doppler factor distribution, the viewing angle increases with the increasing peak frequency from LBLs to IBLs, but, it smooths out upward.

5. Discussion

In Sect. 3.1, our observations have shown that all the jets of seven BL Lac objects are very straight, and they do not exhibit large bending between the small and large scales. This result is similar with the observations of HBLs in Rector et al. (2003), in which two of our sources are included. This indicates that these sources are either intrinsically straighter or are seen further off-axis than LBL jets. In three sources with measured proper motion (Sect. 3.1), it shows that different components of the same source have different apparent speeds, and the apparent speed increases with the distance from the core. This is similar to the results in Piner et al. (2006), in which BL Lac object 0235+164 and two FSRQs were studied. This phenomena will need a change in either bulk Lorentz factor or viewing angle. However, these changes would also yield predictable changes in the brightness of components due to changing Doppler boosting, and these changes are not seen.

While recent discoveries of low-luminosity LBLs and possible high-luminosity HBLs (Padovani et al. 2003; Caccianiga & Marchã 2004; Giommi et al. 2005) seems to undermine the blazar sequence, an anti-correlation between radio power and peak frequency was found for a large sample of BL Lac objects (Nieppola et al. 2006), though with a large scatter. We improved their work by using the intrinsic low-frequency radio power and the intrinsic synchrotron peak frequency, instead. It appears that LBLs are intrinsically more powerful than other types of BL Lac objects, and the distribution of the low-frequency power of BL Lac objects as a whole is comparable to those of FR I radio galaxies. Although there is a correlation between the intrinsic low-frequency power and intrinsic peak frequency, the scatter of this relation seems large, which contrast with the much tighter relation of "blazar sequence". More important, some LBLs have low radio power, which is difficult to explain by the radiation cooling process, which was used to explain the blazar sequence. In fact, these sources tend to weaken the blazar sequence; however, they are not enough to eliminate the correlation in this work. While the blazar sequence was suggested for a sample of blazars including FSRQs, of which the peak frequency can be lower than those of LBLs, our sample only includes BL Lac objects, although our sample is much larger. Moreover, the original peak frequency used in this work is directly adopted from Nieppola et al. (2006), which was derived by simply fitting the synchrotron component of the SED with a parabolic function. The determination of peak frequency is thus influenced by the data quality and sampling. As Nieppola et al. (2006) discuss, the peak frequencies of the most extreme objects can be exaggerated by using a simple parabolic function in the fitting procedure. Furthermore, the large scatter in Fig. 14 implies that other parameters may be at work, and the scatter can be much lower once this parameter is included. Besides the significant anti-correlation between the intrinsic low-frequency luminosity and intrinsic peak frequency, there is a positive correlation between the viewing angle and intrinsic peak frequency. LBLs apparently have smaller viewing angle, while the viewing angle of

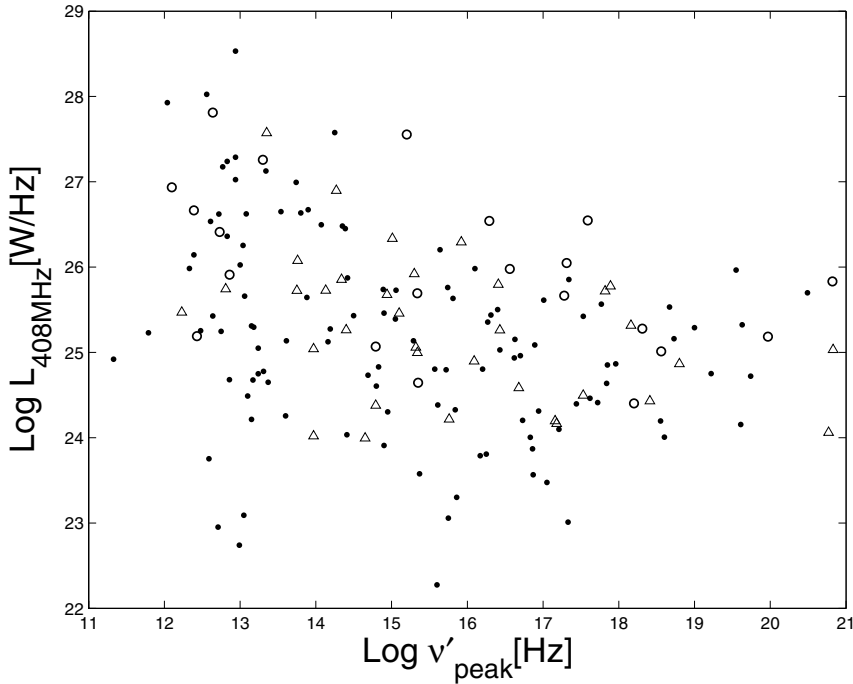


Fig. 14. The low-frequency 408 MHz luminosity versus the intrinsic synchrotron-peak frequency ν'_{peak} . The open circles are the sources with the direct measurements of 408 MHz radio flux and known redshift, the open triangles are the sources calculated from either the 360 MHz, or 330 MHz radio flux with known redshift, while the solid circles are those estimated from the extended flux (at 5 GHz or 1.4 GHz), the total 1.4 GHz radio flux, or low-frequency radio flux (with unknown redshift) (see text for details).

