THE RADIO STRUCTURE OF HIGH-ENERGY–PEAKED BL LACERTAE OBJECTS

TRAVIS A. RECTOR
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; trector@nrao.edu

DENISE C. GABUZDA
Department of Physics, National University of Ireland, University College, Cork, Ireland

AND

JOHN T. STOCKE
Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389

Received 2002 October 18; accepted 2002 December 4

ABSTRACT

We present VLA and first-epoch VLBA observations that are part of a program to study the parsec-scale radio structure of a sample of 15 high-energy–peaked BL Lacertae objects (HBLs). The sample was chosen to span the range of logarithmic X-ray to radio flux ratios observed in HBLs. As this is only the first epoch of observations, proper motions of jet components are not yet available; thus, we consider only the structure and alignment of the parsec- and kiloparsec-scale jets. Like most low-energy–peaked BL Lacertae objects (LBLs), our HBL sample shows parsec-scale core-jet morphologies and compact, complex kiloparsec-scale morphologies. Some objects also show evidence for bending of the jet 10–20 pc from the core, suggesting interaction of the jet with the surrounding medium. Whereas LBLs show a wide distribution of parsec- to kiloparsec-scale jet misalignment angles, there is weak evidence that the jets in HBLs are more well aligned, suggesting that HBL jets are either intrinsically straighter or are seen further off-axis than LBL jets.

Key words: BL Lacertae objects: general

1. INTRODUCTION

BL Lacertae objects are an extreme type of active galactic nuclei (AGNs), whose hallmark is their “featureless” optical spectrum. By definition, any emission lines present must have rest $W_\lambda \leq 5$ Å; e.g., Stocke et al. (1991). BL Lac objects are a member of the blazar class; like other blazars, they are characterized by their rapid variability, their polarized optical and radio emission, and their flat-spectrum radio emission. See Urry & Padovani (1995) for an excellent summary of their properties.

Due to their luminous emission at these wavelengths, BL Lac objects have been primarily discovered via X-ray and radio surveys; thus, traditionally they have been labeled as radio-selected and X-ray–selected (RLBs and XBLs, respectively). In recent years this terminology has given way to a more physically meaningful classification based upon the overall spectral energy distribution (SED) of the object. In “low-energy–peaked” blazars (LBLs), the peak of the synchrotron radiation occurs at radio/IR wavelengths, whereas in “high-energy–peaked” blazars (HBLs) this peak occurs in the UV/X-ray. Historically, optical surveys have not been efficient in discovering BL Lac objects (Fleming et al. 1993; Jannuzi 1990). It is therefore not surprising that, until recently, known BL Lac objects have shown a bimodal distribution of logarithmic X-ray to radio flux ratios, $\log (f_x/f_r)$ from 1 keV to 5 GHz, with an approximate dividing line defined by $\log (f_x/f_r) \sim -5.5$ (Wurtz, Stocke, & Yee 1996). For the most part XBLs are HBLs and RLBs are LBLs, although exceptions do exist (e.g., Mrk 501 is an HBL in the 1 Jy RRL sample). We choose to use the term HBL when referring to the BL Lac objects studied herein because all were chosen with a log $(f_x/f_r) \geq -5.5$ criterion.

New surveys, e.g., the ROSAT–Green Bank (RGB) survey (Laurent-Muehleisen et al. 1999) and the DXRBS survey (Perlman et al. 1998), have found BL Lac objects with intermediate log $(f_x/f_r)$ values, indicating a continuum of SEDs in BL Lac objects and likely rendering the LBL/ HBL terminology obsolete. The detailed properties of these new BL Lac objects with intermediate log $(f_x/f_r)$ values are not yet well known. So, although LBLs and HBLs have different observed properties (Urry & Padovani 1995 and references therein), it is not yet known whether LBLs and HBLs are distinct classes of AGNs or merely extremes of a continuum of properties for a single class of AGNs. We have therefore chosen to include three intermediate objects from the RGB sample in our sample of study.

Most BL Lac objects are believed to be low-power radio galaxies whose jet axes are oriented at small angles to the line of sight; and as such their jets are relativistically beamed (e.g., Orr & Browne 1982; Wardle, Moore, & Angel 1984; Urry & Padovani 1995). It has been proposed that HBLs and LBLs are both beamed, low-luminosity FR-I radio galaxies and that the observed differences between the two classes is a result of orientation. In this unification model, hereafter the “orientation” model, HBLs are believed to be viewed further from the jet axis than LBLs (Jannuzi, Elston, & Smith 1994; Perlman & Stocke 1994). The comparable X-ray luminosities for HBLs and LBLs require that either the beam pattern or physical jet opening angle for the X-ray emission is larger than that for the radio emission (e.g., Stocke 1989; Urry, Padovani, & Stickel 1991; Ghisellini et al. 1993; Celotti et al. 1993). Several observed properties are consistent with this hypothesis. Compared to LBLs, HBLs are more numerous, their cores are less radio luminous, and they are less optically variable (Jannuzi, Smith, & Elston 1993). HBLs also emit less compact radio emission.
(Perlman & Stocke 1993; Perlman & Stocke 1994; Laurent-Muehleisen et al. 1993), contain larger fractions of starlight in
the optical (Morris et al. 1991), and have smaller degrees of optical polarization, often with a preferred optical polar-
ization angle, $\pm 15^\circ$ (Jannuzi et al. 1994). However, several observed properties which should be independent of orien-
tation, e.g., observed evolution, optical emission-line strengths, and extended radio powers, do not agree between
HBLs and LBLs, indicating that orientation alone is insufficient to explain the observed distinctions between the two
classes (Rector & Stocke 2001). In fact, many LBLs appear to be beamed, high-luminosity FR-Is; and at least one is a
gravitationally lensed object, the “smallest Einstein ring” object 1Jy 0218+357 (O’Dea et al. 1992). The picture seems
to be more clear for HBLs, whose properties are very consistent with being beamed FR-Is (Rector et al. 2000). Several
observations support this picture, e.g., extended radio luminosity and morphology (Antonucci & Ulvestad 1985; Perl-
am & Stocke 1993), host galaxy luminosity and morphology (Abraham, Crawford, & McHardy 1991; Wurtz et al. 1996), and comparative space densities and luminosity functions (Padovani & Urry 1990; Morris et al. 1991).

