Impact of the VLA: Physics of AGN Jets

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1 Introduction

I will begin by revisiting a VLA observation of the radio jets in NGC 315 that was made twenty years ago almost to the day. I make this my starting point partly because it gave us an early hint of how the VLA could impact the study of AGN jets, and partly because it involves (yet) another "Barry Clark story". In what follows, I will not try to summarize all of the different ways in which the VLA has added to our knowledge of AGN jets, but will focus on questions about jet velocity fields and the differences between the two primary jet "flavors", using NGC 315 as a guide.

2 NGC 315 twenty years ago

On 23 June 1978, Ed Fomalont, Mike Davis, and I were given time to observe the radio galaxy NGC 315 with the "sub-VLA" — a dozen antennas on 10.5 km of the West arm and 1.5 km of the East arm. NGC 315 is one of the "giant", *i.e.*, Mpc-scale, radio galaxies, covering almost a degree on the sky (Bridle *et al.* 1976). We had previously used the Green Bank Interferometer to show that the radio source contained a narrow, kiloparsec-scale feature next to an unresolved component in the nucleus of the elliptical galaxy. The narrow feature was aligned with a bridge of emission linking the galaxy to one lobe of the giant structure, so we thought that it might be the innermost part of an exceptionally long "radio jet". Although the largest-scale structures would be resolved out, we hoped that a long synthesis would allow us to image the narrow feature in some detail because most of its flux density could be captured whenever the short-baseline fringes aligned with it.

We were not disappointed. We got good data from most of the antennas at 4885 MHz and 1465 MHz. The bases of the jet and of a counterjet were not only detected, but also *transverse*-resolved. We could therefore measure the jet's opening angle, or spreading rate, as a function of distance from the nucleus. We also saw that to make full use of the data we needed to deconvolve the sub-VLA's sidelobe pattern from a large area of sky by 1978 standards — fully 256 × 256 pixels! We needed to make a 512 × 512 dirty image and beam to do this using the Högbom (1974) CLEAN algorithm. This was a non-trivial computation in 1978, because the CLNMAP program had to be run in the same heavily-loaded DEC-10 that handled most of the off-line computing at the VLA site. Only 128 × 128 CLEANs could be submitted to the DEC-10 routinely, so we needed Barry Clark's permission to run ours.

At this early stage of VLA work, deconvolution did not have the central role in image processing that it has today. CLEAN was still seen as a temporary stop-gap, a processing step that might not be needed when the VLA was completed. (The VLA had been designed to give sidelobe levels low enough that its "dirty" images could be used directly for science.) Despite the nuisance value of our request, Barry let us run an "over-sized" CLEAN on NGC 315 on a weekend when the DEC-10 was lightly loaded.

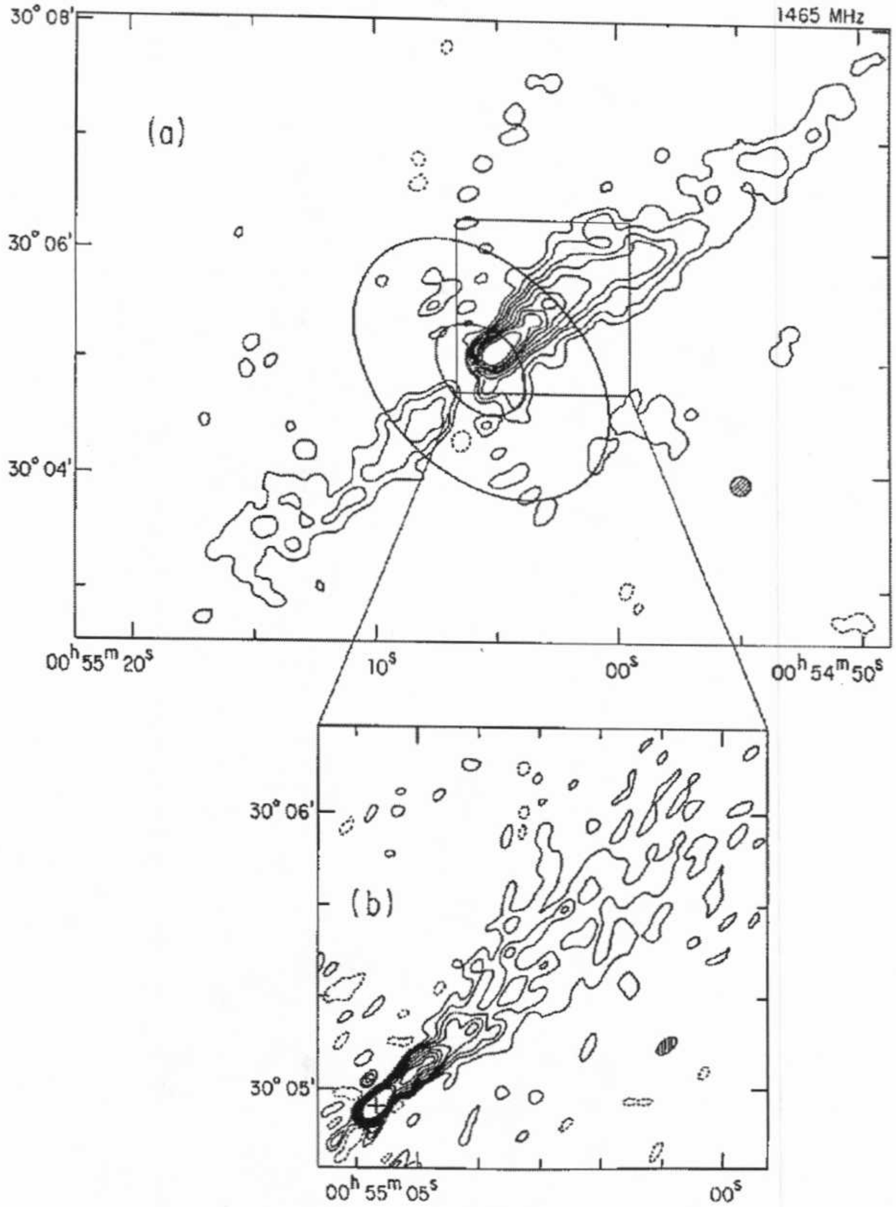

Figure 1: The upper panel shows the 1465 MHz contour plot of NGC 315 at 11″ resolution; an unresolved nuclear source was subtracted. The ellipses show the size and orientation of the overexposed core and outer envelope of the galaxy on the red-sensitive *National Geographic Society – Palomar Observatory Sky Survey* print. The inset shows the VLA data at 2.5″ resolution. (From Bridle *et al.* 1979.)

