AGN jets: from largest to smallest angular scales

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Abstract. Relativistic jets are associated with microquasars and active galactic nuclei (AGN), and thought responsible for the gamma-ray bursts (GRBs). The acceleration, collimation and stability/propagation properties of the observed jets remain key jet issues. Producing and modeling these jets theoretically requires general relativistic or special relativistic magnetohydrodynamics (GRMHD/RMHD) along with the radiation microphysics. The task is to relate the observed emission structure to the radiation microphysics and macroscopic dynamics. In this proceedings article I concentrate on reviewing the development of our understanding of jets in the context of the relativistic jets associated with AGN, what past observations from the largest to the smallest angular scales have revealed, and the questions that might be answered through observing AGN jets at the smallest angular scales.

1. Introduction

The highly collimated jets from active galactic nuclei (AGN) are subject to the Kelvin-Helmholtz (KH) instability when kinetically dominated and, where current flows are high and jets are magnetically dominated, to current driven (CD) instability. Instability is predicted theoretically from the linearized magnetofluid equations or, when the electromagnetic fields exceed the rest mass energy, the force-free “Poynting-flux” approximation. Structures associated with the predicted instabilities are observed in laboratory experiments, in numerical simulations, and in AGN jets. Numerical simulations reveal how structures develop and which structures come to dominate the jet dynamics. Comparison to theoretically predicted structures indicates how observed jet structures are related to macroscopic jet properties. The observation of instability generated structure on AGN jets can be used to provide clues to macroscopic jet properties and at the smallest angular scales to conditions in the jet launching region.

Jets at the larger angular scales are kinetically dominated and may contain pressure equipartition magnetic fields. However, strong magnetic fields will exist close to the acceleration and collimation region. Here GRMHD simulations of jet formation (e.g., Koide et al. 2000; Nishikawa et al. 2005; De Villiers et al. 2003, 2005; Hawley & Krolik 2006; McKinney & Gammie 2004; McKinney 2006; Mizuno et al. 2006) and earlier theoretical work (e.g., Lovelace 1976; Blandford 1976; Blandford & Znajek 1977; Blandford & Payne 1982) suggest the necessity for strong magnetic fields. GRMHD simulations indicate that Poynting flux jets driven by magnetic fields threading a rotating black hole’s ergosphere reside within a broader slower kinetically dominated sheath outflow driven by magnetic fields anchored in the accretion disk (e.g., McKinney 2006; Hawley & Krolik 2006; Mizuno et al. 2006). At small angular scales the TeV BL Lacs require large Lorentz factors that when contrasted with much slower observed proper motions suggest the presence of a spine-sheath jet morphology (Ghisellini et al. 2005).
turn a jet spine sheath configuration may reside in a broader accretion disk wind (e.g., Nishikawa et al. 2005). Such a sheath wind configuration is also indicated by observations indicating QSOs winds with speeds, $\sim 0.1 - 0.4c$, (Chartas et al. 2002, 2003; Pounds et al. 2003a, 2003b; Reeves et al. 2003; Hidalgo et al. 2008).

Multi-epoch observation of emission at the smallest angular scales will provide a window into the spatial and temporal behavior of jets and the workings of the central engines in AGN. In order to place the importance of future work at these smallest angular scales in context, I begin by reviewing what has been learned at larger spatial and angular scales.

2. Jets at the Largest Spatial and Angular Scales

At the largest spatial and angular scales jets serve as probes of the external environment. For example, the large scale radio structure shown in Figure 1 associated with Virgo A (Owen, Eilek & Kassim 2000) is created by a buoyant plume that rises through the galaxy and cluster gravitational potential (Churazov et al. 2001; Reynolds, Heinz & Begelman 2002), and the orbital motion of a galaxy in a cluster gravitational potential is revealed in Figure 2 by the tailed radio structure of NGC 1265 (O’Dea & Owen 1986). These large angular structures tell us that jets are less dense than the intra-cluster medium and carry a large energy flux (De Young 2006).

