Radio and X-ray emission in MOJAVE blazars: The case of 0106+013

Preeti Kharb (Rochester Institute of Technology, Rochester, NY. Email: kharb@cis.rit.edu,
Herman Marshall (Massachusetts Institute of Technology), Matthew Lister (Purdue University)

Introduction

MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA Experiments, *http://www.physics.purdue.edu/MOJAVE*) is a long-term program to monitor radio brightness and polarization variations in AGN jets on parsec-scales with Very Long Baseline Interferometry (VLBI) (*Lister et al., 2009, AJ, 137, 3718*; see Fig. 1). The MOJAVE sample consists of 135 sources satisfying the criteria: (1) J2000.0 declination > -20 deg; (2) galactic latitude > 2.5 deg; (3) VLBA 15 GHz correlated flux density > 1.5 Jy (2 Jy for declination south of 0 degrees) at any epoch between 1994.0 and 2004.0. Of the 135 AGNs, 101 are classified as quasars, 22 as BL Lac objects, and 8 radio galaxies of mostly the FRII-type.

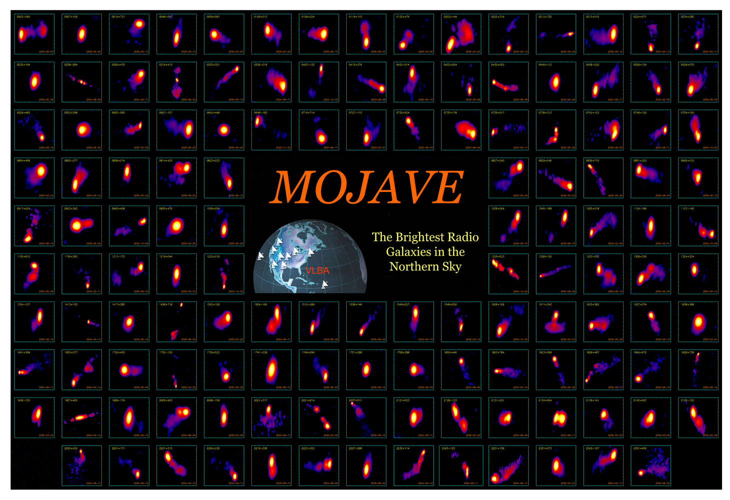

Fig. 1. 15 GHz parsec-scale images of the entire MOJAVE blazar sample.

Recent Kpc-scale Radio Observations

We have recently concluded a study of the kpc-scale radio emission in the MOJAVE blazars using the Very Large Array (VLA) in the A-array configuration at 1.4 GHz (*Cooper et al., 2007, ApJS, 171, 376, Kharb et al., 2009, submitted to ApJ*). The radio morphology varies widely across the sample, with many bent/distorted structures observed, most likely to be a result of the sources being oriented at small angles to line of sight. However, based solely on the radio morphology (eg., on the presence of hot spots), the BL Lacs cannot be distinguished from the quasars (Fig. 2).