Our 1465-MHz data traced the jet and counterjet for a few tens of kiloparsecs away from the nucleus (see Figure 1). The key result was that the structure of these jets changes with distance from the nucleus in several ways. The jet ridge lines "wiggle", the brighter jet clearly spreads at a variable rate, and its degree of linear polarization increases outwards. This was evidence for *ongoing* changes in the jets' collimation and internal structures, including the magnetic field configuration, on scales that were easily resolvable by the VLA. VLA observations of such jets might therefore be able to provide important clues to the physics of jet propagation on kiloparsec (and greater) scales in galactic environments.

The clientele for CLEANing "large" fields of view ballooned as more extended sources were studied with the sub-VLA. But the DEC-10 could not handle the growing demand for the Högbom CLEAN. Fortunately, Barry turned this computing problem into a wonderful opportunity, and gave us the "Clark CLEAN" (Clark 1980).

To move some of the deconvolution load out of the DEC-10, Barry coded a CLEAN for a PDP 11/70 and FPS 120B Array Processor that were later to become part of the spectral-line "pipeline" system. The FPS 120B had three control panel lights: one for power, one showing data transfer activity, and one showing array processor activity — actual computation. Barry says that watching these lights showed him that his first CLEAN code spent too little time doing the computations. Most of the time instead went into shuffling data in and out of the AP memory. The more efficient algorithm that he developed to keep the "AP activity" light lit up saved our bacon in the early 1980's. Without it, the practice of feeding CLEAN models back into self-calibration, which was the route to high image fidelity, would have been slow to develop. Barry's efficient AP microcode later went around the world as part of AIPS, and the "computation" light stayed lit up on the AP's of thankful VLA users for years thereafter.

Our early look at NGC 315 with the sub-VLA previewed some features of FR I jets which may still be central to understanding differences between jet propagation in FR I and FR II sources; but it may have advanced the field more by being one of the early projects that got Barry Clark thinking about an efficient CLEAN algorithm.

Figure 2 shows the radio jets and the galaxy in modern dress, superposing a 4885 MHz VLA multi-configuration image of the radio jets on the red-sensitive image of NGC 315 from the *Digitized National Geographic Society – Palomar Observatory Sky Survey.*

3 AGN jets before 1978

Use of the term "jet" in extragalactic astronomy dates back to Baade & Minkowski (1954), who described an optical feature in M 87 as "a unique peculiarity known for a long time ... a straight jet extending from the nucleus in p.a. 290°, bluer than the nebula itself ... several strong condensations". This feature was first recorded by Curtis (1918), as "a curious straight ray apparently connected with the nucleus by a thin line of matter". Its linear polarization at optical wavelengths (Baade 1956) provided early evidence for synchrotron emission from extragalactic radio sources.

The existence of radio emission from AGN jets was also known for many years before the VLA went into operation.

The first sign of radio emission from a "jet" had come via Schmidt's (1963) identification of "a star of about thirteenth magnitude and a faint wisp or jet" near the accurate positions of the radio components of 3C 273 (Hazard *et al.* 1963). Schmidt's identification of radio component 'B' with the "star" marks the start of the quasar industry. His identification of component 'A' with the tip of the "faint wisp or jet" likewise marks the start of a radio jet industry that developed much more slowly. Six years passed before Hogg *et al.* (1969) showed that a compact extranuclear radio component in 3C 274 coincided with the brightest knot in M 87's optical jet (thus providing evidence for radio emission *from*, rather than just *around*, that optical feature).