![Figure 1. M87 buoyant radio plumes and hot bubbles in the Virgo cluster (Owen, Eilek & Kassim 2000). Image courtesy of NRAO/AUI/NSF.](image1)

![Figure 2. NGC1265 radio tail in the Perseus cluster (O’Dea & Owen 1986). Optical overlay by Alan Bridle. Image courtesy of NRAO/AUI/NSF.](image2)

3. Jets at Intermediate Spatial and Angular Scales

At intermediate angular scales radio source morphology begins to reveal differences indicative of differences in the jets powering these objects. The two basic source morphology types classified originally by Fanaroff & Riley (1974) are now referred to as type FR I (Figures 3 & 4) and type FR II (Figures 5 & 6). In general, the jets in FR I type radio sources decollimate to form long flocculent tails, and the jets in FR II type radio sources remain highly collimated to the outer edge of large radio lobes. The morphology relates to overall jet power in the sense that on average FR II type radio sources are more powerful. This indicates that the jets in FR II type sources are more powerful but at these angular scales a morphology jet power connection
remains complicated by environmental effects associated with the galaxy/environment in which the AGN resides (Bicknell, 1995).

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** Morphology of the FR I type radio galaxy 3C31 (Laing et al. 2008). Image courtesy of NRAO/AUI/NSF.

**Figure 4.** Morphology of the FR I type quasar 3C215 (Bridle et al. 1994). Image courtesy of NRAO/AUI/NSF.

![Figure 5](image3.png)  ![Figure 6](image4.png)

**Figure 5.** Morphology of the FR II type radio galaxy 3C353 (Swan, Bridle & Baum 1998). Image courtesy of NRAO/AUI/NSF.

**Figure 6.** Morphology of the FR II type quasar 3C175 (Bridle et al. 1994). Image courtesy of NRAO/AUI/NSF.

Differences between FR I and FR II radio source morphology can be traced to the stability properties of the jets that power these sources. It has become clear that the jets in FR I type radio sources lose their collimation as mass is entrained into the jet from the surrounding environment. In particular, the observed properties of the jets in 3C31 (Figure 3 above) have been used by Laing & Bridle (2004) to construct a mass entraining model for this source and by extension to other FR I type sources as illustrated in Figure 7. At smaller spatial scales the jet is collimated but shocks slow the jet and entrainment is initiated as the Kelvin-Helmholtz instability develops at the jet external medium interface. Numerical simulations confirm this basic premise (Perucho & Marti 2007) and we may regard the 3C31 jets as being the prototypical example of the FR I radio source. Since entrainment and loss of collimation is primarily a result of the Kelvin-Helmholtz instability, there has been a large amount of research done to
investigate the instability of jet flows and, in particular, to find the conditions needed for jets to remain highly collimated as in the FR II type radio sources.

In general, growth of the Kelvin-Helmholtz instability is slowed by high Lorentz factor, \( \gamma \), and high Mach number, \( M \), e.g., spatial growth length is proportional to \( \gamma MR \) where \( R \) is the jet’s radius. Other secondary factors that can be stabilizing include: (1) transverse gradients in the jet profile (Birkenshaw 1991) that can inhibit development of short wavelength Kelvin-Helmholtz instability, and (2) development of a hot thin shear layer around the jet (Perucho et al. 2007) or development of the hot low density radio cocooning lobe in FR IIs [effects that reduce mass entrainment and are likely to accompany high Lorentz factor and high Mach number jets]. Circumstantial evidence for some type of transverse structure in highly collimated large scale jets comes from observation of x-ray emission from the PKS 1127-145 radio jet at 300 kpc scales that can be explained by a spine-sheath jet structure (Siemignowska et al. 2007). More direct evidence for suppression of short but not long wavelength instability comes from radio images of the FR II type radio source Cygnus A whose prominent jet shows a long wavelength helical (helical KH mode) and subtle dual filament (elliptical KH mode) twist inside the radio lobe (Figure 8). The jet in Cygnus A might be regarded as proto-typical of the combination of effects that enhance jet stability. The jet likely has a relatively high Lorentz factor and Mach number that reduces the spatial growth rate of the KH instability. The high jet power but low jet density relative to the undisturbed external environment has led to slow advance of the jet front and the creation of a large radio lobe consisting of jet plasma processed through

**Figure 7.** Jet spine and entraining shear layer from Laing & Bridle (2004).

**Figure 8.** Radio jets and lobes in the FR II radio galaxy Cygnus A (Carilli, Perley, Barthel & Dreher 1996). Image courtesy of NRAO/AUI/NSF.
the terminal jet shock. The radio lobe has a density less than that of the jet and this results in minimal mass entrainment. The low lobe and cocoon density reduces the spatial growth of the remaining long wavelength KH modes via more rapid advection. Rapid advection can also transport a long wavelength (relative to the jet radius) outwards along an expanding jet into the shorter wavelength (relative to the jet radius) regime where non-linear saturation at relatively small amplitudes can occur.