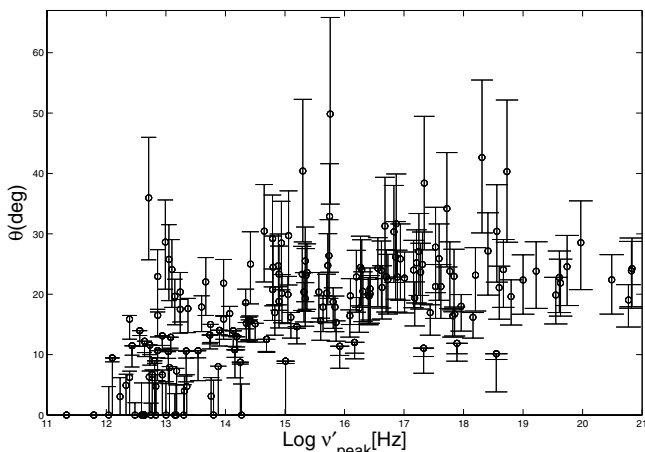


Fig. 15. The viewing angle versus the intrinsic synchrotron peak frequency ν'_{peak} . The viewing angle is estimated by assuming a Lorentz factor of 5 and using the estimated Doppler factor in Sect. 4.4. The errorbar is indicated with the viewing angle of Lorentz factors of 3 and 10.

IBLs is comparable to that of HBLs. We conclude that the intrinsic synchrotron peak frequency is related not only to the intrinsic luminosity, but maybe also to the viewing angle. In fact, some HBLs like Mrk 421 and Mrk 501 are supposed to have $\delta \geq 10$, which was estimated by Celotti et al. (1998) based on their TeV flux variability. However, the studies of jet morphology, core dominance, the fit to the trend of the jet brightness, and Full-Width Half-Maximum (FWHM) all show that the radio jet emission is oriented to larger angles with respect to the line of sight (Giroletti et al. 2004b; Giroletti et al. 2006).

There are only a small fraction of low-luminosity LBLs in our sample, and actually no evidence of very high-luminosity HBLs (Nieppola et al. 2006). This precludes us from draws any firm conclusion about the validity of the blazar sequence. Actually, the FSRQs with a high ν_{peak} found in DXRBS do not reach the extreme ν_{peak} values of HBLs. It is still unclear whether this fact indicates an intrinsic, physical limit to this

parameter. An alternative scenario is one where really high-power-high- ν_{peak} blazars have their thermal emission swamped by the non-thermal, featureless jet emission, which makes their redshift determination impossible. While our results seem to undermine the blazar sequence, the anti-correlation between the intrinsic emission and intrinsic peak frequency needs further investigation. It is important to compile a larger sample including various subclasses of blazars, especially blue quasars, low-luminosity LBLs, and high-luminosity HBLs and to calculate the accurate peak frequency and intrinsic luminosity. Only then, the physical mechanism of the different peak frequencies can be explored. While the peak frequency is believed to be determined by the magnetic strength and the energy distribution of relativistic electrons, the shift of the peak frequency in blazars can give us clues to this information. It might also be important to investigate the relationship between the SEDs of blazars and the central engine, such as accretion rate (Wang et al. 2002) and/or black hole mass.

6. Conclusions

In this paper, we have presented EVN and VLBA images at 5 GHz for seven BL Lac objects selected from an RGB sample (Laurent-Muehleisen et al. 1999). We collected multi-epoch data from EVN and the VLBA archive for three of them. The radio data were collected for a sample of 170 BL Lac objects selected from Nieppola et al. (2006) to study the relation of the intrinsic synchrotron peak frequency with the intrinsic low-frequency radio luminosity and the viewing angle. The main conclusions can be summarized as follows:

1. We found that all seven sources show a core-jet structure on a pc scale, and no counter-jets were found. The jets of these sources are straight, and only small changes in the position angle are found between small and large scales. The superluminal motion is detected in all three sources with the available multi-epoch data, and the apparent speed of components are increases with the increasing distance of components to the core.

2. Based on the method suggested in Giovannini et al. (2001) and Giroletti et al. (2004a), we calculated the Doppler factor for 170 BL Lac objects selected from Nieppola et al. (2006). Using the total 408 MHz luminosity to indicate the intrinsic radio power and correcting the synchrotron peak frequency for Doppler factor, we found a significant anti-correlation between the total 408 MHz luminosity and the intrinsic synchrotron peak frequency. However, the scatter is much larger than that of the blazar sequence. Especially, several low-power LBLs are clearly present. Our results seem to undermine the blazar sequence.
3. The viewing angle of BL Lac objects are constrained using the estimated Doppler factor, and assuming a Lorentz factor of 5. We found a strong positive correlation between the viewing angle and the intrinsic synchrotron peak frequency. The BL Lacs show a continuous distribution of the viewing angle, and LBLs have lower values than for IBLs and HBLs. However, the IBLs are similar to HBLs for the viewing angle.

In conclusion, our results show that the intrinsic peak frequency is related not only to the intrinsic radio power (though much looser than the blazar sequence), but also to the viewing angle. A complete, large sample of BL Lacs (or blazars) is needed for future investigations.

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Online Material

Table 1. The VLBI observational log.

