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Parsec-scale Jets in Lobe-dominated Quasars

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Abstract. In order to test relativistic jet and AGN models over a wide range of orientations, we are conducting a VLBI survey of a complete sample of 3CR lobe-dominated quasars. With the benefit of intensive VLBA/HSA observations during the period 1995-2005, the nuclei in all 25 objects have been imaged at one or more frequencies between 5 and 22 GHz. In 22 objects, we find one-sided parsec-scale jets (three sources have barely resolved cores). The jets typically show bends of a few degrees in their inner few parsecs. Multiple-epoch observations have yielded at least rough speed estimates in 15 sources. Component speeds range from $\sim$0 to $\sim$10c, and there is a strong tendency for outer components to move faster than inner ones (3C245 is an exception, with alternating fast and slow components). Both the average and maximum speeds tend to correlate with R, the ratio of nuclear to extended emission at 5 GHz (emitted). Polarized emission has been detected in five objects: four show significant rotation measures in their cores/inner jets, two have long jets with longitudinal magnetic fields, and one has a distant jet feature with a transverse field. Implications for jet and AGN models are discussed.

1. Introduction

In unification scenarios for active galactic nuclei (AGN), there is general acceptance of a "sub-unification" of powerful radio-loud sources, in which these objects are intrinsically similar but appear different with increasing angle, θ, of their radio jet axes relative to our line-of-sight. This yields the sequence blazars, core-dominated quasars (CDQs), lobe-dominated quasars (LDQs), and powerful Type II radio galaxies. However, the detailed physics of the parsec-scale jets in these sources is still not well understood. Great effort has gone into VLBI surveys of blazars and CDQs at small θ – e.g., Pearson & Readhead (1988), Kellermann et al. (2004), Lister & Homan (2005) – and these have been critical to the development of jet models. To complement this work, studies of LDQs offer an important means of testing jet models over a wide range of orientation (e.g., $\theta\sim10^\circ$-45°) using objects with nuclei bright enough for VLBA imaging.

2. The 3CR Lobe-dominated Quasar Sample and VLBI Observations

Hough & Readhead (1989) defined a complete, flux-density-limited sample of 25 LDQs from the 3CR catalog. To minimize orientation bias, the objects were chosen on the basis of their low-frequency extended emission only. As an orientation indicator, we use the ratio, R, of core to extended emission at 5 GHz (emitted). Hough et al. (2002) reported mostly pre-VLBA VLBI images of 19 one-sided jets. Jet speed estimates for 10 objects, many of them tentative, are in the range ~0-10c. Optical spectrophotometry by Aars et al. (2005) provides evidence for a disk-like component perpendicular to the radio jet.

New observations to complete imaging of all 25 LDQs were made during 1997-2004, using VLBA/HSA 8.4 GHz phase-referencing on six sources in the ~1-5 mJy range. Further observations to measure jet speeds were made during 1995-2005, mostly at 8.4 GHz. Eight sources over a wide range of R were observed at many epochs, often at intervals of 2-3 months to unambiguously identify components and minimize uncertainties in their speeds; five sources were imaged at two epochs. Our first polarization-sensitive imaging was done during 1996-1999 with 5 (usually), 8.4, and 15 GHz observations of seven sources. Data reduction, imaging, and analysis were done with the NRAO AIPS and Caltech DIFMAP packages. Typically, the resolution is ~1 mas and the image noise is ~0.1 mJy/beam at 8.4 GHz (see Fig. 1 and Fig. 2 for examples).

3. Jet Morphology, Speeds, and Polarization Structure

All 25 nuclei in the 3CR LDQ sample have now been imaged. In 22 sources, we find a one-sided parsec-scale jet – often bent by a few degrees in its inner few parsecs – fairly well aligned with the kiloparsec-scale jet (within a few degrees). Three sources – 3C68.1, 3C181, and 3C432 – show only barely resolved VLBI cores. Useful multiple-epoch images have been obtained for 15 objects. For 10 sources, apparent transverse jet speeds have been well determined, and they fall in the range $\beta_{app} = v_{app}/c$ ~0-10. These 10 sources are used in the analyses below. (For the other five sources, β_{app} was measured for only a single component, and with a large uncertainty: 3C14 at 5±5, 3C191 at 4±4, 3C205 at −4±7, 3C275.1 at 2±2, 3C336 at 2±2.)

In Fig. 3, we plot β_{app} vs. projected distance r_{proj} along the jet (we assumed q_o=0.5, H_o=70 km/s/Mpc, Ω_m=0.3, and Ω_Λ=0.7). Except for 3C245, it is clear that *component speeds tend to be faster at larger projected distances from the core*. Hough et al. (2002) assigned each source a "pseudo-angle" based on both R and projected linear size, assuming a range from 10° to 45°, but this is inconsistent with β_{app} in several cases. Therefore, we have reassigned orientation angles using R only, and have used them to find the jet Lorentz factor γ vs. deprojected distance r along the jet (assumed to be straight) shown in Fig. 4 (which details the only two remaining inconsistencies). There is a positive correlation between γ and r at the >99.9% confidence level (linear correlation coefficient = 0.61). Also, the maximum (and average, omitting three single-knot sources) jet knot speed shows a positive correlation with *log R* at the 98.5% confidence level.