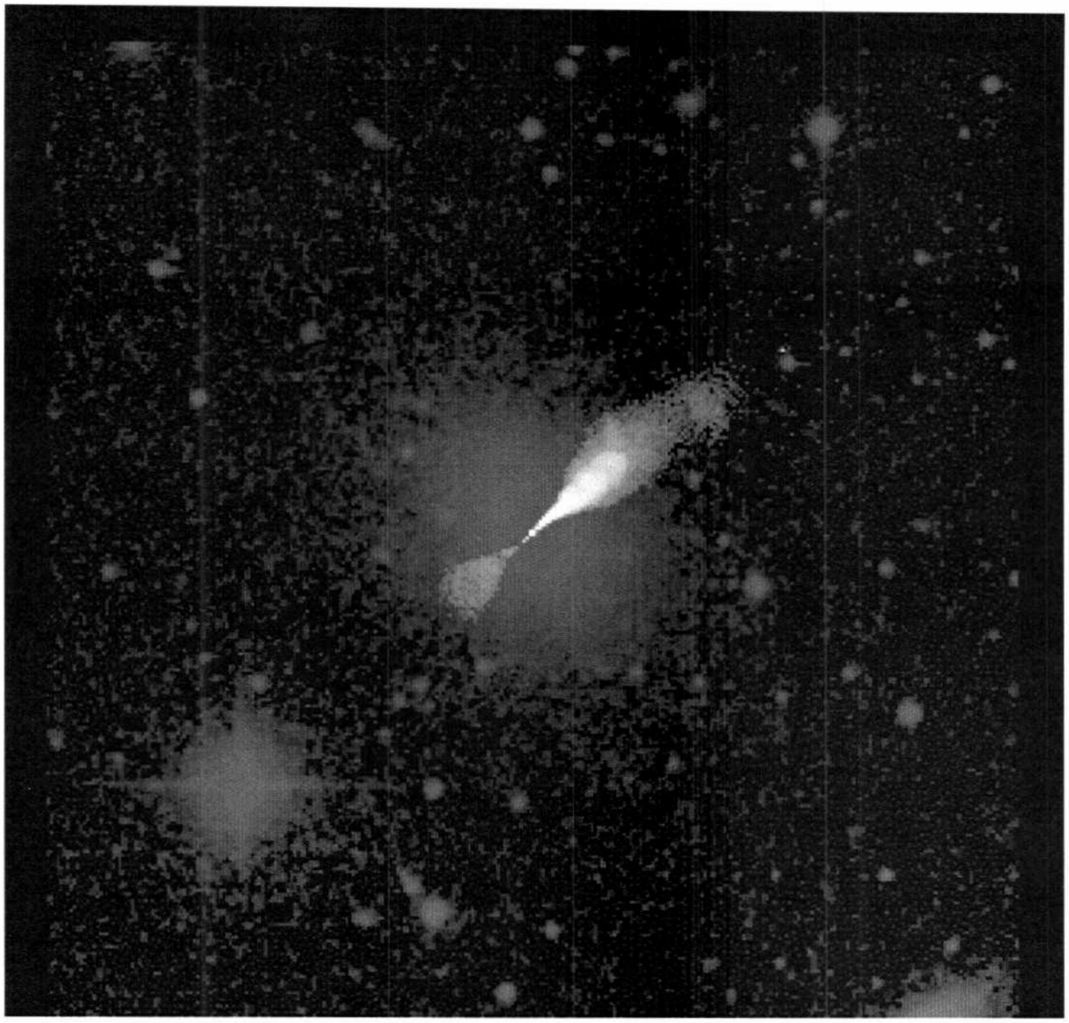

Figure 2: A modern VLA image of NGC 315 at 2″ resolution superposed on an image of the galaxy from the E plate of the *Digitized National Geographic Society – Palomar Observatory Sky Survey.*

The next evidence for radio jets came from observations made at Cambridge. Northover (1973) found a "narrow jet of emission linking the galactic nucleus to one of the extended regions" in the low-power plume-like radio source 3C 66B, and suggested that this implied a continuous resupply of energy from the nucleus to the extended source (in compact sub-components that he interpreted as buoyant "bubbles"). Hargrave & Ryle (1974) used high-resolution imaging of Cygnus A's hot spots and spectral-aging analysis to argue for "continuous replenishment of energetic electrons within the two main compact components", favoring models with "continuing ejection of beams of energetic particles or low frequency waves from the nucleus of the galaxy". The first *direct* evidence for a radio jet in a powerful "classical double" source came when Turland (1975) detected the abbreviated jet in the radio galaxy 3C 219. A spectacularly long and narrow one-sided jet was found in the giant radio galaxy NGC 6251 by Waggett *et al.* (1977).

Radio jets were also recognized in WSRT images of several radio galaxies at about this time: van Breugel & Miley (1977) reported jets in B0844+319 and 3C 129, and gave retrospective evidence for jets in several other galaxies, including 3C 449 (Högbom & Carlsson 1974) and 3C 83.1 (Miley *et al.* 1975).

4 The VLA and large scale features of jets

The VLA greatly accelerated the study of radio jets, for several reasons. It had the sensitivity to detect weak jets with short observations, the dynamic range to do so in the presence of bright unresolved emission in the galactic nuclei, and the angular resolution to separate the jets convincingly from surrounding extended structures. It also allowed polarization imaging with good sensitivity and resolution, and this revealed key details of the jets' magnetic configurations.

VLA observations quickly provided examples of jets in all types of radio-loud AGN. The detection of radio emission from, or at least closely associated with, the presumed pathways of energy transport in continuous-outflow models cemented the case for these models[1]. Furthermore, numerous correlations between the properties of the jets and other attributes of the radio sources became apparent. These included:

- **Correlations between jet properties and the Fanaroff-Riley structure classes:** The plume-like, low-luminosity, Fanaroff-Riley Class I sources (Fanaroff & Riley 1974) have two-sided, rapidly spreading and prominent jets (*e.g.*, Figure 3). The "classical double", higher-luminosity, FR II sources have one-sided, narrowly-collimated jets that are more prominent in quasars than in radio galaxies (Bridle & Perley 1984).
- **Correlations between kiloparsec and parsec scales:** The brighter kiloparsec-scale (VLA) jet is always a plausible extension of the brighter parsec-scale (VLB) jet. The kiloparsec-scale jets are also well aligned with the parsec-scale jets in the FR I sources (Giovannini *et al.* 1995; Venturi *et al.* 1994, 1995), as exemplified by NGC 315 in Figure 4, and in lobe-dominated FR II sources. The *angular* relationships are more complex in core-dominated sources whose jets appear more bent, but even in these sources the brighter large-scale jet is usually a plausible continuation of the brighter small-scale jet.
- **Correlations between jet sidedness and depolarization asymmetry:** In sources whose jets differ greatly in brightness, the brighter jet is on the side of the source that depo-

[1]The models had their roots in early papers by Morrison (1969), who outlined a pulsar-like model for an AGN emitting a continuous relativistic beam, and by Rees (1971), who suggested that the sources were powered by low-frequency electromagnetic beams. Longair *et al.* (1973) argued for an energy transport time scale "comparable with the age of the source" and Scheuer (1974) explored the dynamics of radio sources powered by relativistic beams. Blandford & Rees (1974) suggested a "twin-exhaust" collimation mechanism for relativistic plasma flows (on 100-pc scales).