Object	z	Epoch	HPBW (mas \times mas, $^\circ$)	Noise (3σ) (mJy beam $^{-1}$)	Peak (mJy beam $^{-1}$)	Array
1011+496	0.2	1997.055	$2.5 \times 2.08, -8.36$	0.60	116.0	1
		1998.493	$2.47 \times 1.72, -2.76$	0.56	103.0	1
		1999.893	$2.8 \times 1.35, -38.6$	1.83	81.7	2
1133+704	0.046	1997.055	$2.77 \times 2.04, -32.5$	0.30	118.0	1
		1998.493	$2.72 \times 1.7, 87.7$	0.39	98.7	1
		1999.893	$1.87 \times 1.32, -30.4$	1.01	77.5	2
1424+240	0.16	1999.696	$2.96 \times 1.92, -0.412$	0.94	125.0	1
		1999.893	$5.95 \times 1.98, 12.8$	1.57	134.0	2
		2003.447	$3.02 \times 1.61, -8.25$	0.60	164	1
1542+614	...	1999.893	$2.26 \times 1.48, 7.24$	0.87	93.4	2
4C+37.46	1.271	1999.893	$4.65 \times 2.17, 15.7$	1.38	32.2	2
1727+502	0.055	1995.534	$2.12 \times 1.87, -34.6$	0.37	80.1	1
		1997.055	$3.05 \times 2.43, 3.03$	0.35	85.7	1
		1998.493	$2.62 \times 1.52, -10.8$	0.46	66.9	1
		1999.893	$4.58 \times 2.3, 4.5$	0.93	81.4	2
		2002.403	$2.31 \times 1.64, 16$	0.63	72.9	2
1741+196	0.083	1997.055	$3.75 \times 2.13, 11.8$	0.37	103.0	1
		1997.378	$3.07 \times 1.67, -5.62$	0.42	80.1	1
		1998.493	$3.09 \times 1.58, -5.37$	0.39	85.4	1
		1999.893	$5 \times 1.79, 16.2$	1.14	98.4	2
		2002.400	$7.68 \times 4.92, 67.8$	0.90	131.0	2
		2003.447	$2.98 \times 1.72, -6.07$	0.41	100.0	1

1: VLBA, 2: EVN.

Table 2. Model parameters.

Source	Epoch	Component	S (Jy)	r (mas)	PA (deg)	a (mas)
1727+502	1995.534	C0	0.068	0.00	0.0	0.27
	1995.534	C1	0.027	1.15 ± 0.05	-73.3	0.36
	1995.534	C2	0.016	2.61 ± 0.11	-57.4	0.91
	1995.534	C3	0.016	4.90 ± 0.28	-58.8	1.91
	1995.534	C4	0.013	7.48 ± 0.51	-55.8	3.12
	1995.534	C5	0.012	11.01 ± 0.72	-45.9	4.53
	1997.055	C0	0.065	0.00	0.0	0.00
	1997.055	C1	0.030	1.20 ± 0.71	-75.4	0.60
	1997.055	C2	0.030	2.73 ± 0.08	-58.8	0.97
	1997.055	C3	0.010	4.99 ± 0.32	-58.8	1.84
	1997.055	C4	0.012	8.06 ± 0.44	-54.4	3.62
	1997.055	C5	0.014	13.94 ± 0.41	-46.4	5.00
	1998.493	C0	0.062	0.00	0.0	0.33
	1998.493	C1	0.023	1.13 ± 0.06	-81.7	0.46
	1998.493	C2	0.022	2.50 ± 0.48	-59.0	1.12
	1998.493	C3	0.028	4.73 ± 0.11	-60.9	1.88
	1998.493	C4	0.012	7.19 ± 0.40	-53.7	2.55
	1998.493	C5	0.015	15.78 ± 0.54	-50.5	5.62
	1999.893	C0	0.082	0.00	0.0	0.67
	1999.893	C2	0.039	2.84 ± 0.26	-57.5	1.69
1999.893	C3	0.014	6.11 ± 0.76	-53.4	1.00	
1999.893	C4	0.009	9.16 ± 1.35	-50.2	4.00	
1999.893	C5	0.003	17.76 ± 1.44	-51.4	3.32	
2002.403	C0	0.071	0.00	0.0	0.53	
2002.403	C1	0.017	1.01 ± 0.11	-63.9	1.09	
2002.403	C2	0.030	2.88 ± 0.10	-55.3	1.30	
2002.403	C3	0.021	6.90 ± 0.25	-56.1	1.87	
2002.403	C4	0.009	12.52 ± 0.39	-51.9	3.09	
1741+196	1997.055	E0	0.070	0.00	0.0	0.00
	1997.055	E1	0.040	0.74 ± 0.013	70.2	0.65
	1997.055	E2	0.018	2.86 ± 0.079	77.9	1.60
	1997.055	E3	0.009	5.96 ± 0.13	81.1	2.01
	1997.055	E4	0.004	12.83 ± 1.50	85.2	6.41
	1997.378	E0	0.073	0.00	0.0	0.35
	1997.378	E1	0.019	0.93 ± 0.10	70.4	0.51
	1997.378	E2	0.015	2.65 ± 0.079	79.6	1.32
	1997.378	E3	0.010	5.40 ± 0.22	81.3	2.41
	1997.378	E4	0.004	11.93 ± 1.25	84.5	5.04
	1998.493	E0	0.076	0.00	0.0	0.28
	1998.493	E1	0.022	0.86 ± 0.14	72.0	0.69
	1998.493	E2	0.017	2.65 ± 0.090	78.0	1.41
	1998.493	E3	0.009	5.95 ± 0.25	81.6	2.47
	1998.493	E4	0.004	13.39 ± 1.79	85.4	5.55
	1999.893	E0	0.095	0.00	0.0	0.64
	1999.893	E1	0.003	1.25 ± 0.71	88.6	0.00
	1999.893	E2	0.020	2.79 ± 0.17	78.3	0.83
	1999.893	E3	0.006	6.95 ± 0.38	82.0	0.64
	1999.893	E4	0.001	13.36 ± 2.72	89.9	2.32
2003.447	E0	0.092	0.00	0.0	0.31	
2003.447	E1	0.023	1.09 ± 0.082	66.1	0.64	
2003.447	E2	0.015	2.80 ± 0.11	80.2	1.58	
2003.447	E3	0.008	5.82 ± 0.30	84.1	2.39	
2003.447	E4	0.004	13.83 ± 1.21	85.0	5.35	
1133+704	1997.055	M0	0.099	0.00	0.0	0.38

Table 2. continued.