Alternatively, it has also been suggested that the differ-
ence between LBLs and HBLs lies not in orientation, but in
the high-energy cutoff in their energy distributions, such
that HBLs and LBLs represent a single family of objects
with a smooth energy distribution followed by a sharp cutoff. For LBLs this cutoff occurs in the near-IR/optical and
for HBLs it is at UV/X-ray or higher energies (Giommi & Padovani 1994; Padovani & Giommi 1995; Sambruna et al. 1996). In this model, hereafter the “energy-cutoff” model, HBLs have intrinsically lower radio luminosities than LBLs, and strong selection effects explain why most known BL Lac objects are of the HBL variety.

Observational studies of BL Lac objects at radio wave-
lengths have proven to be an effective test of unification
models for two reasons. First, the kpc-scale extended radio flux is likely unbeamed and is therefore indicative of the
actual AGN power; and second, the core and parsec-scale extended flux is highly beamed and is therefore strongly
dependent on the orientation and relativistic nature of the
jet. If HBLs are seen further off-axis than LBLs, radio images will reveal several distinct trends. First, relativistic
Doppler boosting and apparent proper motion are strongly
sensitive to the orientation angle and bulk Lorentz factor of the
jet. Thus, if seen close to their jet axis, LBLs should be
more core-dominated, show more instances of superluminal motion, and have larger jet-to-counterjet brightness ratios.
And if HBLs and LBLs share the same parent population,
both should have similar jet Lorentz factors. Second, geo-
metrical projection effects will cause jets with intrinsically
small bends to appear highly distorted when seen close to
the line of sight. Thus, the projected jet position angle (P.A.) in these highly inclined objects is very sensitive to
the jet structure. It is known that LBLs show a wide
range of parsec- and kpc-scale jet misalignment angles ($\Delta$P.A. $\equiv [P.A._{\text{kpc}} - P.A._{\text{pc}}]$), presumably from a “knootty” or helical jet seen close to the line of sight (Kollgaard et al. 1992; Conway & Murphy 1993; Appl, Sol, & Vicente 1996). If HBLs are seen further off-axis than LBLs, geometrical projection effects will cause the parsec- and kpc-scale projected jet position angles of HBLs to be more aligned than LBLs.

If the “energy-cutoff” model is correct and there is no
orientation bias, LBLs and HBLs should show similar parsec-
and kpc-scale radio structure, similar distributions of parsec-
and kpc-scale jet misalignment, assuming they share the same parent population. But since LBLs are
more core-dominated, show more instances of superluminal
motion, and have larger jet-to-counterjet brightness ratios.
Thus, if seen close to their jet axis, LBLs should be
more core-dominated, show more instances of superluminal
motion, and have larger jet-to-counterjet brightness ratios.
And if HBLs and LBLs share the same parent population,
both should have similar jet Lorentz factors. But since LBLs
are generally more luminous than HBLs (Fossati et al. 1998), their parsec-scale structures may differ intrinsically from HBLs.

In this paper we present deep VLA and first-epoch VLBA observations of a sample of 15 BL Lac objects that span the
full range of log ($f_{\text{core}}/f_{\text{obs}}$) seen in HBLs ($\S$ 2). These maps are used to compare the parsec and kpc-scale structure of these
objects. In $\S$ 3 we discuss the results of these observations,
compare them to similar studies of LBLs, and discuss their
implications for unification models. As these are only the
first epoch of observations, proper motions of jet compo-
nents are not yet available; thus, we consider only the align-
ment and structure of the parsec-scale jets. In $\S$ 4 we present the conclusions.

2. OBSERVATION AND REDUCTION

Due to their relative radio faintness, few HBLs have been
studied with VLBI techniques. Kollgaard, Gabuzda, & Feigelson (1996) presented images of four HBLs from the bright HEAO-1 survey (Schwartz et al. 1989), all of which have log ($f_{\text{core}}/f_{\text{obs}}$) values close to the LBL/HBL boundary. J. E. Conway et al. (1997 private communication) completed VLBA observations of eight HBLs from the Einstein Medium Sensitivity Survey (Morris et al. 1991; Rector et al. 2000); however, parsec-scale extended structure was not
detected in most of these objects, most likely due to their
faintness ($f_{\text{core}} \approx 25$ mJy at 5 GHz).

In order to better determine the parsec-scale structure of
HBLs, we completed deep VLA and VLBA observations of
a sample of HBLs that covers a factor of $\sim 30$ in log ($f_{\text{core}}/f_{\text{obs}}$). The initial goal was to determine their morphology and core
dominance on VLBI scales as well as to measure the pro-
jected alignment of their parsec- and kpc-scale radio jets. At
the time this project was begun, the availability of phase-
reference calibrators for the VLBA was limited, so we chose
only targets which were likely bright enough for self-calibra-
tion ($f_{\text{core}} \geq 50$ mJy at 4.964 GHz). Since HBLs are for the
most part too radio faint to observe a statistically complete
sample without phase referencing, we chose a sample that
represented the full range of log ($f_{\text{core}}/f_{\text{obs}}$) values observable in
HBLs, as shown in Figure 1. Our sample was selected primar-
ily from the Einstein “Slew” Survey (1ES; Perlman et al. 1996). Objects that are LBL-like [i.e., log ($f_{\text{core}}/f_{\text{obs}}$) $< -5.5$]
were discarded. This sample was supplemented with three objects from the RGB BL Lac sample to fill in the log ($f_{\text{core}}/f_{\text{obs}}$)
distribution with objects intermediate to LBLs and HBLs.
The final sample consists of 15 HBLs with an even distribu-
tion of log ($f_{\text{core}}/f_{\text{obs}}$) ranging from $-3.96$ to $-5.66$ and is com-
pared to the complete 1 Jy BL Lac sample in Figure 1.