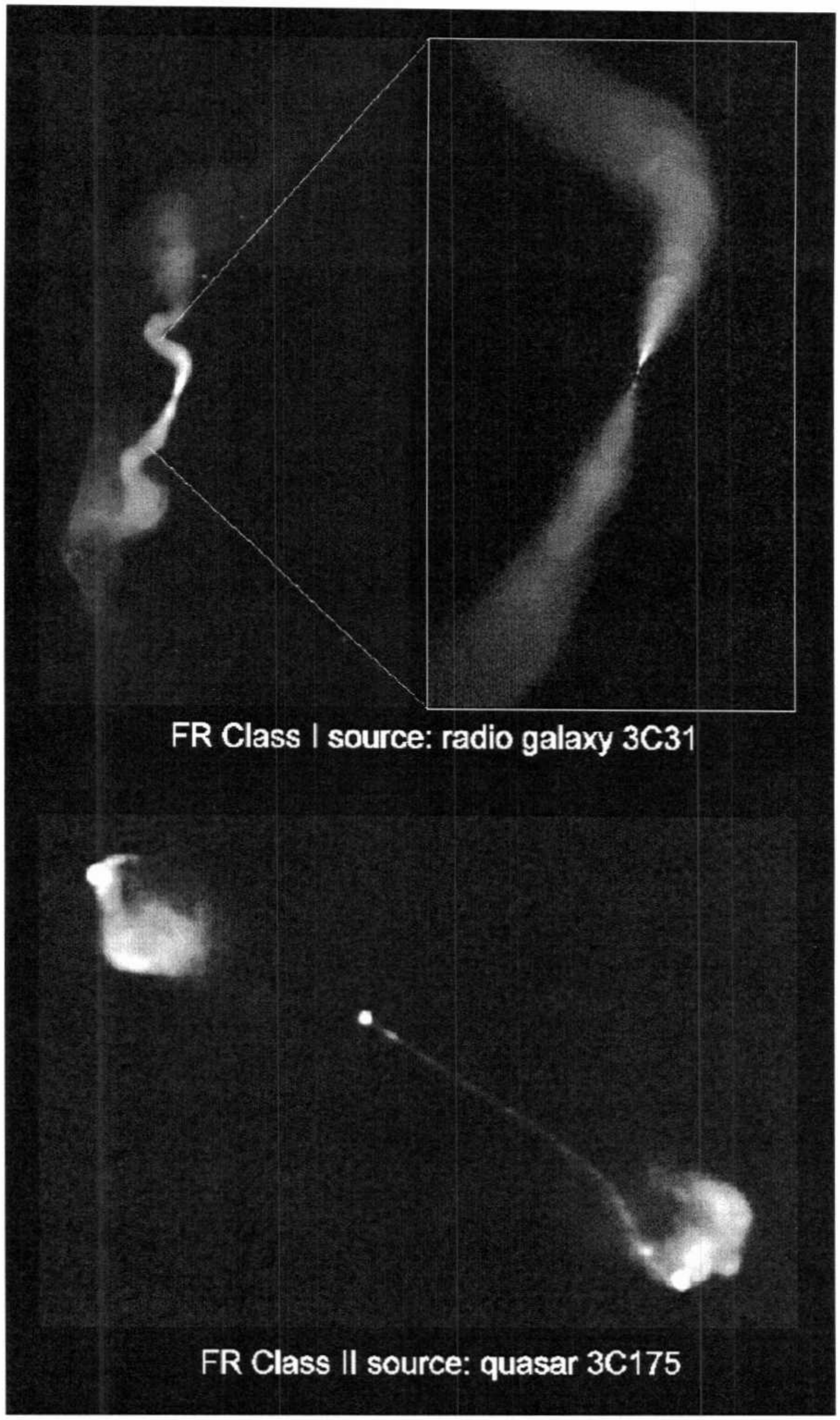

Figure 3: VLA images of jets in a Fanaroff-Riley Class I source (3C 31: 1.4 GHz, 5.5″ FWHM and 8.4 GHz, 0.3″ FWHM) and a Class II source (3C 175: 4.9 GHz, 0.35″ FWHM).