Source	Epoch	Component	S (Jy)	r (mas)	PA (deg)	a (mas)
	1997.055	M1	0.027	0.74 ± 0.13	111.1	0.51
	1997.055	M2	0.006	2.99 ± 0.50	99.0	2.23
	1997.055	M3	0.005	6.23 ± 0.88	76.7	4.16
	1997.055	M4	0.005	15.61 ± 1.40	73.1	7.15
	1998.493	M0	0.091	0.00	0.0	0.31
	1998.493	M1	0.018	1.27 ± 0.12	106.9	0.70
	1998.493	M2	0.008	3.34 ± 0.25	100.9	1.29
	1998.493	M3	0.004	14.99 ± 1.66	73.1	5.26
	1998.493	M4	0.003	7.55 ± 1.66	76.0	3.42
	1999.893	M0	0.080	0.00	0.0	0.35
	1999.893	M1	0.003	0.92 ± 0.42	119.6	0.00
	1999.893	M2	0.013	2.71 ± 0.61	93.0	1.03
	1999.893	M3	0.003	8.47 ± 0.26	78.8	0.75

Table 3. Proper motions.

Object	Component	μ (mas yr ⁻¹)	β_{app}	δ	θ (deg)	Γ	$\theta_{\Gamma=5}$ (deg)
1133+704	M1	0.040 ± 0.015	0.12 ± 0.045				
	M2	0.18 ± 0.032	0.56 ± 0.10				
	M3	0.78 ± 0.31	2.4 ± 0.97	0.8	41.6	4.6	39.9
1727+502	C1	0.0074 ± 0.0085	0.027 ± 0.031				
	C2	0.032 ± 0.013	0.12 ± 0.049				
	C3	0.16 ± 0.014	0.58 ± 0.051				
	C4	0.47 ± 0.31	1.72 ± 1.15				
	C5	1.53 ± 0.26	5.64 ± 0.96	1.9	18.1	9.6	23.7
1741+196	E1	0.043 ± 0.013	0.24 ± 0.071				
	E2	0.0064 ± 0.019	0.035 ± 0.11				
	E3	0.031 ± 0.049	0.17 ± 0.27				
	E4	0.23 ± 0.21	1.25 ± 1.13	3.3	12.3	2.0	16.6

Table 4. The sample of 170 BL Lac objects selected from Nieppola et al. (2006).