A summary of the sample properties is given in Table 1.
The columns are (1) the object name; (2–3) the right ascen-
sion and declination in $J2000$ coordinates; (4) the log ($f_{\text{core}}/f_{\text{obs}}$)
value (Perlman et al. 1996; Laurent-Muehleisen et al. 1999); and (5) the redshift (Laurent-Muehleisen et al. 1999; Perlman et al. 2003). The redshifts for 1ES 0647+250 and 1ES 1028+511 are marked with a colon because they are
tentative.
2.1. VLBA Observations

Twelve BL Lac objects in our sample were observed with the NRAO Very Long Baseline Array (VLBA) on 1997 May 17. We chose to observe at 4.964 GHz in order to obtain both high resolution and high sensitivity to maximize the probability of detecting and resolving faint VLBI jets in these compact objects. A single 24 hour time allocation was used with the complete VLBA array of 10 \( \frac{25}{\text{m}} \) antennas. This allowed approximately twelve 6.5 minute scans per source, which were well spaced in hour angle for optimal \((u, v)\) plane coverage. To minimize potential phase and amplitude errors due to poor source positions in the correlator model, high-resolution “snapshots” were completed with the NRAO Very Large Array (VLA) B array at 3.6 cm prior to the VLBA observations to obtain core positions with \(0.01\) accuracy. These are the positions given in Table 1. The data were initially calibrated with the AIPS software package in the standard manner. Self-calibration and imaging were then done with the DIFMAP software package (Shepherd 1997). The resultant maps each have an rms noise level of \(\sigma \approx 0.1 \text{ mJy beam}^{-1}\). The three RGB sources in our

This allowed approximately twelve 6.5 minute scans per source, which were well spaced in hour angle for optimal \((u, v)\) plane coverage. To minimize potential phase and amplitude errors due to poor source positions in the correlator model, high-resolution “snapshots” were completed with the NRAO Very Large Array (VLA) B array at 3.6 cm prior to the VLBA observations to obtain core positions with \(0.01\) accuracy. These are the positions given in Table 1. The data were initially calibrated with the AIPS software package in the standard manner. Self-calibration and imaging were then done with the DIFMAP software package (Shepherd 1997). The resultant maps each have an rms noise level of \(\sigma \approx 0.1 \text{ mJy beam}^{-1}\). The three RGB sources in our

---

**TABLE 1**

| Object          | R.A. (J2000)   | Decl. (J2000)  | \(\log (f_x/f_r)\) | z     |
|-----------------|---------------|----------------|-------------------|------|
| 1ES 0033+595    | 00 35 52.644  | +59 50 04.59   | -4.07             | 0.086|
| 1ES 0229+200    | 02 32 48.616  | +20 17 17.45   | -4.23             | 0.139|
| 1ES 0414+009    | 04 16 52.494  | +01 05 23.91   | -3.88             | 0.287|
| 1ES 0647+250    | 06 50 46.489  | +25 02 59.63   | -4.09             | 0.203|
| RGB 0656+426    | 06 56 10.72   | +42 37 02.7    | -5.49             | 0.059|
| 1ES 0806+524    | 08 09 49.188  | +52 18 58.24   | -4.69             | 0.136|
| 1ES 1028+511    | 10 31 18.524  | +50 53 35.79   | -3.96             | 0.359|
| 1ES 1212+078    | 12 15 10.977  | +07 32 04.67   | -5.14             | 0.135|
| 1E 1415+259     | 14 17 56.680a | +25 43 26.24   | -4.56             | 0.237|
| RGB 1427+238    | 14 27 00.392b | +23 48 00.04   | -5.60             | 0.360|
| 1ES 1553+113    | 15 55 43.044  | +11 11 24.37   | -4.99             | 0.083|
| 1ES 1741+196    | 17 43 57.838  | +19 35 08.99   | -4.89             | 0.267|
| RGB 1745+398    | 17 45 37.71   | +39 51 31.8    | -5.66             | 0.048|
| 1ES 1959+650    | 19 59 59.852  | +65 08 54.69   | -4.43             | 0.048|
| 1ES 2344+514    | 23 47 04.838  | +51 42 17.88   | -4.87             | 0.044|

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* The core position for 1E 1415 +259 was determined from the FIRST survey.
* The core position for RGB 1427 +238 was reported in Ma et al. 1998.
sample were observed by Bondi et al. (2001) and Fey & Charlot (2000).

All of the objects except for 1ES 0647+250 and 1ES 1028+511 are clearly resolved; however, these two objects do show evidence for very faint extended structure. In all sources 60%–90% of the VLA core flux, as determined by snapshots in Perlman et al. (1996), was detected on parsec scales. All of the resolved objects show a core-jet morphology, as is typical of LBLs and core-dominated quasars (Pearson & Readhead 1988). All are core dominated on parsec scales. All of the resolved objects show a core-jet morphology, as is typical of LBLs and core-dominated quasars (Pearson & Readhead 1988). All are core dominated on parsec scales. All of the resolved objects show a core-jet morphology, as is typical of LBLs and core-dominated quasars (Pearson & Readhead 1988). All are core dominated on parsec scales. All of the resolved objects show a core-jet morphology, as is typical of LBLs and core-dominated quasars (Pearson & Readhead 1988). All are core dominated on parsec scales.

2.2. VLA Observations

Eleven BL Lac objects in our sample were observed with the VLA on 1998 October 10. We chose to observe with the B array at 1.425 GHz with a 50 MHz bandwidth to maximize sensitivity to extended, steep-spectrum structure while achieving ~4′ resolution. The B array was chosen based upon the redshifts of the objects in our sample to avoid over-resolution of the extended structure. Three or four 8 minute scans, each bracketed by a 90 s scan on a primary VLA flux calibrator, were made for each source. Scans were spaced to optimize coverage in the (u, v) plane. Objects that were sufficiently resolved in previous efforts (Laurent-Muehleisen et al. 1993; Perlman et al. 1996) were not reobserved here.

Epoch 1995.2 VLA values were used to flux calibrate the maps using multiple observations of 3C 286. Since these sources are highly core dominated, a point source model was assumed to start the self-calibration process. Phase-only self-calibration in decreasing solution time intervals was used for the first four iterations. Amplitude and phase self-calibration were then used until the maximum dynamic range was achieved, usually requiring only one or two more iterations. The AIPS task IMAGR was used to generate the maps and clean components. Robust weighting (ROBUST = 0.5) was used to achieve a smaller beam FWHM with only a 10%–12% increase in noise over natural weighting; see Briggs (1995) for an explanation. The core flux densities were measured by fitting the core with a single Gaussian with the synthesized beam’s parameters.

The extended flux was determined by measuring the total flux density with a box enclosing the entire source and then subtracting the core flux density.

For unresolved sources, conservative upper limits on extended radio flux densities were calculated by assuming that each source has uniformly bright extended emission at the 1σ detection level over a 3000 kpc2 area surrounding the core.