Organized magnetic fields in pressure equipartition can also provide significant stabilization and reduction in mass entrainment as illustrated by numerical simulation results (Rosen, Hardee, Clarke & Johnson 1999) shown in Figures 9 & 10. Here in Figure 9 we see the development of a long wavelength helical twist, along with elliptical and other distortion of the jet cross section leading to mass entrainment and disruption of highly collimated flow. Note how elliptical and

![Image](image1.png)

**Figure 9.** Numerical simulation with an axial equipartition magnetic field.

![Image](image2.png)

**Figure 10.** Numerical simulation with a helical equipartition magnetic field.

higher order distortions are reduced by the helical magnetic field case shown in Figure 10 and how the flow remains more highly collimated on the computational grid.

It is not clear whether magnetic fields have organized helical structure along kinetically dominated jets at these intermediate angular scales but velocity shear between the jet and the external medium will tend to flow align the fields in the velocity shear region. Such fields have been shown in numerical simulations to reduce mass entraining vorticies (Frank et al. 1996; Jones et al. 1997; Keppens & Toth 2000; Ryu et al. 2000), and in the spine-sheath configuration relatively strong axial magnetic fields can provide significant growth rate reduction of long wavelength jet distortions (Hardee 2007; Mizuno et al. 2007).

While the intermediate angular scale observations can provide valuable parameter constraints based on stability and structure requirements, e.g. the helically twisted jets in 3C 449 (Hardee, Clarke & Reynolds 1981) detailed knowledge of the flow properties remains elusive at these intermediate spatial and angular scales.

4. Jets at Smaller Spatial and Angular Scales

Kelvin-Helmholtz instability driven structures identified at intermediate angular scales are also found at spatial scales of tens to hundreds of parsecs. At these spatial and associated angular scales the identification of twisted emission structures with Kelvin-Helmholtz modes of instability can allow more detailed determination of jet properties (Perucho, Lobanov & Kovalev 2008). A precursor to this type of analysis was first attempted for the curved trajectories and accelerating motions of components in the 3C 345 jet (Hardee 1987). The inherent difficulty of this type of analysis is indicated by different results from analysis of the twisted filaments in the 3C 273 jet (Lobanov & Zensus 2001; Perucho et al. 2006). Nevertheless, physical jet properties can be revealed by the internal jet structure, e.g., the jet in 0836+710 (Perucho & Lobanov 2007).

This technique shows considerable promise for identifying the macroscopic properties of kinetically dominated jet flows through analysis of internal jet structure combined with motions,
e.g., through analysis of the moving knot/interknot projected helical structure shown in Figures 11 (Gómez et al. 1999, 2001) & 12 (Hardee, Walker & Gómez 2005) in the 3C120 jet at tens of milliarcsec scales, or by analysis of moving twisted structures identified by Lobanov through single and dual Gaussian fits (Lobanov et al. 2003, 2005) to the transverse emission profile of the M87 jet shown in Figure 13. In order to extract jet parameters for these jets the fastest proper motions are identified with the flow speed and slower proper motions are associated with the pattern/knot speed. The viewing angle is constrained by the fastest proper motions. Model calculations fitting the observed wavelengths then provide the macroscopic properties of the

**Figure 11.** Moving emission knots in the inner 8 mas of the 3C120 jet (Gómez et al. 1999, 2001).

**Figure 12.** Moving emission knots in the inner 30 mas of the 3C120 jet (Hardee, Walker & Gómez 2005).

**Figure 13.** The inner part of the jet contains a twisted dual filament pair from HST-1 to knot A only easily observable at knot E, and a very small amplitude sinusoidal oscillation of the ridgeline only easily observable beyond knot A (Lobanov et al. 2003, 2005).
expanding flow. Emission images from theoretical modeling including all light travel time and Doppler boosting effects illustrating the appearances of KH twisted structures on the two jets are shown in Figures 14 (3C 120) & 15 (M87).