IAU name	Source	z	$\log \nu'_{\text{peak}}$	$\log P_{408 \text{ M}}$	$\log P_{\text{core}}$	f_{ext}	Refs.	δ	θ_3	θ_5	θ_{10}
0006-063	NRAO 5	0.347	12.10	26.94 ^a	26.65	...	1	6.0	0.0	9.4	8.8
0007+472	RX J0007.9+4711	0.302*	15.81	25.63 ^b	25.18	...	2	2.8	21.1	18.7	14.3
0035+598	1ES 0033+595	0.086	18.60	24.01 ^c	24.02	4.50	3	2.3	24.7	21.1	15.9
0040+408	1ES 0037+405	0.271*	16.62	24.93 ^c	24.42	3.07	3	1.9	28.8	23.9	17.7
0050-094	PKS 0048-097	0.537	12.94	27.29 ^c	26.60	139.00	4	4.4	11.5	13.1	10.9
0110+418	NPM1G +41.0022	0.096	17.72	24.41 ^d	23.58	...	2	1.1	43.5	34.2	24.5
0112+227	S2 0109+22	0.473*	12.83	26.36 ^b	26.60	...	2	8.5	0.0	4.7	6.7
0115+253	RXS J0115.7+2519	0.350	13.15	25.31 ^d	24.92	...	2	2.6	22.5	19.7	14.9
0123+343	1ES 0120+340	0.272	17.96	24.86 ^c	24.75	2.59	3	2.9	19.9	18.0	13.9
0124+093	MS 0122.1+0903	0.339	15.37	23.58 ^c	23.60	0.08	5	2.0	28.4	23.6	17.5
0136+391	B3 0133+388	0.271*	16.31	25.44 ^a	24.95	...	2	2.4	23.7	20.5	15.5
0141-094	PKS 0139-09	0.733	12.77	27.17 ^c	26.99	50.00	6	7.4	0.0	6.7	7.5
0148+140	1ES 0145+138	0.125	15.76	24.22 ^c	22.88	...	7	0.5	65.8	49.9	34.9
0153+712	8C 0149+710	0.022	14.65	23.99 ^b	23.50	...	2	1.3	38.2	30.4	22.0
0201+005	MS 0158.5+0019	0.299	17.62	24.46 ^c	24.29	0.83	5	2.3	24.9	21.3	16.0
0208+353	MS 0205.7+3509	0.318	14.90	23.91 ^c	24.10	0.20	5	2.7	21.2	18.8	14.4
0214+517	87GB 02109+5130	0.049	17.53	24.50 ^b	23.94	...	2	1.5	34.4	27.8	20.3
0222+430	3C 66A	0.440	15.20	27.55 ^a	26.65	...	8	3.9	14.3	14.6	11.8
0232+202	1ES 0229+200	0.140	19.22	24.75 ^d	24.32	...	7	1.9	28.7	23.8	17.7
0238+166	AO 0235+164	0.940	12.83	27.24 ^c	27.35	31.40	9	10.8	0.0	0.0	5.3
0301+346	MS 0257.9+3429	0.245	13.10	24.49 ^c	24.14	1.38	5	1.9	29.1	24.1	17.8
0314+247	RXS J0314.0+2445	0.054	12.71	22.95 ^d	22.60	...	2	1.0	46.0	36.0	25.7
0326+024	2E 0323+0214	0.147	19.61	24.16 ^c	24.01	2.00	10	2.1	27.2	22.8	17.0
0416+010	2E 0414+0057	0.287	20.49	25.70 ^d	24.99	...	1	2.1	26.6	22.4	16.7
0422+198	MS 0419.3+1943	0.512	16.63	25.15 ^c	24.73	1.14	5	2.3	24.7	21.1	15.9
0424+006	PKS 0422+004	0.310	15.01	26.33 ^b	26.32	...	9	6.2	0.0	8.9	8.5
0505+042	RXS J0505.5+0416	0.027	16.87	23.57 ^d	23.17	...	2	1.2	39.9	31.7	22.8
0507+676	1ES 0502+675	0.314	18.55	24.20 ^c	24.90	0.40	3	5.6	3.8	10.2	9.2
0508+845	S5 0454+84	0.112	12.59	23.75 ^c	25.19	5.10 ^f	4,9	10.8	0.0	0.0	5.3
0509-040	4U 0506-03	0.304	17.77	25.57 ^c	24.82	36.00 ^f	11	1.9	28.7	23.8	17.7
0613+711	MS 0607.9+7108	0.267	14.41	24.03 ^c	24.39	0.40	5	3.5	16.4	15.8	12.5
0625+446	87GB 06216+4441	0.473*	13.04	26.25 ^d	26.15	...	8	5.5	5.2	10.5	9.4
0650+250	1ES 0647+250	0.203	17.85	24.85 ^c	24.83	4.89	3	3.2	17.9	16.7	13.1
0654+427	B3 0651+428	0.126	14.79	25.07 ^a	24.70	...	2	2.4	24.2	20.8	15.7
0656+426	NPM1G +42.0131	0.059	17.34	25.85 ^c	24.30	699.00 ^f	12	0.9	49.5	38.4	27.3
0710+591	EXO 0706.1+5913	0.125	20.83	25.03 ^b	24.46	...	7	1.9	29.3	24.3	17.9
0721+713	S5 0716+714	0.300	14.07	26.50 ^c	25.85	316.00 ^f	4	3.2	18.0	16.8	13.1
0738+177	PKS 0735+17	0.424	12.64	25.43 ^c	27.10	12.00 ^f	4	29.4	0.0	0.0	0.0
0744+745	MS 0737.9+7441	0.315	13.24	24.75 ^c	24.71	1.42	5	3.1	19.1	17.5	13.6
0753+538	S4 0749+54	0.200	12.23	25.47 ^e	26.12	...	13	9.3	0.0	3.1	6.2
0757+099	PKS 0754+100	0.266	12.48	25.26 ^c	26.56	6.70	9	17.7	0.0	0.0	2.0
0806+595	SBS 0802+596	0.300	16.43	25.26 ^c	24.81	...	2	2.4	24.3	20.9	15.7
0809+523	1ES 0806+524	0.137	16.09	24.90 ^c	24.88	...	3	3.3	17.4	16.4	12.9
0818+423	OJ 425	0.245	12.73	26.41 ^a	26.17	...	14	5.0	8.3	11.6	10.0
0823+223	4C 22.21	0.951	12.94	28.53 ^c	26.96	602.60	4	2.7	21.4	18.9	14.5
0825+031	PKS 0823+033	0.506	11.79	25.23 ^c	26.98	1.40	14	29.4	0.0	0.0	0.0
0831+044	PKS 0829+046	0.174	12.81	25.74 ^b	25.95	...	7	6.2	0.0	9.0	8.6
0831+087	1H 0827+089	0.941	13.90	26.67 ^d	26.15	...	11	4.0	13.3	14.0	11.4
0832+492	OJ 448	0.548	12.33	25.98 ^c	26.36	23.40 ^f	4	8.4	0.0	4.9	6.8
0854+441	US 1889	0.382	17.31	26.05 ^a	25.06	...	2	1.8	30.3	24.9	18.4
0854+201	OJ 287	0.306	12.75	25.25 ^c	26.56	17.00 ^f	4,9	17.9	0.0	0.0	2.0
0915+295	B2 0912+29	0.302*	15.64	26.20 ^b	25.59	...	2	3.0	19.7	17.9	13.8

Table 4. continued.