2.3. Summary of Radio Properties

The VLA and VLBA maps are shown in Figures 2–20. A summary of the radio properties is given in Table 2. The columns are (1) the object name; (2–3) the 1.425 GHz VLA core and extended flux densities (mJy); (4) the VLA jet position angle (5–6) the 4.964 GHz VLBA core and extended flux densities (mJy); and (7) the VLBA jet position angle.

The errors in the flux densities are ~0.1 mJy beam−1 for both the VLA and VLBA maps. The cumulative errors in the extended flux densities depend upon the solid angular extent of the measured flux. Note that, as discussed in § 3, measured jet position angles are subjective; and in most objects the jet morphology is more complex than what can be modeled with a single P.A. value. Thus, the discussion of individual sources below should be consulted for each source.

2.4. Discussion of Individual Sources

1ES 0033+595.—The VLBA map (Fig. 2) shows a diffuse jet extending in P.A. = +65°. It is not clear whether or not the parsec-scale jet is well collimated. There is some

| Object       | \( f_{\text{core}} \) (mJy) | \( f_{\text{ext}} \) (mJy) | P.A.\(^\text{a}\) (deg) | \( f_{\text{core}} \) (mJy) | \( f_{\text{ext}} \) (mJy) | P.A.\(^\text{a}\) (deg) |
|--------------|-----------------------------|-----------------------------|--------------------------|-----------------------------|-----------------------------|--------------------------|
| 1ES 0033+595 | 90.4                        | 61.3 ± 12                   | +62                      | 39.7                        | 12.8 ± 0.8                  | +65                      |
| 1ES 0229+200 | 51.8                        | 34.7 ± 8.7                  | +100                     | 22.7                        | 7.7 ± 0.8                   | +170                     |
| 1ES 0414+009 | ...                        | ...                        | ...                      | 36.4                        | 12.9 ± 0.8                  | +68                      |
| 1ES 0647+250 | ...                        | ...                        | ...                      | 46.0                        | 11.0 ± 0.7                  | ...                      |
| RGB 0656+426 | 252.8                       | 699 ± 32                    | -140                     | ...                        | ...                        | -150                     |
| 1ES 0806+524 | 189.1                       | <10                        | ...                      | 111.2                       | 39 ± 1.1                    | +13                      |
| 1ES 1028+511 | 215.7                       | <15                        | ...                      | 22.4                        | 3.5 ± 0.4                   | ...                      |
| 1ES 1212+078 | 87.4                        | 48.6 ± 12.9                 | +178                     | 36.3                        | 16.6 ± 0.8                  | +92                      |
| 1E 1415+259  | ...                        | ...                        | ...                      | 8.7                         | 17.1 ± 0.7                  | ...                      |
| RGB 1427+238 | 331.7                       | 130.2 ± 2.9                 | -10                      | ...                        | ...                        | ...                      |
| 1ES 1553+113 | 271.1                       | 13.9 ± 4.8                  | +160                     | 258.7                       | 21.8 ± 0.6                  | +48                      |
| 1ES 1741+196 | ...                        | ...                        | +91                      | 83.5                         | 38.2 ± 0.9                  | +86                      |
| RGB 1745+398 | 372.5                       | 272 ± 5.5                   | +105                     | ...                        | ...                        | -175                     |
| 1ES 1959+650 | 227.5                       | 18 ± 10                     | -5                       | 181.7                       | 37.7 ± 1.0                  | -5                       |
| 1ES 2344+514 | 217.0                       | 128 ± 50                    | +105                     | 109.                         | 59.7 ± 2.0                  | +145                     |

\(^a\) Please read §§ 2.4 and 3 regarding the measurement of jet position angles.
evidence for the jet curving to the north. Thus, the measured P.A. is likely resolution dependent. The VLA image (Fig. 3) of this source shows a diffuse halo surrounding the core. Jets are not clearly resolved; however, the core is elongated in the P.A. = 62° and P.A. = 105° directions, so the parsec- and kpc-scale jets appear to be well aligned if the parsec-scale jet is assumed to be related with the P.A. = 62° extension of the VLA core. HST PC observations of this object shows two unresolved sources of similar brightness separated by 1°58 (Scarpa et al. 1999), which might have been explained as multiple images of a gravitationally lensed system. However, the VLA astrometric observations presented here do not detect a second radio source, ruling out that possibility.

1ES 0229+200.—The VLBA map (Fig. 4) shows a jet extending to the south (P.A. = 170°), with weak evidence for a broad jet opening angle of ~30°. The VLA image (Fig. 5) shows curved jets to the north and south, both of

Fig. 2.—VLBA 4.964 GHz map of 1ES 0033+595. The contour levels are -0.54%, 0.54%, 1.07%, 2.15%, 4.30%, 8.59%, 17.18%, 34.37%, and 68.73% of the peak flux of 3.72 × 10^{-2} Jy beam^{-1}. The beam, shown in the lower left corner, has a FWHM of 2.26 × 1.80 mas, P.A. = -17°. The date of observation is shown in the upper right corner of the map.

Fig. 3.—VLA 1.425 GHz map of 1ES 0033+595. The beam is shown in the lower left corner. The contour levels are 0.5%, 1%, 2%, 5%, 10%, 20%, 50%, and 100% the peak flux of 8.39 × 10^{-2} Jy beam^{-1}.

Fig. 4.—VLBA 4.964 GHz map of 1ES 0229+200. The contour levels are -0.91%, 0.91%, 1.82%, 3.63%, 7.27%, 14.54%, 29.07%, and 58.15% of the peak flux of 2.20 × 10^{-2} Jy beam^{-1}. The beam, shown in the lower left corner, has a FWHM of 2.97 × 1.78 mas, P.A. = -3°. The date of observation is shown in the upper right corner of the map.

Fig. 5.—VLA 1.425 GHz map of 1ES 0229+200. The beam is shown in the lower left corner. The contour levels are 0.5%, 1%, 2%, 5%, 10%, 20%, 50%, and 100% the peak flux of 4.99 × 10^{-2} Jy beam^{-1}.
which curve to the west. Measuring the jet position angles from the inner contours gives \( \text{P.A.} = -10^\circ \) and \( \text{P.A.} = 180^\circ \). The VLBA jet appears to be well aligned with the southern jet (\( \Delta \text{P.A.} = 10^\circ \)).