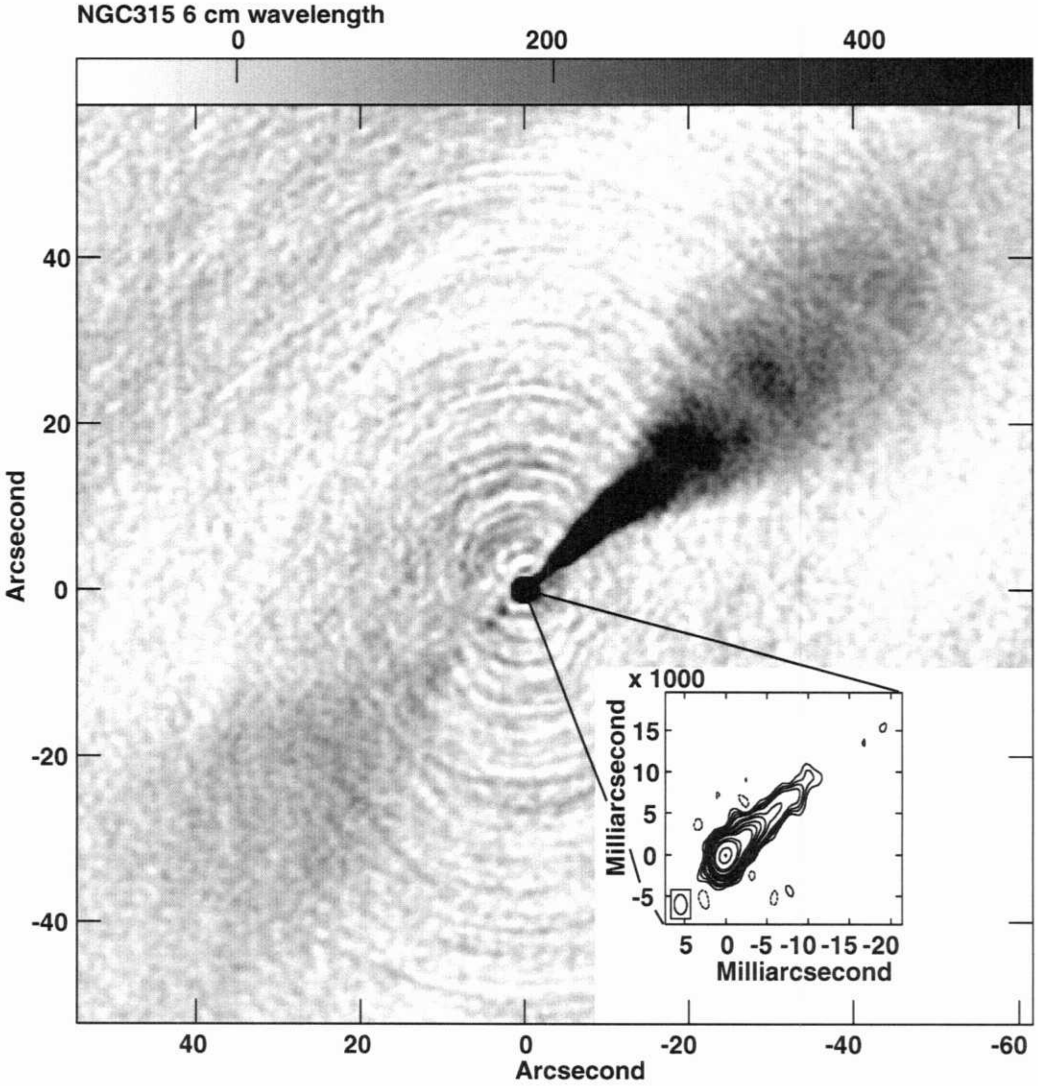

Figure 4: The correlated sidedness and good alignment of the kiloparsec-scale and parsec-scale jets in NGC 315 (superposition kindly provided by W.D. Cotton). The gray scale image is from VLA B configuration data at 4885 MHz, the inset contour plot is from VLBA data at the same frequency.

larizes less at long wavelengths (Laing 1988; Garrington *et al.* 1988, 1991; Parma *et al.* 1996). This is consistent with the brighter jet always being on the nearer side of the source.

- **Correlations between magnetic field orientation and jet sidedness:** well-resolved jets are often highly linearly polarized, so their magnetic fields are partially ordered — one-sided jet features in FR II jets and at the bases of FR I jets are dominated by field components along the jet axes, but straight FR I jets are dominated by perpendicular field components further from the AGN (Bridle 1984).

Jet modelers now had some clear observational correlations to explain. Much early debate centered on side-to-side asymmetries and their implications for jet velocities. The bending of "head-tail" sources, many of which resolved into U-shaped twin jets, was modeled as an effect of the relative motion of the host galaxy and an intracluster medium: their symmetries in the presence of the bending argued for subrelativistic velocities and moderate Mach numbers (O'Dea 1985). The excellent collimation of jets in FR II sources suggested low jet densities and high Mach numbers (Payne & Cohn 1985; Williams 1991). The brightness asymmetries of FR II jets on many-kiloparsec scales encouraged the idea that their bulk velocities stay relativistic, like those of their one-sided and often superluminally-moving parsec-scale counterparts, even on these large scales.

5 The VLA and internal structures of jets

VLA images of bright, well-resolved FR I and FR II jets have shown that they exhibit a rich variety of internal knots, rings, loops and filaments, including some apparently helix-like structures. These internal details also provide input to models of jet physics, including:

- In FR I sources, as NGC 315 shows quite dramatically (see Figure 5), jet collimation is not determined once and for all on parsec scales. The side-to-side brightness asymmetries of FR I jets also decrease with distance from the nucleus, and towards the outer edges of the jets from their axes (Laing 1996). The innermost regions of FR I jets also resemble FR II jets (well-collimated and dominated by magnetic field components parallel to the jet axis). The collimation and internal structure of these jets evidently change dramatically on just the scale where their sidedness characteristics also change.

- The detailed radio structure of M 87's jet closely resembles that of the optical jet (Biretta 1996), and superluminal proper motions have been inferred for several features (Biretta *et al.* 1995).

- Semi-periodic strings of knots are seen in some FR II jets (*e.g.*, Bridle *et al.* 1994). A variety of phenomena could produce this effect: nonlinear growth of Kelvin-Helmholtz instabilities, criss-crossing oblique shock patterns in confined jets, or regular perturbations of the flow velocity or direction. Higher resolution imaging and polarimetry (*e.g.*, with the upgraded VLA) are needed to clarify the nature of this phenomenon, which could lead to (model-dependent) estimates of Mach number in the jets.

- In the jets of some FR II sources, limb-brightening and flat-topped emission profiles (Swain *et al.* 1996, 1998; Carilli *et al.* 1996, their Figure 5) imply diminished emissivity on the jet axis relative to the jet edges, in regions away from bright knots. It is not yet clear whether this effect is due to differential Doppler boosting in a relativistic jet with a slow boundary layer (as suggested below) or to enhanced *in situ* particle acceleration or magnetic field amplification in a boundary layer. In either case, our visualization of phenomena in FRII jets may be biased toward their outer (boundary) layers. Again, higher angular resolution and sensitivity (*e.g.*, an upgraded VLA) are needed to explore this fully.