On the 3C 120 jet a shorter wavelength, amplitude saturated helical twist is overwhelmed by a more slowly growing longer harmonic wavelength about half way across the image. The helically twisted emission ridgeline lies within the expanding 3C 120 jet, and this indicates a short wavelength as long wavelengths move the jet body from side to side. Knots resulting from projection of the helical twist at a small viewing angle initially at the bottom of the jet also appear at the top of the jet as jet flow, wave speed and relativistic aberration increase (Hardee, Walker & Gómez 2005). The required high Lorentz factor and Mach number accelerating flow for the 3C 120 jet explains its stability and hundreds of kiloparsec length.

![Figure 14](image1.png)  
*Figure 14. Theoretically generated radio intensity image of the helical twist on the 3C 120 jet at milliarcsec scales.*

![Figure 15](image2.png)  
*Figure 15. Theoretically generated radio intensity image of the dual twisted filaments on the M87 jet at arcsec scales.*

On the M87 jet dual twisted filaments lie within the expanding decelerating jet and the image of moving KH elliptical mode structure at arcsec scales shows that the appearance changes along the jet like the observed change in appearance between HST-1 and knot A (Lobanov, Hardee & Eilek 2003, 2005; & in preparation). The required low Lorentz factor and Mach number decelerating flow explains the jet’s instability and kiloparsec length.

5. Jets at the Smallest Spatial and Angular Scales

At the smallest spatial scales relative to the central engine, organized magnetic fields are likely to become important to jet dynamics and structure. Strong organized magnetic fields lead to

![Figure 16](image3.png)  
*Figure 16. Pseudo-synchrotron intensity images illustrating the effect of moving the Alfvén point inwards from top to bottom images. The top image contains a purely axial magnetic field and destabilizes about half-way across the image. The bottom image destabilizes about a quarter-way across the image and contains a helical field that first leads to jet pinching and then enhances destabilization when the jet becomes super-Alfvénic but trans-magnetosonic.*

modification of KH instability driven structure and stabilization (Hardee 2007) when the flow is sub-Alfvénic as is illustrated by the numerical simulation results shown in Figure 16 (Hardee
The enhanced destabilization seen in the lower image is associated with the current flows that accompany a strong helically twisted magnetic field (Appl 1996; Lery et al. 2000; Baty & Keppens 2003; Nakamura & Meier 2004; Baty 2005). This enhanced helical twisting accompanying a strong helically twisted magnetic field on a trans-magnetosonic jet is also seen in the numerical simulation results shown in Figure 17 (Nakamura, Uchida & Hirose 2001). Here we see a portion of the jet behind a propagating jet front and the large amplitude twist moves at about the jet flow speed. However, even when a jet is sub-Alfvénic but contains a strong helical magnetic field the current flow alone can lead to CD driven helical instability (Begelman 1998; Lyubarskii 1999) like that shown in a laboratory experiment in Figure 18 (Hsu & Bellan 2002), and whose development is shown in numerical simulation results in Figure 19.

**Figure 17.** Numerical simulation showing CD/KH helical twisting of a trans-Alfvénic jet. Density isosurface in green with arrows indicating the velocity field and selected magnetic field lines wrap around the growing helical distortion (Nakamura, Uchida & Hirose 2001).

**Figure 18.** Laboratory experiment showing CD helical twisting of a sub-Alfvénic jet. The jet base is at the left side of the image with the jet front almost to the right edge of the image (Hsu & Bellan 2002).

**Figure 19.** Density isosurface (green) and helically twisted magnetic field lines (white lines) associated with the growing helical distortion of a CD unstable force-free magnetic field.