**1ES 0414+009.**—The VLBA map (Fig. 6) resolves a jet that initially extends to the east-northeast (P.A. = +68\(^\circ\)) of the core. There is also weak, extended (\( \sim 4 \sigma \)) emission to the southeast of the jet, which suggests either that the jet is collimated and bends to the south 10 pc from the core, or that the projected jet opening angle is wide (\( \sim 60^\circ \)). If the jet does indeed bend to the southeast, the misalignment angle could be as large as \( \Delta \text{P.A.} \approx 60^\circ \); however, the inner portion of the jet is well aligned (\( \Delta \text{P.A.} = 5^\circ \)) to the kpc-scale jet shown in Figure 3 of Laurent-Muehleisen et al. (1993).

**1ES 0647+250.**—The VLBA map (Fig. 7) of this source does not show a distinct jet but there is some evidence for a faint, diffuse halo around the core, with weak evidence of elongation of the core to the north at P.A. = -10\(^\circ\). VLA snapshot observations (Perlman & Stocke 1993) of this source show a jet extending to the southwest (P.A. = -124\(^\circ\)) as well as a possible extension to the northwest; although the reality of the extended structure is questioned because of the poor quality of this map. A deep VLA map is necessary to better determine the kpc-scale structure of this source. Because of the uncertainty of the VLA and VLBA structure a \( \Delta \text{P.A.} \) for this source is not considered in analysis. The redshift of 1ES 0647+250 is tentative and must be confirmed by further optical spectroscopy.

**RGB 0656+426.**—The VLA map of this source (Fig. 8) shows a jet-core-jet source embedded in a bright halo, with a jet at P.A. = +40\(^\circ\) and a collinear counterjet. The VLBA map of this source (Bondi et al. 2001) resolves a well-collimated jet at P.A. = -150\(^\circ\), which is well aligned (\( \Delta \text{P.A.} = 10^\circ \)) with the counterjet. The halo morphology on kpc scales suggests this object is seen very close to the jet axis.

**1ES 0806+524.**—The VLBA map (Fig. 9) shows a jet to the north with P.A. = +13\(^\circ\). Very faint, diffuse extended emission surrounds the jet, suggesting it has a broad opening angle that may be as wide as 70\(^\circ\). A deep VLA map of this source is unresolved; no extended flux is detected at the 0.2 mJy beam\(^{-1}\) level.
1ES 1028+511.—This source is unresolved by both the VLBA (this paper) and in a VLA snapshot by Perlman et al. (1996). The VLBA core flux is only \( \frac{1}{2} \)\% of the VLA core flux, indicating either variability or extended flux which is too faint or resolved out on parsec scales. The redshift for this source is tentative and must be confirmed by further optical spectroscopy.

1ES 1212+078.—The VLBA map of this source (Fig. 10) shows a well-collimated jet extending to the east (P.A. = +92°). The jet is straight as far as 50 pc; and it has several discrete components. A deep VLA map of this source (Fig. 11) shows an unusual, diffuse halo around the source, with no clear evidence of a jet in any direction. Measuring from the core to the brightest hot spot gives P.A. = +178° and \( \Delta \)P.A. = 86°, although this is highly speculative. However, a very large \( \Delta \)P.A. does seem likely for this source.

1E 1415+259.—This source was detected by the VLBA, but due to its faintness its extended structure cannot be modeled.

RGB 1427+238.—The VLA map of this source (Fig. 12) shows a compact structure that consists of a core and either a halo or roughly colinear jets extending north P.A. = \(-10°\) and south P.A. = \(-175°\). The VLBA source is unresolved on the 1.1 mJy beam\(^{-1}\) level (Fey & Charlot 2000).

1ES 1553+113.—The VLBA map (Fig. 13) shows a jet extending to the northeast (P.A. = +48°). Beyond 20 pc the jet is very faint and diffuse, thus it is difficult to determine the opening angle or if the jet is bent.

No jet continuous from the core is detected in a deep VLA map (Fig. 14); however, a faint lobe is detected south of the core, with a weak “hot spot” at P.A. = +160°, giving a large misalignment angle of \( \Delta \)P.A. = 112° if we assume the VLBA jet is related to the southern lobe.

1ES 1741+196.—The VLBA map of this source (Fig. 15) shows a well-collimated jet extending to the east (P.A. = +86°). The jet is very straight, although it does show evidence for \( 5° \) bend to the south, 15–20 pc from the core.

The VLA snapshot of this source (Perlman et al. 1996) shows a jet that is well aligned with the parsec-scale jet (\( \Delta \)P.A. = \( 5° \)).
RGB 1745+398.—RGB 1745+398 is the unusual object to the north in the VLA map shown in Figure 16. It has an edge-darkened, FR-I morphology that is highly distorted. One jet appears to emerge from the core at P.A. = −28° before bending to the west. The other jet emerges from the core at P.A. = +105° before bending to the southeast. Both jets show sharp bends, of up to 70°. This object lies close to the center of a moderately massive galaxy cluster (Nilsson et al. 1999); thus, its distorted shape may be the result of interaction with either the ICM or the halos of other cluster members. This hypothesis is supported by the presence of another highly distorted radio source to the southwest of RGB 1745+398 in Fig. 16, which may also be a cluster member. A VLBA map of RGB 1745+398 (P. Kharb 2002, private communication) shows a component emerging due south from the core at P.A. = −175°. Thus, ΔP.A. = 80° in this very distorted source.

Fig. 12.—VLA 1.425 GHz map of RGB 1427+238. The beam is shown in the lower left corner. The contour levels are 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20%, 50%, and 100% the peak flux of 3.102 × 10⁻¹ Jy beam⁻¹.

Fig. 13.—VLBA 4.964 GHz map of 1ES 1553+113. The contour levels are −0.08%, 0.08%, 0.16%, 0.32%, 0.63%, 1.27%, 2.53%, 5.06%, 10.12%, 20.24%, 40.49%, and 80.98% of the peak flux of 2.529 × 10⁻¹ Jy beam⁻¹. The beam, shown in the lower left corner, has a FWHM of 3.42 × 1.70 mas, P.A. = 67°. The date of observation is shown in the upper right corner of the map.

Fig. 14.—VLA 1.425 GHz map of 1ES 1553+113. The beam is shown in the lower left corner. The contour levels are 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20%, 50%, and 100% the peak flux of 2.706 × 10⁻¹ Jy beam⁻¹.