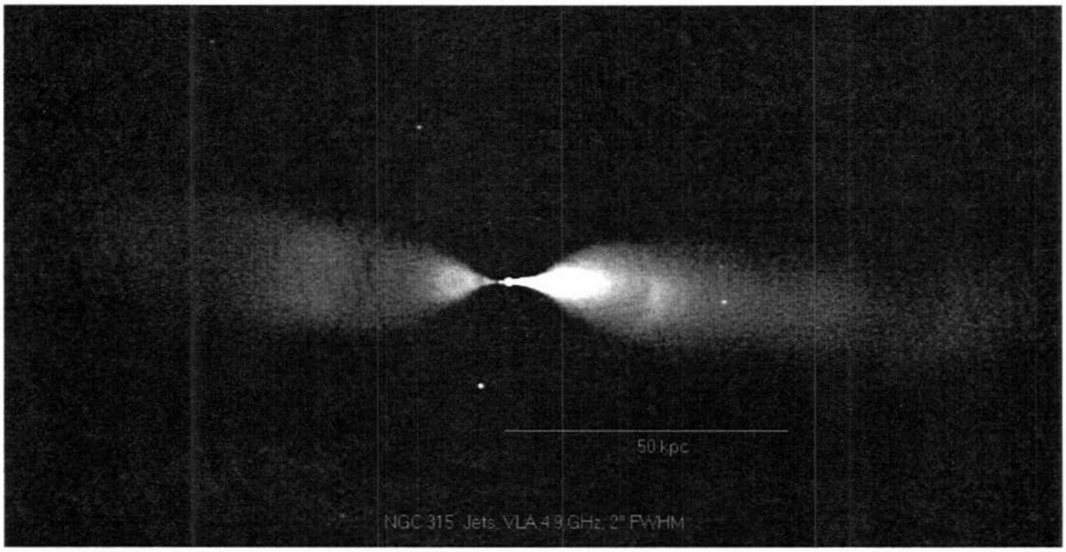

Figure 5: The recollimation of the NGC 315 jets on 20 to 30-kpc scales is clear in this VLA 4885 MHz image at 2″ resolution. The data have been rotated so that the axis of the large-scale jet is horizontal. The data combine syntheses in the B, C and D configurations (Cotton, W.D., Bridle, A.H., Laing, R.A., & Giovannini, G., in preparation.)

6 Implications for jet physics

Many aspects of AGN radio jets can now be understood in the context of bulk-relativistic outflows launched from relativistically-deep potential wells in galactic nuclei. The most likely launching mechanism is "B++" — a *b*lack hole ***plus*** a rotating accretion disk ***plus*** a magnetic field that is wound up by the rotation of the disk. In all models of jet launching from AGN by this mechanism, the jets emerge perpendicular to the axis of the disk. Direct evidence for the black holes, and for larger-scale disks around them, in active galactic nuclei is now coming from VLBI (*e.g.*, Miyoshi *et al.* 1995; Herrnstein 1998), the HST (*e.g.*, Harms *et al.* 1994; Ferrarese *et al.* 1996; Bower *et al.* 1998), and X-ray spectroscopy (*e.g.*, Tanaka *et al.* 1995).

The VLA lets us examine how these outflows evolve as they propagate in the environments of their host galaxies and surrounding groups or clusters. It now seems likely that most jets, whether in FR I or FR II sources, retain a fast relativistic component out to the kiloparsec scale where the VLA begins to resolve them transversely. A key difference between the two Fanaroff-Riley classes (Fanaroff & Riley 1974) may be that the fast central "spine" decelerates to subrelativistic speeds within the galaxy in FR I sources, but persists as far as the distant hot spots in FR II sources.

Doppler favoritism of the approaching relativistic jet can explain why the observed brightness asymmetries (or sidedness) of the kiloparsec-scale (VLA) and parsec-scale (VLB) jets are so well correlated with each other, and with the depolarization asymmetry, in both Fanaroff-Riley structure types — these attributes all diagnose which of the two jets is approaching us.

Doppler boosting and dimming in relativistic jets at different angles to our line of sight can also explain why the jets in FR II radio galaxies are harder to detect than those in lobe-dominated quasars. If the broad-line region of radio galaxies is obscured by material in a torus in roughly the same plane as the accretion disk, and if the jets indeed emerge perpendicular to this plane, then FR II radio galaxy jets will generally be closer to the plane of the sky than those in lobe-dominated quasars. (The latter are tilted towards us, allowing a view of the inner, broad-line, region.) The approaching jet in an FR II quasar can therefore be Doppler *boosted*, making it more prominent relative to the lobes (as well as strongly "one-sided"), while both jets in an FR II radio galaxy are Doppler *dimmed*, making them hard to detect until they terminate at the hot spots.

In the context of relativistic-jet models, the symmetrization of the jets in FR I sources with increasing distance from the galactic nucleus suggests that they decelerate as they propagate through the galactic environment on kiloparsec scales. The idea that some relativistic flow extends to ~ 1-kpc scales even in FR I sources is bolstered by the large proper motions found in M 87 on these scales (Biretta *et al.* 1995). Bicknell (1995) showed how the bulk deceleration of FR I flows by mass entrainment from galactic atmospheres might explain why the FR I to FR II transition depends on both the luminosity of the radio source and on the optical luminosity of the galaxy (acting as a proxy for the central gas pressure).

If these ideas are correct, then high-resolution imaging of the bases of jets in FR I sources like NGC 315 and 3C 31 offers a way to probe how the galactic environment decelerates outflows whose initial momentum fluxes are lower than in FR II sources. Robert Laing and I are exploring how well models of decelerating relativistic jets can match the detailed intensity and polarization distributions of several FR I sources that are well resolved by the VLA. We assume that the fast-moving jet spine develops a slower-moving boundary layer, across which there is transport of gas from the galactic atmosphere, causing the spine to decelerate. The flow is initially fast, resembling that in an FR II source. But for a source at an intermediate angle to the line of sight, first the slower moving flow in the boundary layer, and then the flow in the jet spine, pass through the velocity at which their emission is optimally Doppler boosted. As pointed out by Komissaroff (1988, 1990) this can explain why both jets appear to brighten after an initially dim region (as they emerge from Doppler "hiding"). It can also explain:

- why the bases of FR I jets look so much like the FR II jets (both are fast, well-collimated, and faint on both sides because of Doppler "hiding" at high speeds and large angles to the line of sight),
- why the FR I jets spread so rapidly where they apparently brighten (the deceleration that brings the spine to optimum Doppler boost also dumps bulk kinetic energy into internal energy and inflates the jet against the surrounding gas pressure), and
- why the outer isophotes of FR I jets are more side-to-side symmetric at all distances from the nucleus than their inner isophotes (they are where the flow is slower, at all distances).