IAU name	Source	z	$\log v'_{\text{peak}}$	$\log P_{408 \text{ M}}$	$\log P_{\text{core}}$	f_{ext}	Refs.	δ	θ_3	θ_5	θ_{10}
0916+526	RXS J0916.8+5238	0.271*	17.01	25.61 ^d	24.92	...	2	2.1	27.0	22.7	16.9
0929+502	RXS J0929.2+5013	0.370	13.76	26.08 ^e	26.50	...	8	9.2	0.0	3.1	6.2
0930+498	1ES 0927+500	0.188	20.77	24.06 ^e	24.18	...	3	2.7	21.6	19.1	14.6
0930+350	B2 0927+35	0.302*	14.35	26.48 ^b	25.95	...	8	3.7	15.3	15.2	12.1
0952+656	RGB J0952+656	0.302*	14.90	25.46 ^e	24.78	...	2	2.0	28.0	23.3	17.3
0954+492	MS 0950.9+4929	0.380	16.73	24.20 ^c	24.06	0.26	5	2.1	26.6	22.4	16.7
0958+655	S4 0954+65	0.368	13.06	25.66 ^c	25.97	28.60 ^f	4,15	6.8	0.0	7.9	8.0
1012+424	RXS J1012.7+4229	0.364	20.82	25.83 ^a	24.98	...	2	1.9	28.7	23.9	17.7
1015+494	GB 1011+496	0.200	16.41	25.80 ^b	25.22	...	16	2.6	22.5	19.7	14.9
1031+508	1ES 1028+511	0.360	18.16	25.32 ^e	25.16	...	3	3.4	17.0	16.2	12.7
1037+571	RXS J1037.7+5711	0.302*	14.50	25.43 ^d	25.30	...	2	3.7	15.2	15.1	12.1
1047+546	1ES 1044+549	0.473*	12.86	24.68 ^d	24.32	...	3	2.0	27.4	22.9	17.1
1053+494	MS 1050.7+4946	0.140	14.95	24.30 ^c	24.26	3.12	5	2.5	23.3	20.2	15.3
1104+382	MRK 421	0.031	18.20	24.40 ^a	24.14	...	7	2.0	27.7	23.2	17.2
1109+241	1ES 1106+244	0.271*	16.70	24.96 ^d	24.50	...	3	2.1	27.4	22.9	17.1
1120+422	EXO 1118.0+4228	0.124	17.21	24.10 ^d	23.83	...	2	1.8	30.7	25.2	18.6
1136+701	MRK 180	0.046	18.73	25.16 ^c	23.80	237.00	3	0.8	52.2	40.3	28.6
1136+676	RXS J1136.5+6737	0.134	17.18	24.17 ^e	24.23	...	2	2.6	22.0	19.4	14.8
1149+246	EXO 1449.9+2455	0.402	19.63	25.32 ^d	24.79	...	2	2.2	25.8	21.9	16.4
1150+242	B2 1147+245	0.200	13.18	25.30 ^c	25.79	50.00 ^f	4,15	7.1	0.0	7.3	7.7
1151+589	RXS J1151.4+5859	0.302*	16.10	25.98 ^b	25.33	...	2	2.6	22.6	19.7	15.0
1209+413	B3 1206+416	0.302*	13.88	25.64 ^a	25.95	...	8	6.7	0.0	8.0	8.1
1215+075	1ES 1212+078	0.130	15.57	24.80 ^d	24.56	...	7	2.5	23.6	20.4	15.4
1217+301	B2 1215+30	0.130	15.10	25.46 ^b	25.24	...	7	3.4	17.0	16.2	12.7
1220+345	GB2 1217+348	0.130	13.97	25.04 ^e	25.01	...	2	3.5	16.5	15.9	12.5
1221+301	PG 1218+304	0.182	18.80	24.86 ^e	24.65	...	7	2.6	22.4	19.6	14.9
1221+282	ON 231	0.102	14.16	25.12 ^c	25.43	41.00	3	5.3	6.2	10.8	9.5
1223+806	S5 1221+80	0.473*	13.74	26.99 ^e	26.41	...	8	4.3	11.8	13.2	10.9
1224+246	MS 1221.8+2452	0.218	13.60	24.25 ^c	24.38	1.05	5	3.0	19.7	17.9	13.8
1230+253	RXS J1230.2+2517	0.135	14.40	25.26 ^b	25.18	...	2	3.6	15.8	15.4	12.3
1231+642	MS 1229.2+6430	0.164	15.84	24.33 ^c	24.43	2.34	5	3.0	19.7	17.9	13.8
1237+629	MS 1235.4+6315	0.297	15.61	24.38 ^c	24.48	0.70	17	3.0	19.3	17.6	13.6
1241+066	1ES 1239+069	0.150	17.05	23.48 ^c	23.73	0.40	3	2.5	23.6	20.4	15.4
1248+583	PG 1246+586	0.847	14.27	26.90 ^b	27.17	...	8	11.1	0.0	0.0	5.1
1253+530	S4 1250+53	0.302*	14.39	26.45 ^b	25.89	...	8	3.5	16.2	15.7	12.4
1257+242	1ES 1255+244	0.141	16.83	24.00 ^d	23.51	...	3	1.3	38.0	30.3	22.0
1310+325	AUCVn	0.996	12.61	26.54 ^c	27.74	5.40	9,15	27.7	0.0	0.0	0.0
1322+081	1ES 1320+084N	0.049	12.99	22.74 ^d	22.81	...	3	1.4	35.6	28.6	20.8
1341+399	RXS J1341.0+3959	0.163	19.97	25.19 ^a	24.33	...	2	1.4	35.5	28.5	20.8
1402+159	MC 1400+162	0.244	16.29	26.54 ^a	25.41	...	1	1.9	29.0	24.1	17.8
1404+040	MS 1402.3+0416(went)	0.344	15.74	25.76 ^c	24.80	11.89	3	1.6	32.3	26.4	19.3
1409+596	MS 1407.9+5954	0.496	16.40	25.50 ^c	25.02	2.75	5	2.6	22.8	19.8	15.1
1415+485	RGB J1415+485	0.500	14.13	25.73 ^e	25.57	...	2	4.1	13.1	14.0	11.4
1415+133	PKS 1413+135	0.247	12.39	26.66 ^a	26.01	...	1	3.5	16.5	15.9	12.6
1417+257	2E 1415+2557	0.237	19.00	25.29 ^d	24.74	...	2	2.1	26.5	22.4	16.7
1419+543	OQ 530	0.152	13.17	24.68 ^c	25.81	22.00 ^f	4,7	11.4	0.0	0.0	5.0
1427+238	PKS 1424+240	0.160	15.34	25.69 ^a	25.18	...	2	2.7	21.9	19.3	14.7
1427+541	RGB J1427+541	0.106	14.79	24.38 ^e	23.80	...	2	1.4	36.4	29.2	21.2
1428+426	H 1426+428	0.129	18.41	24.43 ^e	23.93	...	7	1.6	33.5	27.2	19.9
1439+395	PG 1437+398	0.344	16.56	25.98 ^a	25.05	...	2	1.9	29.4	24.3	18.0
1442+120	1ES 1440+122	0.162	16.20	24.80 ^d	24.41	...	3	2.1	27.3	22.9	17.0
1444+636	MS 1443.5+6349	0.298	16.94	24.31 ^c	23.93	0.59	5	1.7	31.6	25.9	19.0
1448+361	RXS J1448.0+3608	0.271*	16.43	25.03 ^d	24.72	...	2	2.5	23.1	20.1	15.2
1458+373	B3 1456+375	0.333	12.86	25.91 ^a	25.93	...	8	5.4	5.7	10.7	9.5
1501+226	MS 1458.8+2249	0.235	14.69	24.73 ^c	25.06	2.66	5	4.6	10.4	12.5	10.5

Table 4. continued.