Five of seven sources observed show polarized emission. In both 3C207 and 3C245, we find a longitudinal jet magnetic field **B**. In 3C334, there is an isolated knot ~100 mas from the core with a transverse **B**. Rest-frame rotation measures RM in/near the core are ~600 rad/m^2 in 3C207, ~1600 rad/m^2 in 3C245, ~2000 rad/m^2 in 3C275.1, and ~3000 rad/m^2 in 3C263. Finally, the fractional polarization is ~0.01-0.05 in the cores, and ~0.1-0.5 in the jets.

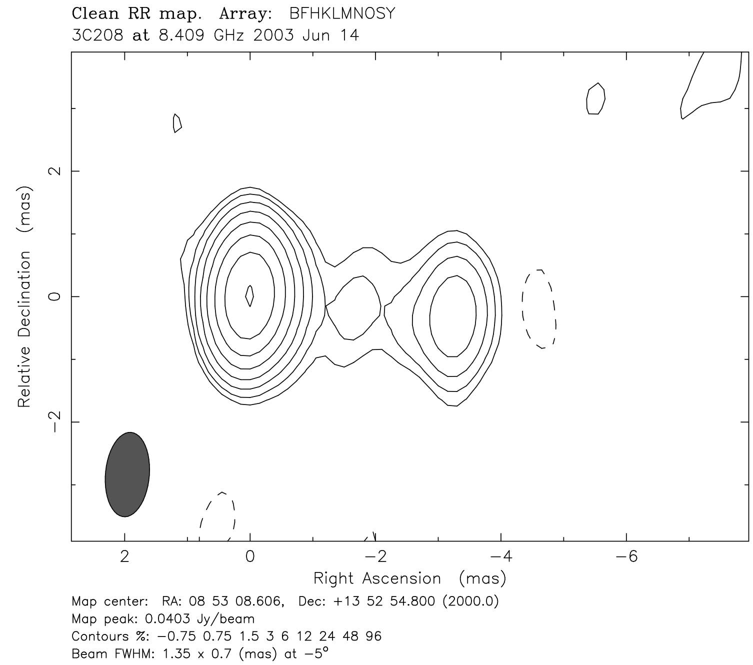

Figure 1. The parsec-scale jet in the nucleus of 3C208, 2003 June 14. The contours show total intensity at 8.4 GHz. This ∼50-mJy source is representative of the majority of 3CR LDQ nuclei, which span ∼1-100 mJy.

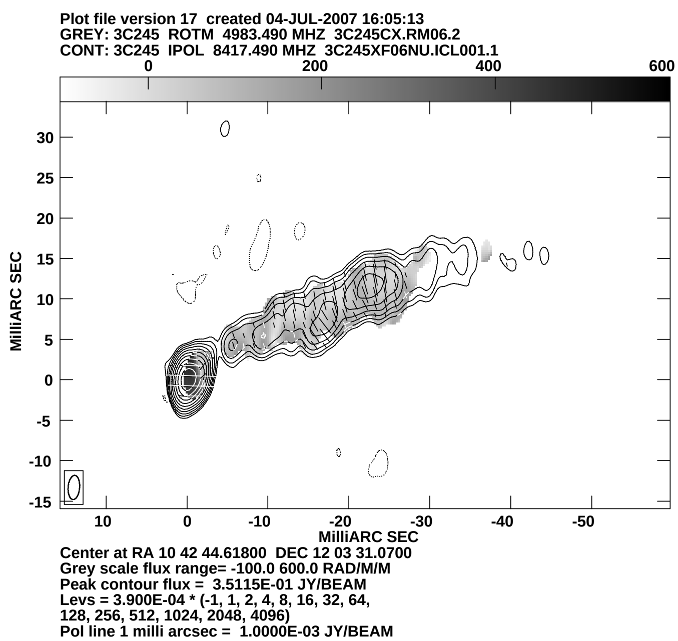

Figure 2. The parsec-scale jet in the nucleus of 3C245, 1996 June 22. The contours show total intensity at 8.4 GHz, the vectors indicate polarization intensity and position angle at 8.4 GHz, and the grey-scale represents observed rotation measure between 5 and 8.4 GHz. At ∼1 Jy, 3C245 and the similar source 3C207 have the two strongest nuclei in the 3CR LDQ sample.