Figure 6 compares a model of the emission from a decelerating relativistic jet with VLA data for 3C 31 at the same resolution. In this model, the fast-moving spine, which occupies about 40% of the jet by radius, has a single velocity across the jet but decelerates with increasing distance from the nucleus. In the outer layer the flow velocity decreases linearly from the spine velocity closest to the axis to a low value at the edge of the jet. The jet and counterjet are intrinsically identical. The velocity field, the variation of the emissivity with distance from the nucleus, and the jet geometry have all been adjusted to fit the data. The (fitted) angle of the jet to the line of sight is 52°; the spine velocity decreases from $0.88c$ closest to the nucleus to $0.17c$ furthest from the nucleus, while the velocity at the edge of the jet decreases from $0.7c$ to $0.11c$.

We have also specified the jet's internal magnetic field configuration. We assume that the spine contains random loops of magnetic field with no component along the direction of motion, while the boundary layer contains random loops with no component across the velocity shear. By accounting for the relativistic aberration of these partially-ordered magnetic fields we can also account for both jets' polarization properties, as shown in the lower half of Figure 6.

Although some details of the polarization "weather" (particularly a loop-like structure in the brighter jet) are unexplained, the model describes the total intensity and polarization "climate" in

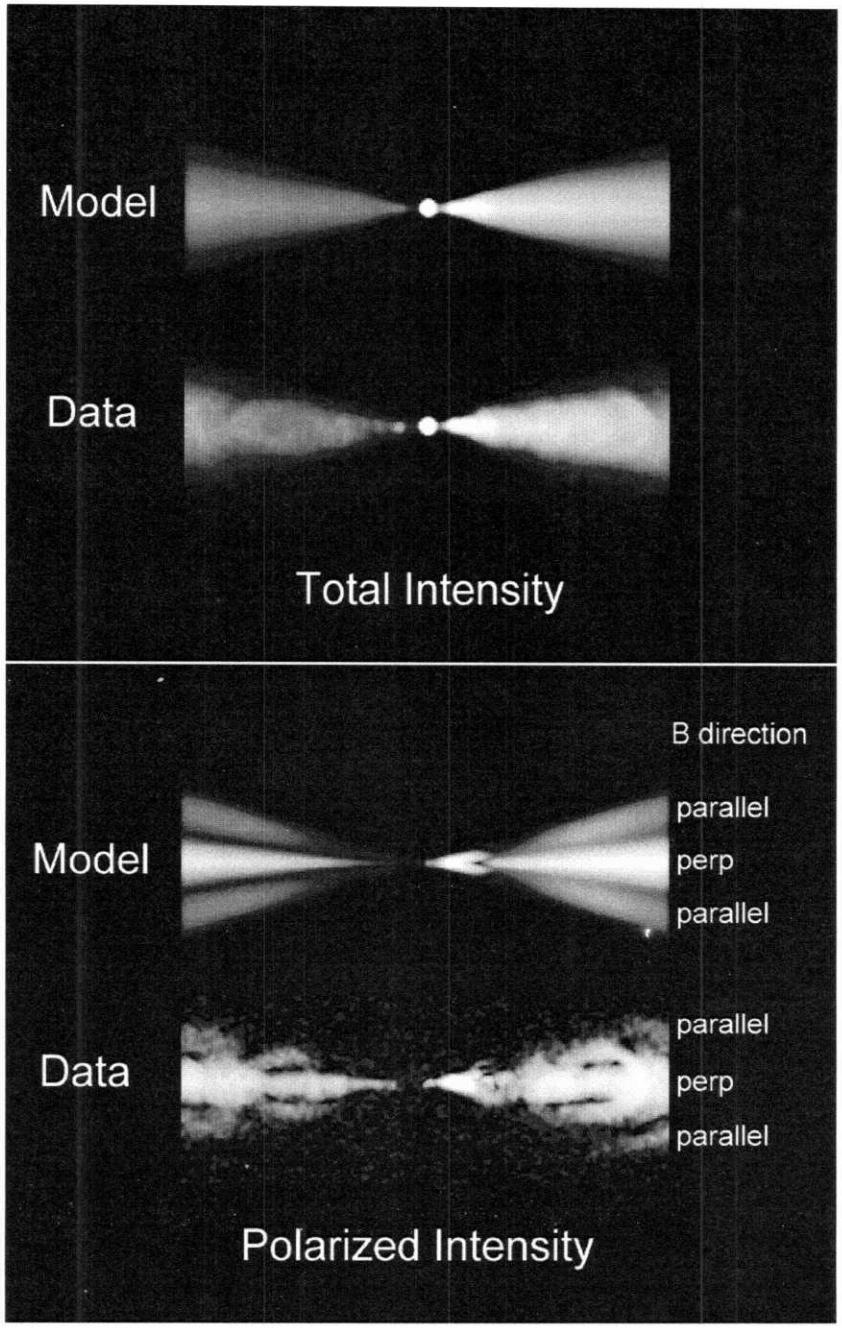

Figure 6: Direct comparisons of a decelerating relativistic-jet model (see text for details) and the VLA total (upper panel) and polarized (lower panel) intensity data for the inner parts of the jets in 3C 31 at 8460 MHz (Laing, R.A., & Bridle, A.H., in preparation).