Fig. 15.—VLBA 4.964 GHz map of 1ES 1741+196. The contour levels are −0.26%, 0.26%, 0.53%, 1.05%, 2.11%, 4.21%, 8.42%, 16.84%, 33.69%, and 67.38% of the peak flux of 7.60 × 10⁻² Jy beam⁻¹. The beam, shown in the lower left corner, has a FWHM of 3.10 × 1.67 mas, P.A. = −5.4°. The date of observation is shown in the upper right corner of the map.
IES 1959+650.—The VLBA map (Fig. 17) shows a broad, diffuse jet to the north (P.A. ≈ −5°). The opening angle of the jet is wide (~55°). The core is unresolved in a deep VLA map (Fig. 18); however, very faint extended flux is detected to the north (P.A. ≈ −5°) and south (P.A. ≈ +175°) of the core. Thus, the VLBA jet appears to be well aligned with the northern lobe.

IES 2344+514.—The VLBA map (Fig. 19) shows a jet extending to the southeast (P.A. = +145°); it appears to be well collimated for about 10 pc before bending 25° to the south and broadening into a cone with a ~35° opening angle. A deep VLA map (Fig. 20) detects emission extending to the east (P.A. = +105°) in a 50° cone. The ΔP.A. for this source is at least 40°.
3. RESULTS AND DISCUSSION

Previous studies of the VLBI structure of BL Lac objects, nearly all of which were of LBLs, have shown that large misalignment angles are common in these objects (Kollgaard et al. 1992; Appl et al. 1996; Cassaro et al. 2002). This is to be expected in sources that are seen close to the line of sight, as projection effects will magnify the apparent distortion from intrinsic bends and complex structure within these jets.

Measuring the parsec-scale jet position angles in BL Lac objects is very difficult for several reasons. Many of these objects show jets which bend within several parsecs from the core; and in many cases the emission where the bending occurs is very faint. Thus, the measured P.A. is very sensitive to the linear resolution and the sensitivity of the observations, which of course depend on the observed wavelength, the distance to the object, the (u, v) coverage, and the overall quality of the observations. The parsec-scale jets seen in Mrk 501 and 1Jy 1147+245 are good examples of this problem (Conway & Wrobel 1995; Gabuzda et al. 1999; Cassaro et al. 2002). Adding another dimension to the problem, there is evidence that the jet trajectory for some of these objects can change on short timescales; e.g., 1Jy 0735+178 (Gómez et al. 2001).

Like the VLBI maps, the measured jet position angles in the VLA maps are also dependent on sensitivity and resolution; e.g., the measured position angles can differ by as much as 60° based upon the resolution of the maps for 1Jy 0814+425 and 1Jy 2131–021 (Cassaro et al. 2002; Rector & Stocke 2003). Additionally, the kpc-scale structure of these sources are usually highly distorted, often with a “halo” that surrounds the core with no clear P.A. Thus, it is not surprising that we see such a range of ΔP.A. values, even without considering the enormous difference in physical scales between the VLA and VLBI maps and the physical environments through which a jet propagates from the core to kiloparsec scales.

Despite the uncertainties inherent in such measurements, we have measured parsec- and kpc-scale jet position angles for our HBL sample. We include the four HBLs observed by Kollgaard et al. (1996) into our HBL sample.

For comparison, we consider all of the LBLs in the complete 1 Jy sample (Stickel et al. 1991) for which high–dynamic-range VLA maps exist (Rector & Stocke 2001, 2003, and references therein) and that have been studied in detail with VLBI techniques (Cassaro et al. 2002; Fey & Charlot 1997, 2000; Fomalont et al. 2000; Gabuzda, Pushkarev, & Cawthorne 1999, 2000; Gabuzda & Cawthorne 2000; Kellermann et al. 1998; Ros et al. 2001; Shen et al. 1997, 1998). For consistency, we measure jet position angles from these maps using the methodology described below rather than use published values.

There are only a few cases where the jet P.A. is unambiguous. Thus, the parsec- and kpc-scale jet position angles were measured with the following methodology. For both the VLA and VLBI maps the P.A. is measured from the core through contiguous jet components that are more than 2–3 σ detections. In some cases the P.A. on VLBI scales is uncertain because the jet is diffuse with a broad opening angle (e.g., 1ES 0806+524 and 1ES 1959+650). In these cases the P.A. is measured either down the center of the jet or along the brightest contours within the jet. Also, there are four objects in our HBL sample (1ES 0033+595, 1ES 0414+009, 1ES 1741+196, and 1ES 2344+514) that have bright, well-collimated parsec-scale jets close to the core and show evidence of bending further from the core. For these objects the jet is diffuse with a broad opening angle (e.g., 1ES 0806+524 and 1ES 1959+650). For consistency, we measure jet position angles from the bright jet components near the core. In three of the four objects the kpc-scale structure is well aligned with these measurements; the exception is 1ES 2344+514, for which no measurement of the P.A. will align it with the VLA P.A. Thus, it is possible that the jets in these objects are bending and may not be well aligned as measured.

The better alignment of the parsec-scale jet near the core with the kpc-scale jets in these sources may be the result of collisions with dense clouds of gas near the core. For a powerful jet, such collisions are not effective at deflecting the jet in a coherent manner; however, they may result in temporary distortions of the jets on timescales of <107 yr (De Young 1991; Wang, Witta, & Hooda 2000). Thus, it is possible that the observed VLBI morphologies could be explained by an off-center collision with a dense gas cloud 10–20 pc from the core which distorts the observed P.A. at this distance but does not affect the long-term propagation of the jet to kpc distances.

It is worth noting that Hough et al. (2002) find significant P.A. differences between inner and outer VLBI jet components in a sample of lobe-dominated quasars, wherein the outer VLBI jet components are better aligned with the kiloparsec-scale jets. This suggests that, in quasars at least, jets may distort or bend close to the core before becoming well collimated further from the core. The comparison is limited because quasar jets are of much higher power; and due to the much higher redshift of their quasar sample (z > 1), the VLBI maps in Hough et al. (2002) are studying larger physical scales by a factor of ~10. Also, lobe-dominated quasar jets are seen at large angles to the line of sight and therefore do not suffer from projection effects to nearly the degree as BL Lac objects.
In all of the resolved VLBI maps jet structure is apparent; however, the VLA maps reveal that many of these sources have a "halo" morphology, i.e., extended emission that surrounds the core with no clear jet. For these objects the P.A. is measured to the brightest "hot spot" within the lobe; and for objects that have two distinct lobes and no clear jet, the P.A. is measured to the lobe most likely associated with the parsec-scale jet (i.e., to the lobe which minimizes the value of ΔP.A.). Naturally, ΔP.A. could only be determined for objects that were resolved by both the VLA and with VLBI.