IAU name	Source	z	$\log \nu'_{\text{peak}}$	$\log P_{408 \text{ M}}$	$\log P_{\text{core}}$	f_{ext}	Refs.	δ	θ_3	θ_5	θ_{10}
1509+559	SBS 1508+561	0.302*	14.83	24.83 ^e	24.80	...	2	3.2	18.3	17.0	13.2
1516+293	RXS J1516.7+2918	0.130	18.56	25.01 ^a	24.13	...	2	1.3	38.1	30.4	22.0
1517+654	1H 1515+660	0.702	17.82	25.72 ^e	25.39	...	2	3.3	17.4	16.4	12.9
1532+302	RXS J1532.0+3016	0.064	16.86	23.87 ^d	23.64	...	2	1.7	32.0	26.1	19.2
1533+342	RXS J1533.4+3416	0.810	17.89	25.78 ^e	25.75	...	2	4.9	8.9	11.9	10.1
1534+372	RGB J1534+372	0.143	13.97	24.02 ^e	23.98	...	2	2.2	25.8	21.8	16.3
1535+533	1ES 1533+535	0.890	19.55	25.96 ^d	25.31	...	3	2.5	22.8	19.9	15.1
1536+016	MS 1534.2+0148	0.312	18.67	25.53 ^c	24.79	8.78	5	1.9	29.1	24.1	17.8
1540+819	1ES 1544+820	0.271*	17.53	25.42 ^e	24.89	...	3	2.3	24.9	21.3	16.0
1540+147	4C 14.6	0.605	14.25	27.58 ^c	27.10	202.00	9	6.3	0.0	8.7	8.4
1542+614	RXS J1542.9+6129	0.302*	14.19	25.27 ^e	25.36	...	2	4.4	11.3	13.0	10.8
1554+201	MS 1552.1+2020	0.222	16.89	25.09 ^c	24.58	6.86	5	2.1	27.3	22.9	17.0
1555+111	PG 1553+11	0.360	15.92	26.29 ^b	26.11	...	2	5.1	7.7	11.4	9.9
1602+308	RXS J1602.2+3050	0.302*	16.27	25.36 ^d	24.65	...	2	1.8	29.6	24.5	18.1
1626+352	RXS J1626.4+3513	0.497	15.05	25.39 ^d	24.95	...	2	2.5	23.0	20.0	15.1
1644+457	RXS J1644.2+4546	0.225	17.28	25.67 ^a	24.89	...	2	1.9	28.4	23.7	17.5
1652+403	RGB J1652+403	0.240	14.80	24.60 ^d	24.19	...	2	1.8	29.6	24.5	18.1
1653+397	MRK 501	0.034	16.17	23.79 ^c	24.51	67.00 ^f	4,7	4.8	9.3	12.0	10.2
1704+716	RXS J1704.8+7138	0.350	15.32	25.06 ^e	24.72	...	2	2.5	23.6	20.4	15.4
1719+177	PKS 1717+177	0.137	12.43	25.19 ^a	25.42	...	2	5.0	7.9	11.5	9.9
1724+400	B2 1722+40	1.049	12.64	27.81 ^a	26.99	...	8	4.7	9.7	12.2	10.3
1725+118	H 1722+119	0.018	15.75	23.06 ^d	22.80	...	2	1.1	41.6	32.9	23.6
1728+502	IZw187	0.055	17.16	24.20 ^b	23.96	...	10	1.9	28.9	24.0	17.8
1739+476	OT 465	0.473*	13.34	27.13 ^b	26.69	...	8	5.4	5.5	10.6	9.4
1742+597	RGBJ 1742+597	0.400	13.75	25.72 ^e	25.49	...	2	3.7	15.0	15.0	12.0
1743+195	NPM1G +19.0510	0.084	17.44	24.40 ^c	24.53	11.60	3	3.2	18.2	17.0	13.2
1745+398	B3 1743+398B	0.267	17.59	26.55 ^a	25.31	...	2	1.7	31.6	25.9	19.0
1747+469	B3 1746+470	1.484	13.30	27.26 ^a	27.41	...	8	11.3	0.0	0.0	5.0
1748+700	S4 1749+70	0.770	13.80	26.63 ^c	26.91	45.70 ^f	4,14	9.9	0.0	0.0	5.8
1749+433	B3 1747+433	0.473*	13.08	26.62 ^a	26.21	...	8	4.5	11.1	12.9	10.7
1750+470	RXS J1750.0+4700	0.160	18.31	25.28 ^a	23.78	...	2	0.7	55.5	42.7	30.2
1751+096	PKS 1749+096	0.322	11.33	24.92 ^c	26.99	2.00	14	37.1	0.0	0.0	0.0
1756+553	RXS J1756.2+5522	0.271*	19.74	24.72 ^e	24.26	...	2	1.8	29.7	24.6	18.1
1757+705	MS 1757.7+7034	0.407	13.37	24.65 ^c	24.64	0.62	5	3.0	19.3	17.6	13.6
1800+784	S5 1803+784	0.680	13.35	27.57 ^e	27.36	...	4,15	8.5	0.0	4.7	6.7
1806+698	3C 371	0.051	14.42	25.87 ^c	24.95	990.00	4,7	1.8	30.4	25.0	18.4
1808+468	RGB J1808+468	0.450	14.34	25.85 ^e	25.33	...	2	2.8	20.8	18.6	14.3
1811+442	RGB J1811+442	0.350	15.30	25.92 ^e	24.26	...	2	0.8	52.3	40.4	28.7
1813+317	B2 1811+31	0.117	15.34	25.00 ^b	24.37	...	2	1.7	31.1	25.5	18.8
1824+568	4C 56.27	0.664	12.56	28.02 ^c	26.99	452.00	9	4.1	13.2	14.0	11.4
1829+540	RXS J1829.4+5402	0.302*	15.06	25.73 ^e	24.61	...	2	1.3	37.1	29.7	21.5
1838+480	RXS J1838.7+4802	0.300	13.24	25.05 ^d	24.71	...	2	2.5	23.6	20.4	15.4
1841+591	RGB J1841+591	0.530	14.94	25.68 ^e	24.64	...	2	1.4	35.4	28.5	20.7
1853+672	1ES 1853+671	0.212	16.25	23.81 ^c	24.12	0.40	3	3.0	19.5	17.7	13.7
1927+612	S4 1926+61	0.473*	12.72	26.62 ^b	26.67	...	8	7.7	0.0	6.3	7.3
1959+651	1ES 1959+650	0.047	17.33	23.01 ^c	24.10	1.60	3	5.2	6.9	11.1	9.7
2005+778	S5 2007+77	0.342	12.39	26.14 ^c	26.38	28.90	9	7.7	0.0	6.2	7.3
2009+724	S5 2010+72	0.473*	12.94	27.02 ^e	26.90	...	8	7.5	0.0	6.7	7.5
2022+761	S5 2023+76	0.473*	13.54	26.65 ^e	26.39	...	13	5.4	5.7	10.7	9.5
2039+523	1ES 2037+521	0.053	15.60	22.27 ^c	23.31	0.23	3	3.6	16.0	15.6	12.4
2134-018	PKS 2131-021	1.285	12.04	27.93 ^c	27.87	70.80	14	11.9	0.0	0.0	4.7
2145+073	MS 2143.4+0704	0.237	13.61	25.13 ^c	24.79	6.60	5	2.5	22.9	20.0	15.1
2152+175	PKS 2149+17	0.473*	13.00	26.03 ^c	26.57	36.70 ^f	4	10.4	0.0	0.0	5.5
2202+422	BL LAC	0.070	13.15	24.21 ^c	25.73	40.00 ^f	4,7	14.5	0.0	0.0	3.5
2250+384	B3 2247+381	0.119	15.35	24.64 ^a	24.29	...	2	2.0	27.6	23.1	17.2