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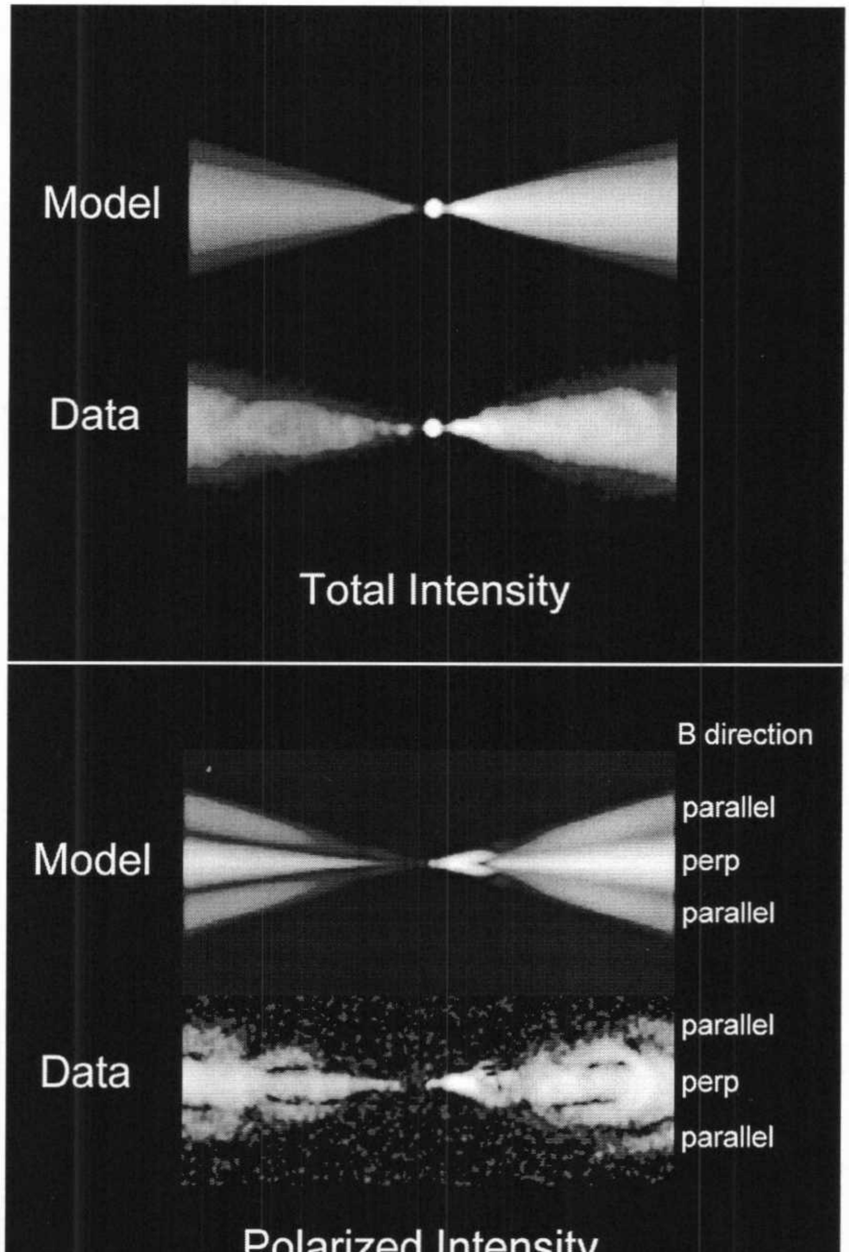

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3C 31 well. Its ability to fit the major features of the observed total and polarized intensities for *both* jets with the same velocity distribution and magnetic field parameters suggests that the basic precepts of the decelerating-jet picture are correct.

Well-resolved VLA data on FR I sources like NGC 315 and 3C 31 may therefore allow us to infer information about the jet velocity fields, and thus about the kinematics of jet-gas interactions, in elliptical galaxies. This will be an important step towards understanding the galactic-scale processes that determine the differences between FR I and FR II sources.

7 Looking ahead

The decelerating-jet picture of FR I sources associates their apparently parallel-field regions with the jet boundary layer, where we expect to find a strong velocity shear. The inter-knot emission from jets in FR II radio galaxies appears to be dominated by parallel-field configurations, so this emission may also be visualizing slower-moving material at the jet edges. If so, outflow velocities derived from the side-to-side brightness asymmetries of such jets may systematically under-estimate the velocities in the jet spines, which may stay hidden from us until they reach the hot spots. It will be important to learn whether the innermost regions of FR I jets, and of jets in FR II radio galaxies, generally appear edge-brightened, or at least flat-topped, when observed with good sensitivity and high transverse resolution. As mentioned earlier, there is evidence for a lack of emissivity near the jet axis in the large-scale jets of the FR II sources 3C353 (Swain *et al.* 1996, 1998) and Cygnus A (Carilli *et al.* 1996) but improved angular resolution and sensitivity (such as offered by the VLA Upgrade) will be needed to pursue these questions in the general population of FR II sources.

It will also be important to determine whether jets and counterjets in the same FR II source have similar transverse intensity and polarization profiles, and whether these profiles are systematically different for narrow-line radio galaxies, broad line radio galaxies, and quasars (which are expected to be at systematically different angles to our line of sight in orientation-based "unification schemes").

Although rapid deceleration of the FR I jets on kiloparsec scales may *de*collimate these jets, the jets also rapidly *re*collimate, as Figure 5 clearly shows. The hot, *extended*, component of the galactic (or circumgalactic) atmosphere required to produce the recollimation by thermal pressure alone has so far eluded detection at X-ray wavelengths in NGC 315 (*e.g.*, Birkinshaw & Worrall 1996). AXAF may tell us how serious this problem is for decelerating-jet models. Alternative explanations for the recollimation phenomenon might be found in the two-fluid (beam-wind) model of Sol *et al.* (1989), which seeks to explain it using $\mathbf{J} \times \mathbf{B}$ forces.

If decelerating-jet models of FR I sources pass further scrutiny, then jet kinematics inferred from VLA imaging may be used to constrain models of mass entrainment into relativistic jets traversing galactic atmospheres. The eventual goal should be to explain the major features of the collimation changes, brightness distributions, and polarimetry of these jets using a full dynamical model of the flows, rather than the simple kinematic modeling illustrated in Figure 6.

8 Acknowledgments

I thank Bill Cotton and Robert Laing for many discussions and ongoing collaborations; and Barry Clark for everything he has done, and still does, to make the work described here possible.

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