Figure 21 shows the distribution of misalignment angles for the HBLs in our sample and the LBLs in the 1 Jy sample. Unfortunately, in only seven of the 15 HBLs in our sample are jets resolved in both VLA and VLBI images. The parsec- and kpc-scale jets are well aligned (ΔP.A. ≤ 10°) for five of the seven.

In three additional sources a VLA P.A. value was determined by the brightest hot spot in a lobe. In only one of these cases is the parsec-scale jet well aligned with the hot spot. The remaining six sources are unresolved in one or both maps. To this sample we added the four HBLs in Kollgaard et al. (1996), although for only one could a ΔP.A. value be determined. While all four are resolved in VLBI maps, a VLA map of 1ES 1133+704 by Ulvestad & Antonucci (1986) shows a halo morphology with no clear P.A.; and VLA maps of the other sources reliably resolve only 1ES 1727+503 (Ulvestad & Antonucci 1986; Laurent-Muehleisen et al. 1993). In the 1 Jy LBL sample we were able to determine ΔP.A. values for only 18 of 37 objects, with an additional three tentative ΔP.A. values. The difficulty in determining ΔP.A. values in the 1 Jy sample is due to unresolved sources as well as many objects that show halo structures around the core with no resolved jet or hot spots.

Whereas most of the HBLs are well aligned (ΔP.A. ≤ 20°), the LBL sample shows a wide distribution of ΔP.A. values, evenly distributed from 0° to 150°. The distributions of ΔP.A. for HBLs and LBLs are different at the 96% level of confidence using a two-sided Kolmogorov-Smirnov test. Additionally, all four extreme HBLs [log (fα/fγ) > -4.5] with well-measured misalignment angles are very well aligned. While not conclusive, this suggests that HBLs either have intrinsically straighter jets than LBLs, or that HBLs are seen further off-axis than LBLs, such that projection effects are not as important. Clearly larger and statistically complete samples are desirable.

We note that the distribution of ΔP.A. values in the 1 Jy LBL sample is consistent with the distribution of ΔP.A. values seen by Kollgaard et al. (1992). We also note that there is no significant evidence for a bimodal distribution of misalignment angles, with two peaks centered on 0° and 90°, as suggested for BL Lac objects by Appl et al. (1996). Thus, we argue that the 1 Jy LBL sample is consistent with a population of radio galaxies whose jet axes are seen close to the line of sight and that complex bend geometries such as those proposed by Conway & Murphy (1993) are not necessary to explain the distributions of ΔP.A. in either of our samples.

If the orientation hypothesis is correct, that is, if HBLs are simply LBLs seen further from the jet axis, there should be a correlation between log (fα/fγ) and ΔP.A. Because LBLs will appear to be more misaligned due to projection effects. Figure 22 shows the distribution of ΔP.A. as a function of log (fα/fγ) for both samples. There is a weak 2 σ evidence (90% probability) that ΔP.A. and log (fα/fγ) are linearly anticorrelated when the samples are combined; but this anticorrelation is not seen in the LBL sample alone. No correlation is seen between ΔP.A. and z for either the full LBL and HBL sample or amongst the LBLs alone.

4. CONCLUSIONS

We have completed VLA and first-epoch VLBA observations as part of a program to study the parsec-scale radio structure of a sample of 15 HBLs. All of the resolved objects are core dominated in the VLA and VLBA maps, and they show a core-jet morphology on parsec scales, similar to LBLs and core-dominated quasars. Some sources show a well-collimated, parsec-scale jet with discrete components, whereas others show a diffuse jet with a wide opening angle. Some objects also show evidence for the interaction of their parsec-scale jets with a dense gas environment. Further modeling is warranted.

While LBLs show a wide distribution of parsec- and kpc-scale jet alignment angles, most of the HBLs considered here have well-aligned jets, suggesting either that HBL jets are seen further off-axis than LBL jets, or that HBL jets are intrinsically straighter. Complex bend geometries, such as those proposed by Conway & Murphy (1993), are not necessary to explain the observed distributions of misalignment angles.
angles seen in our LBL or HBL samples. There is a hint in our data that extreme HBLs \( \log(f_x/f_r) > -4.5 \) have intrinsically straight jets that are viewed well off-axis in that all four extreme HBLs in our sample have very small (<10%) misalignment angles. Observations of other extreme HBLs are needed to test this preliminary result.

While it is now clear that orientation alone cannot be invoked to unify HBLs and LBLs (Rector & Stocke 2001), selection effects may nonetheless cause LBLs to be seen closer to the jet axis than HBLs. For example, LBLs show optical emission lines which are several orders of magnitude more luminous than HBLs. Thus, LBLs may require larger Doppler factors to sufficiently boost the jet continuum relative to the emission lines to remain within the BL Lac spectral criterion (rest \( W_1 \leq 5 \) Å). Similarly, the bright radio flux limit as well as the flat radio spectrum criterion of the 1 Jy sample may also bias LBLs toward more highly beamed objects, whereas the X-ray surveys used to draw our HBL sample do not have any radio-based selection criteria. Thus, LBLs may be systematically more beamed than HBLs even though they may not necessarily share the same parent population.

Research on BL Lac objects at the University of Colorado was supported by NASA grant NAGW-2675. Part of this work is a part of a Ph.D dissertation submitted to the University of Colorado by T. A. R.