(Mizuno et al., in preparation). Thus, we expect jets at even the smallest spatial and angular scales to exhibit instability driven helical structures that are potentially observable. Differences
between the transverse structure and pattern speed of CD and KH driven helical structures may ultimately provide a tool for determination of jet conditions very close to the central engine. KH instability is driven by shear at the jet interface, the perturbations diminish in the jet interior, and the perturbations move at less than the flow speed. CD instability is strongest in the jet interior, and the perturbations move with the flow speed. We might expect to see CD instability driven structures on the sub-Alfvénic and Poynting flux dominated jet close to the central engine, mixed CD and KH structures in the trans-Alfvénic regime farther out and ultimately a transition to the super-Alfvénic and kinetically dominated flow regime at even larger scales. All of these transition points are expected to be located at sub-parsec spatial scales (Giannios & Spruit 2005).

Factors that will modify the location of critical transition points in the flow include the transverse structure of the flow and magnetic field. Here GRMHD numerical simulations of jet launching indicate the likelihood of a high Lorentz factor magnetically dominated jet spine enshrouded in a slower moving matter dominated sheath (McKinney 2006; Hawley & Krolik 2006; McKinney & Narayan 2007) as illustrated in Figure 20. The presence of an external magnetized sheath flow as indicated by GRMHD simulations can delay the onset of the Kelvin-Helmholtz instability (Hardee 2007; Mizuno et al. 2007) as illustrated by the simulation results shown in Figure 21. In this case CD driven helically twisted structures and associated magnetic reconnection might remain important to somewhat larger spatial scales than indicated by the Alfvén point in the jet spine. Circumstantial evidence for a spine-sheath configuration is

**Figure 20.** Schematic (left) from Hawley & Krolik (2006) and results (right) from a GRMHD simulation (Mizuno et al. 2006). In the numerical simulation the color scale indicates the toroidal component of the velocity, \( v_t \), and the arrows indicate the radial component of the velocity.

**Figure 21.** 2d cross sections of the jet density for a KH unstable trans-Alfvénic Lorentz factor 2.5 jet (left panel) stabilized by a c/2 magnetized wind (right panel).
provided by TeV emission from blazars modeled as synchrotron photons generated in a mildly relativistic sheath inverse Compton scattered off electrons in a high Lorentz factor spine as indicated in Figure 22 (Ghisellini et al. 2005). However, alternatives such as rapid jet deceleration

![Figure 22](image)

**Figure 22.** Inverse Compton scattered TeV photons (red) from a high Lorentz factor spine and initial photons (blue) from a mildly relativistic sheath.

(Georganopoulos, Perlman & Kazanas 2005; Kaszas & Georganopoulos 2006) can also generate TeV emission from photons emitted back towards the origin from the slowed jet that subsequently inverse Compton scatter off electrons in the higher Lorentz factor jet nearer to the origin.

### 6. Conclusion

What new things can we learn about AGN jets from astronomy at the highest angular resolution? We now have a reasonable theoretical scenario for the generation and collimation of jets. The scenario suggests a massive black hole surrounded by an accretion disk with jet spine and sheath generated by magnetic fields threading the ergosphere and accretion disk, respectively. The jet generation/launching region at $5 - 50R_s$, $0.5 - 5\text{millipc}$, $5 - 50\mu\text{as}$ is probably unresolved or only slightly resolved at the highest resolutions available. However, the initial acceleration/collimation region at $10 - 300R_s$, $1 - 100\text{millipc}$, $10\mu\text{as} - 1\text{mas}$ is resolvable at the highest resolutions available, and the transition region from Poynting flux dominated to kinetically dominated flow occurs at $\sim 300R_s$, $\sim 0.1\text{ pc}$, $\sim 1\text{mas}$ spatial and angular scales.

Tasks to be accomplished, roughly from larger to smaller scales and degree of difficulty:

1. Locate the base of the kinetically dominated region. This is likely at the modified fast magnetosonic point and marks the outer limit to the transition region.
2. Determine the jet flow/magnetic parameters and structure at the base of the kinetically dominated region.
3. Determine the rate/shape of jet collimation out to the base of the kinetically dominated region.
4. Determine the jet flow/magnetic parameters and structure in the magnetically dominated acceleration/collimation region.
5. Link high energy emission, e.g., TeV emission, to shock structures (if produced in the kinetically dominated super-Alfvénic/magnetosonic flow region) or to magnetic reconnection structures (if produced in the magnetically dominated sub-Alfvénic flow region).

Accomplishing these tasks requires spatial and temporal motion, intensity/spectral and polarization observations at the smallest angular scales.