Table 4. continued.

IAU name	Source	z	$\log \nu'_{\text{peak}}$	$\log P_{408 \text{ M}}$	$\log P_{\text{core}}$	f_{ext}	Refs.	δ	θ_3	θ_5	θ_{10}
2257+077	PKS 2254+074	0.190	13.31	24.78 ^c	25.66	17.00 ^f	9,10	8.9	0.0	4.0	6.4
2319+161	Q J2319+161	0.302*	15.29	25.13 ^d	24.58	...	2	2.0	27.9	23.3	17.3
2322+346	TEX 2320+343	0.098	16.68	24.59 ^b	23.82	...	2	1.2	39.4	31.3	22.6
2323+421	1ES 2321+419	0.059	13.05	23.09 ^d	23.18	...	11	1.7	31.5	25.8	18.9
2329+177	1ES 2326+174	0.213	17.84	24.64 ^d	24.30	...	3	2.0	27.4	23.0	17.1
2339+055	MS 2336.5+0517	0.740	14.89	25.74 ^d	24.88	...	5	1.8	30.0	24.7	18.2
2347+517	1ES 2344+514	0.044	15.86	23.30 ^c	23.97	3.58	3	3.6	15.6	15.3	12.2
2350+196	MS 2347.4+1924	0.515	15.72	24.80 ^d	24.29	...	5	1.8	30.0	24.8	18.3

Notes: Col. 1: the source IAU name (J2000). Col. 2: the source alias name. Col. 3: the redshift. '*' indicate that the redshift is unknown, and taken as the average redshift of LBL/IBL/HBL subclass. Col. 4: the intrinsic synchrotron peak frequency after excluding the Doppler factor. Col. 5: the total radio power at 408 MHz (notes: 'a' – from 408 MHz; 'b' – from 360 MHz; 'c' – from extended flux; 'd' – from total 1.4 GHz; 'e' – from 330 MHz). Col. 6: the 5 GHz core luminosity. Col. 7: the 5 GHz extended flux density in mJy, 'f' indicates the extend flux at 1.4 GHz. Col. 8: the references for core and extended flux: (1: Liu & Zhang (2002) 2: Laurent-Muehleisen et al. (1999) 3: Perlman et al. (1996) 4: Rector & Stocke (2001) 5: Cavallotti et al. (2004) 6: Cassaro et al. (1999) 7: Giroletti et al. (2004b) 8: Taylor et al. (1996) 9: Murphy et al. (1993) 10: Laurent-Muehleisen et al. (1993) 11: Kollgaard et al. (1996b) 12: Rector et al. (2003) 13: Taylor et al. (1994) 14: Rector & Stocke (2003) 15: Cassaro et al. (2002) 16: Augusto et al. (1998) 17: Rector et al. (2000)). Col. 9: the Doppler factor. Cols. 10–12: the viewing angle of $\Gamma = 3, 5$ and 10, respectively.