REFERENCES

Abraham, R. G., Crawford, C. S., & McHardy, I. M. 1991, MNRAS, 252, 482
Antonucci, R. R. J., & Ulvestad, J. S. 1985, ApJ, 294, 158
Appl, S., Sol, H., & Vicente, L. 1996, A&A, 310, 419
Bondi, M., Marchá, M. J. M., Dallacasa, D., & Stanghellini, C. 2001, MNRAS, 325, 1109
Briggs, D. 1995, Ph.D. dissertation, New Mexico Inst. Mining and Technology
Cassaro, P., Stanghellini, C., Dallacasa, D., Bondi, M., & Zappalà, R. A. 2002, A&A, 381, 378
Celotti, A., Maraschi, L., Ghisellini, G., Caccianiga, A., & Maccacaro, T. 1993, ApJ, 416, 118
Conway, J. E., & Murphy, D. W. 1993, ApJ, 411, 89
Conway, J. E., & Wrobel, J. M. 1995, ApJ, 439, 98
De Young, D. S. 1991, ApJ, 371, 69
Fey, A. L., & Charlot, P. 1997, ApJS, 111, 95
———. 2000, ApJS, 128, 17
Fleming, T. A., Green, R. F., Jannuzi, B. T., Liebert, J., Smith, P. S., & Fink, H. 1993, AJ, 106, 1729
Fomalont, E. B., Frey, S., Paragi, Z., Gurvits, I. L., Scott, W. K., Taylor, A. R., Edwards, P. G., & Hiroshyshi, H. 2000, ApJS, 131, 95
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Gabuzda, D. C., & Cawthorne, T. V. 2000, MNRAS, 319, 1056
Gabuzda, D. C., Pushkar'ev, A. B., & Cawthorne, T. V. 1999, MNRAS, 307, 725
———. 2000, MNRAS, 319, 1109
Ghisellini, G., Padovani, P., Celotti, A., & Maraschi, L. 1993, ApJ, 407, 65
Giommi, P., & Padovani, P. 1994, MNRAS, 268, L51
Gómez, J. L., Guirado, J. C., Agudo, I., Marscher, A. P., Alberdi, A., Marcaide, J. M., & Gabuzda, D. C. 2001, MNRAS, 328, 873
Hough, D. H., Vermeulen, R. C., Readhead, A. C. S., Cross, L. L., Barth, E. L., Yu, L. H., Beyer, P. J., & Phifer, E. M. 2002, AJ, 123, 1258
Jannuzi, B. T. 1990, Ph.D. thesis, Univ. Arizona
Jannuzi, B. T., Elston, R., & Smith, P. 1994, ApJ, 428, 130
Jannuzi, B. T., Smith, P. S., & Elston, R. 1993, ApJS, 85, 265
Kellermann, K. I., Vermeulen, R. C., Zensus, J. A., & Cohen, M. H. 1998, ApJ, 115, 1295
Kollgaard, R. I., Gabuzda, D. C., & Feigelson, E. D. 1996, ApJ, 460, 164
Kollgaard, R. I., Wardle, J. F. C., Roberts, D. H., & Gabuzda, D. C. 1992, AJ, 104, 1687
Laurent-Muehleisen, S. A., Kollgaard, R. I., Feigelson, E. D., Brinkmann, W., & Siebert, J. 1999, ApJ, 525, 127
Laurent-Muehleisen, S. A., Kollgaard, R. I., Moellenbrock, G. A., & Feigelson, E. D. 1993, AJ, 106, 875
Ma, C., et al. 1998, AJ, 116, 516
Morris, S. L., Stocke, J. T., Gioia, I. M., Schild, R. E., Wolter, A., & Della Ceca, R. 1991, ApJ, 380, 49
Nilsson, K., Takalo, L. O., Pursimo, T., Sillanpää, A., Heidt, J., Wagner, S. J., Laurent-Muehleisen, S. A., & Brinkmann, W. 1999, A&A, 343, 81
O’Dea, C. P., Baum, S. A., Stanghellini, C., Dey, A., van Breugel, W., Deustua, S., & Smith, E. P. 1992, AJ, 104, 1320
Orr, M. J. L., & Browne, I. W. A. 1982, MNRAS, 200, 1067
Padovani, P., & Giommi, P. 1995, ApJ, 444, 567
Padovani, P., & Urry, C. M. 1990, ApJ, 356, 75
Pearson, T. J., & Readhead, A. C. S. 1988, ApJ, 328, 114
Perlman, E. S., Padovani, P., Giovani, P., Sambruna, R., Jones, L. R., Tzioumis, A., & Reynolds, J. 1998, AJ, 115, 1253

Fig. 22.—Misalignment angle \( \Delta P.A. \) for LBLs (squares) and HBLs (triangles) as a function of \( \log(f_x/f_r) \). The dividing line at \( \log(f_x/f_r) \sim -5.5 \) roughly divides HBLs and LBLs.
Perlman, E. S., & Stocke, J. T. 1993, ApJ, 406, 430
———. 1994, AJ, 108, 56
Perlman, E. S., et al. 1996, ApJS, 104, 251
———. 2003, in preparation
Rector, T. A., & Stocke, J. T. 2001, AJ, 122, 565
———. 2003, AJ, submitted
Rector, T. A., Stocke, J. T., Perlman, E. S., Morris, S. L., & Gioia, I. A. 2000, AJ, 120, 1626
Ros, E., Marcaide, J. M., Guirado, J. C., & Pérez-Torres, M. A. 2001, A&A, 376, 1105
Sambruna, R. M. Maraschi, L., & Urry, M. 1996, ApJ, 463, 444
Scarpa, R., Urry, C. M., Falomo, R., Pesce, J. E., Webster, R., O’Dowd, M., & Treves, A. 1999, ApJ, 521, 134
Schwartz, D. A., Brussenden, R. J. V., Tuohy, I. R., Feigelson, E. D., Hertz, P. L., & Remillard, R. A. 1989, BAAS, 21, 777
Shen, Z.-Q., et al. 1997, AJ, 114, 1999
Shen, Z.-Q., et al. 1998, AJ, 115, 1357
Shepherd, M. C. 1997, in ASP Conf. Ser. 125, Astronomical Data Analysis Software and Systems IV, ed. G. Hunt & H. F. Payne (San Francisco: ASP), 77
Stickel, M., Padovani, P., Urry, C. M., Fried, J. W., & Kühr, H. 1991, ApJ, 374, 431
Stocke, J. T. 1989, in BL Lac Objects, ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Heidelberg: Springer), 242
Stocke, J. T., Morris, S. L., Gioia, I. M., Maccacaro, T., Schild, R., Wolter, A., Fleming, T. A., & Henry, J. P. 1991, ApJS, 76, 813
Ulvestad, J. S., & Antonucci, R. R. J. 1986, AJ, 92, 6
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Urry, C. M., Padovani, P., & Stickel, M. 1991, ApJ, 382, 501
Wang, Z., Wiita, P. J., & Hooda, J. S. 2000, ApJ, 534, 201
Wardle, J. F. C., Moore, R. L., & Angel, J. R. P. 1984, ApJ, 279, 93
Wurtz, R., Stocke, J. T., & Yee, H. K. C. 1996, ApJS, 103, 109