Suppose we use the image of the M87 jet base at $0.5\text{mas}$ resolution shown in Figure 23 (see also Walker in this proceedings) as a guide. With a black hole mass $\sim 3 \times 10^9$ solar masses and at a distance of $\sim 17\text{ Mpc}$, $R_s \sim 3\mu\text{as}$ and the transition region $\sim 1\text{mas}$, the jet is likely largely kinetically dominated at the image angular scale but should show transverse and
magnetic structure that can be directly tied to the magnetically dominated region. While the initial collimation and transition region is inside the image shown here, we still see evidence for additional collimation to $\sim 5\text{mas}$ where a sudden change in emission morphology occurs. Given

![Figure 23. VLBA image of the M87 jet at $\sim 0.5\text{mas}$ resolution (Walker et al. 2008).](image)

a likely $30^\circ$ viewing angle this change occurs at a distance of $\sim 0.6\ \text{pc}$ and $\sim 2500R_S$. One possibility is that we are seeing the collimation shock predicted to occur at the modified fast magnetosonic point and this location might be regarded as the base of the kinetically dominated jet. If true the spatial distance from the origin and the rate of collimation out to this point place useful constraints on GRMHD jet generation schemes. Important observables include transverse emission structure such as the obvious limb brightened structure seen here. When combined with proper motion observations at jet center and edge, a true picture of spine-sheath structure may emerge. The possibility of seeing acceleration or deceleration in proper motions along the jet on these spatial and angular scales will also be of interest. Here the transverse and radial structure should have an impact on such things as TeV emission models. Finally polarization information should indicate the magnetic field geometry and, for example, allow more positive indentification of transition points as indicated by changes in the magnetic structure.

In any event, the observation at the smallest angular scales of: (1) structures such as helical twists or shock transitions, (2) proper motions, (3) polarization and magnetic structure, and (4) the spectral and temporal behavior of emission, e.g., spectral testing of TeV models (Georganopoulos et al. 2006), all are required for a complete understanding of the dynamics and microphysics of jets in AGN.

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References

Appel S 1996 ASP Conf. Series 100: Energy Transport in Radio Galaxies and Quasars ed P E Hardee, A H Bridle and A Zensus (San Francisco: ASP) p 129.

Baty H 2005 A&A 430 9

Baty H and Keppens R 2003 ApJ 580 800

Begelman M 1998 ApJ 493 291

Birkinshaw M 1991 MNRAS 252 73

Bicknell G V 1995 ApJS 101 29

Birkinshaw M 1991 MNRAS 252 73

Blandford R D 1976 MNRAS 176 465

Blandford R D and Payne D G 1982 MNRAS 199 883

Blandford R D and Znajek R L 1977 MNRAS 179 433

Bridle A H, Hough D H, Lonsdale C J, Burns, J O and Laing R A 1994 AJ 108 766

Carilli C, Perley R A, Barthel N and Dreher J 1996 Cygnus A - Study of a Radio Galaxy ed C L Carilli and D E Harris (Cambridge: CUP) p 76