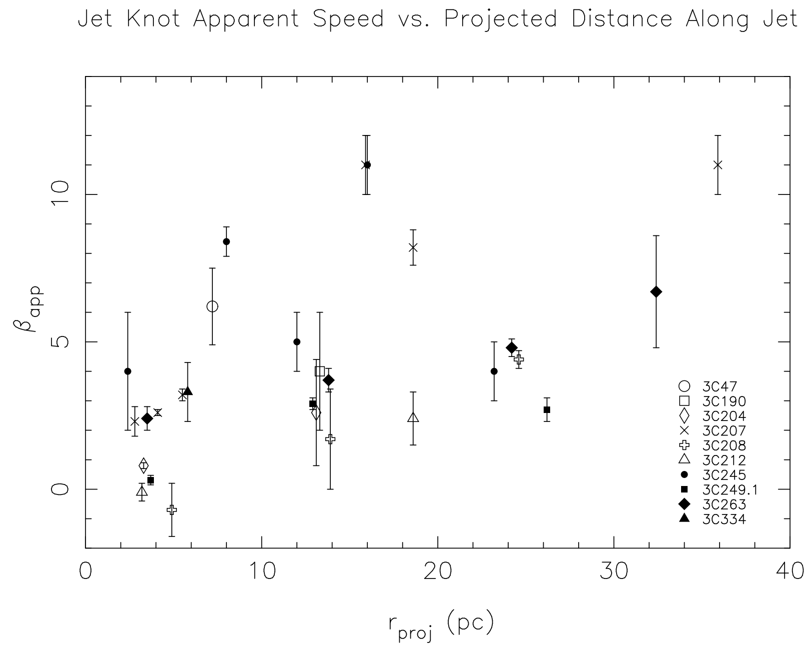

Figure 3. Jet knot apparent speed vs. projected distance along jet for ten 3CR lobe-dominated quasars.

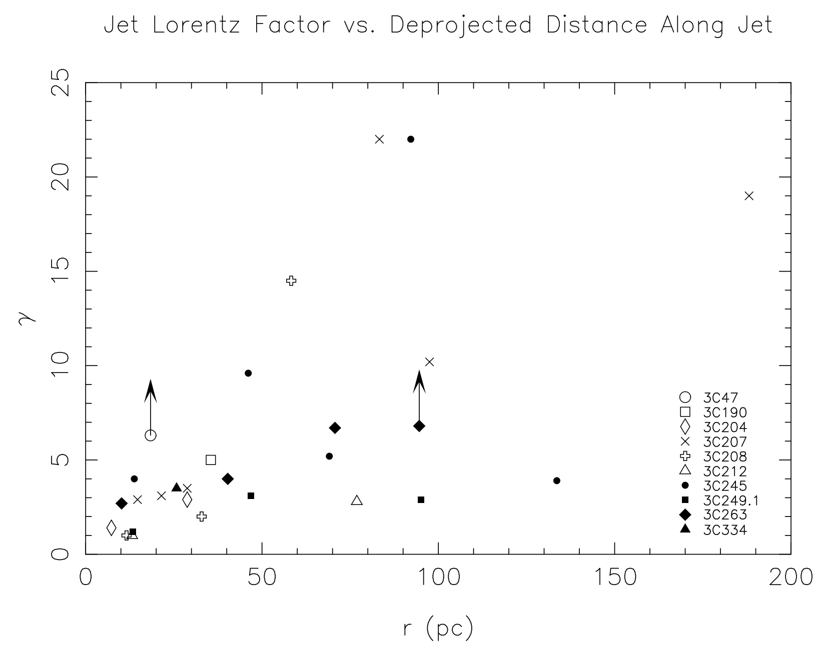

Figure 4. Jet knot Lorentz factor vs. deprojected distance along jet for ten 3CR lobe-dominated quasars. Since their observed β_{app} and assumed θ do not admit solutions for γ, the minimum Lorentz factor has been indicated for 3C47 and the outer knot in 3C263 (this would require a misalignment of the knot position and velocity vectors by $\sim$10°-15°). The values of γ estimated to be >10 for four knots are sensitive to the assumed θ; the correlation retains its >99.9% significance even when the minimum Lorentz factor is used for these four, or in fact *all*, of the knots.

4. Implications for Jet Models

Jet acceleration has usually been thought to occur on scales well below those probed by VLBI (< 0.1 pc) – e.g., Begelman (1995); such models would need to account for the observed patterns in the terminal Lorentz factors of ejected components. Alternatively, jet acceleration could be occurring on scales of tens of parsecs. There is some prior evidence for this from proper motion studies by, e.g., Zensus, Cohen, & Unwin (1995) and Homan et al. (2001). Vlahakis & Königl (2004) and Komissarov et al. (2007) have proposed "magnetic driving" of jet components on these scales. The essential feature of their models and simulations is acceleration by the gradient in the circumferential magnetic-field pressure. They easily obtain terminal Lorentz factors of ∼5-10, and report one case as high as ∼35. However, it is not clear if this model can explain the alternating "fast/slow" superluminal speeds in 3C245. The correlations between β_{app} and $log\ R$ conform to simple beaming, but may involve a selection effect since we can more easily detect fast, faint outer knots in highly-beamed sources.

In the jets, the high fractional polarization is consistent with the well-ordered longitudinal **B** resulting from shear effects, while the transverse-**B** knot suggests a shock. In the cores, significant rotation measures may be due to a Faraday screen; their low fractional polarization could be intrinsic or due to depolarization by the screen. The RM tends to decrease with R, and hence increase with θ. With only four sources the statistics are weak, but this is consistent with the jets at larger θ being viewed along a greater path length through the Faraday screen (Taylor 2000).

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