Chartas G, Brandt W N and Gallagher S C 2003 ApJ 595 85

Chartas G, Brandt W N, Gallagher S C and Garmire G P 2002 ApJ 579 169

Churazov E, Bruggen M, Kaiser C R, Borghiger H and Forman W 2001 ApJ 554 261

De Villiers J-P, Hawley J F and Kroll J H 2003 ApJ 599 1238

De Villiers J-P, Hawley J F, Kroll J H and Hirose S 2005 ApJ 620 878

De Young D S 2006 ApJ 648 200

Fanaroff B L and Riley J M 1974 MNRAS 167 31

Frank A, Jones T W, Ryu D and Gallaas J B 1996 ApJ 460 777

Georganopoulos M, Perelman E S and Kazanas D 2005 ApJL 634 L33

Georganopoulos M, Perelman E S, Kazanas D and McEnery J 2006 ApJL 653 L5

Ghisellini G, Tavecchio F and Chiaberge M 2005 A&A 432 401

Giannios D and Spruit HC 2005 A&A 430 1

Gómez J L, Marscher A P and Alberdi A 1999 ApJL 521 L29

Gómez J L, Marscher A P, Alberdi A, Jorstad SG and Agudo I 2001 ApJL 561 L161

Hardee P E 1981 ApJL 250 L9

Hardee P E 1987 ApJ 318 78

Hardee P E 2007 ApJ 664 26

Hardee P E and Rosen A 1999 ApJ 524 650

Hardee P E, Walker R C and Gómez J L 2005 ApJ 620 646

Hawley J F and Kroll J H 2006 ApJ 641 103

Hsu S C and Bellan P M 2002 MNRAS 334 257

Hildago et al 2008 in preparation

Jones T W, Gallaas J B, Ryu D and Frank A 1997 ApJ 482 230

Kazanas D and Georganopoulos M 2006 ASP Conf Series 350: Blazar Variability Workshop II: Entering the GLAST Era eds H R Miller, K Marshall, J R Webb and M F Aller (San Francisco: ASP) 124

Keppens R and Tóth G 2000 PhysPlasmas 6 1461

Koide S, Meier D L, Shibata K and Kudoh T 2000 ApJ 536 668

Laing R and Bridle A 2004 MNRAS 348 1459

Laing R, Bridle A, Parma P, Feretti L, Giovannini G, Murgia M and Perley R 2008 MNRAS 386 657

Lery T, Baty H and Appl S 2000 A&A 355 1201

Lobanov A, Hardee P and Eilek J 2003 New Science Reviews: The Physics of Relativistic Jets in the CHANDRA and XMM Era 47 629

Lobanov A, Hardee P and Eilek J 2005 ASP Conf Series 340: Future Directions in High Resolution Astronomy eds JD Romney and MJ Reid (San Francisco: ASP) 104

Lobanov A P and Zensus J A 2001 Science 294 128

Lovelace R V E 1976 Nature 262 649

Lyubarskii Yu E 1999 MNRAS 308 1006

McKinney J C 2006 MNRAS 368 1561

McKinney J C and Gammie C F 2004 ApJ 611 977

McKinney J C and Narayan R 2007 MNRAS 375 513

Mizuno Y, Nishikawa K-I, Koide S, Hardee P and Fishman G J 2006 PoS (http://pos.sissa.it) MQW6 045

Mizuno Y, Hardee P E and Nishikawa K-I 2007 ApJ 662 835

Mizuno Y et al 2008 in preparation

Nishikawa K-I, Richardson G, Koide S, Shibata K, Kudoh T, Hardee P and Fishman G J 2005 ApJ 625 60
Nakamura M and Meier D L 2004 *ApJ* **617** 123
Nakamura M, Uchida Y and Hirose S 2001 *New Astronomy* **6** 61
O’Dea C and Owen F N 1986 *ApJ* **301** 841
Owen F N, Eilek J A and Kassim N E 2000 *ApJ* **543** 611
Perucho M and Lobanov P V 2007 *A&A* **469** 23
Perucho M, Lobanov A P, Martí J-M and Hardee P E 2006 *A&A* **456** 493
Perucho M, Lobanov A P and Kovalev Y Y 2008 *Preprint* astro-ph/0802.0602
Perucho M, Hanasz M, Mart J-M and Miralles J-W 2007 *PhRvE* **75** 6312
Pounds K A, King A R, Page K L and O’Brien P T 2003a *MNRAS* **346** 1025
Pounds K A, Reeves J N, King A R, Page K L, O’Brien P T and Turner M J L 2003b *MNRAS* **345** 705
Reeves J N, O’Brien P T and Ward M J 2003 *ApJL* **593** L65
Reynolds C S, Heinz S and Begelman M C 2002 *MNRAS* **332** 271
Rosen A, Hardee P E, Clarke D A and Johnson A 1999 *ApJ* **510** 136
Ryu U, Jones T W and Frank A 2000 *ApJ* **545** 475
Siemiginowska A, Stawarz Ł, Cheung C C, Harris D E, Sikora M, Aldcroft T L and Bechtold J 2007 *ApJ* **657** 145
Swain M R, Bridle A H and Baum S A 1998 *ApJL* **507** L29
Walker R C, Ly C, Junor W and Hardee P E 2008 *ASP Conf Series* **386**: *Extragalactic Jets: Theory and Observation from Radio to Gamma Ray* eds T Rector and D DeYoung (San Francisco: ASP) p 87