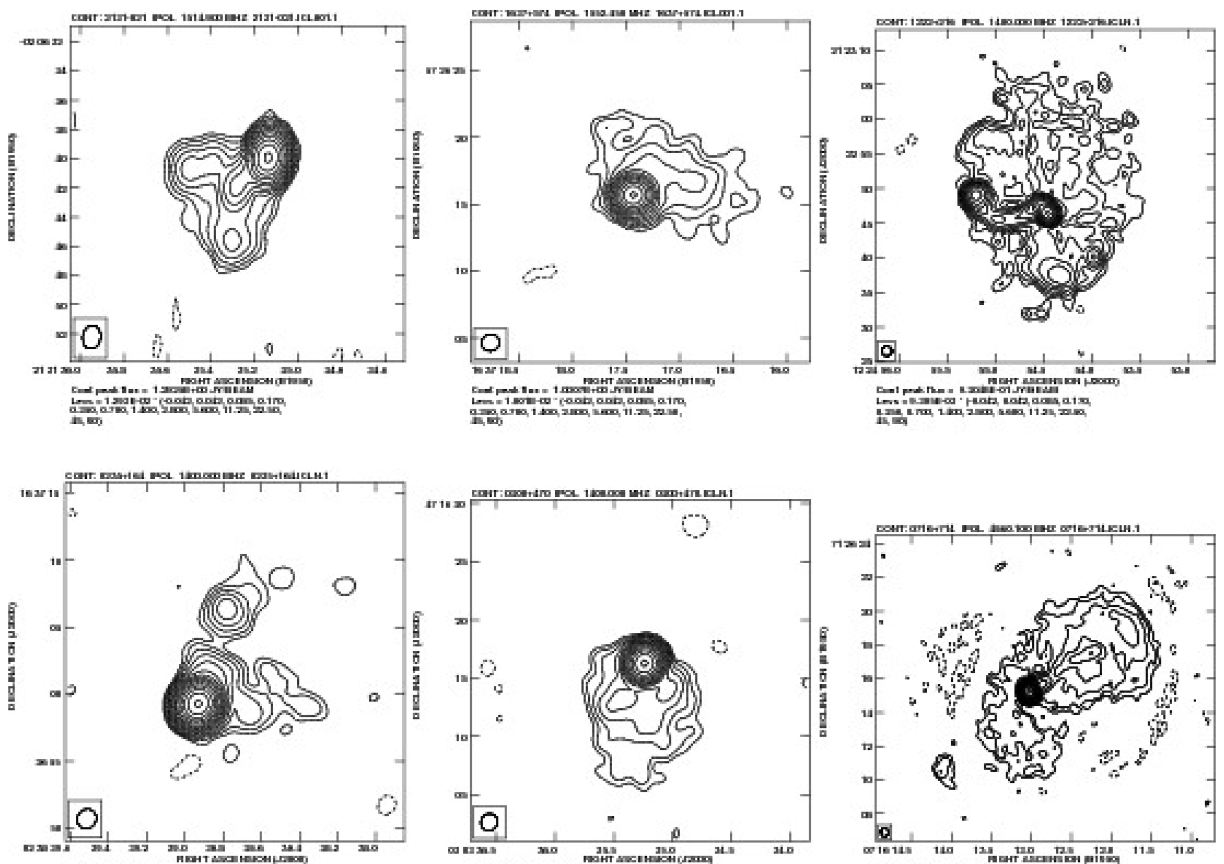

Fig. 2. 1.4 GHz radio contour images showing the kpc-scale radio emission in a few MOJAVE blazars. A wide variety of radio morphologies are observed, and the quasars (top row) are difficult to distinguish from BL Lacs (bottom row).

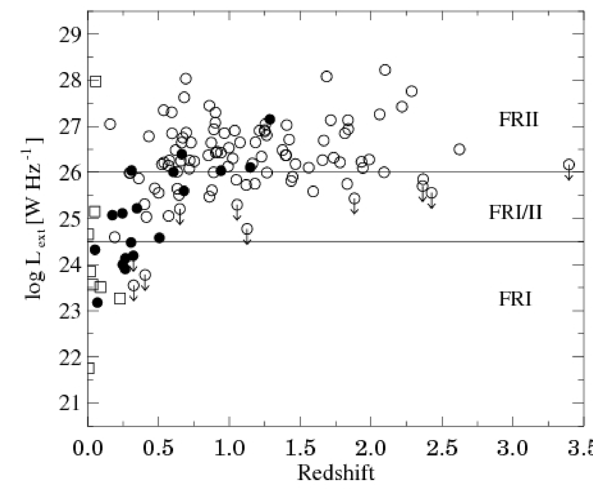

Fig. 3. The 1.4 GHz extended luminosity versus redshift. Open and filled circles denote quasars and BL Lacs, respectively, while open squares denote radio galaxies. Core-only sources are represented as upper limits.

Fanaroff-Riley Dichotomy and Unified Scheme

A majority of BL Lacs possess radio hot spots, while some quasars have diffuse "edge-dimmed" FRI-like structures. One-third of the BL Lacs also have FRII-like total radio powers (Fig. 3). One-fourth of the quasars have intermediate FRI/II radio powers. We believe that this may be due to the MOJAVE selection criterion, which is based on beamed parsec-scale radio emission, and therefore picks sources with a large range in intrinsic radio powers. These results pose challenges to the simple unified scheme that posits that BL Lacs and quasars are the beamed counterparts of FRI and FRII radio galaxies, respectively (e.g., *Urry & Padovani, 1994, PASP, 107, 803*).

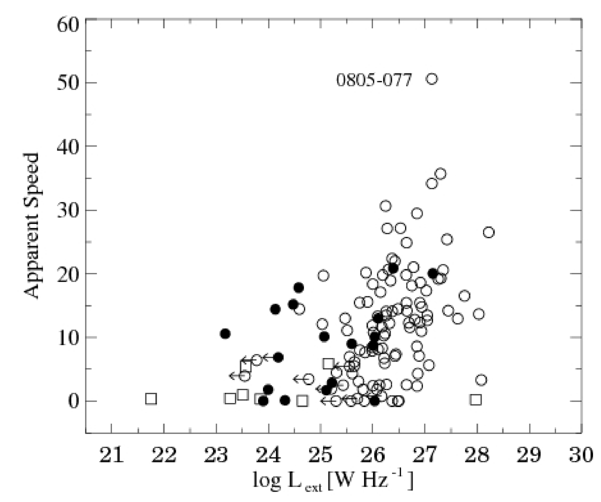

Fig. 4. 1.4 GHz extended luminosity versus the apparent jet speed. Open and filled circles denote quasars and BL Lacs, respectively, while open squares denote radio galaxies. Core-only sources are represented as upper limits.

Jet Speeds and Lobe powers

The MOJAVE monitoring has resulted in apparent speeds for individual components in the parsec-scale jets, spanning nearly a decade. We find that the kpc-scale lobe emission in the MOJAVE blazars is correlated with the fastest parsec-scale jet component speeds (Fig. 4). *More radio luminous sources have faster jets.* Both the radio powers and jet speeds vary smoothly between the BL Lac and quasar subclasses. Therefore, at least in terms of radio jet properties, the BL Lacs and quasars do not appear to be distinctly different.

Relationship to Large-scale Environment

As there have been suggestions that the lobe power is affected by jet-environment interactions on kpc-scales, we have defined the ratio of the lobe radio power to the blazar absolute optical magnitude to be a proxy for environmental effects. This ratio is correlated with redshift, as expected (e.g., *Best et al., 1999, MNRAS, 303*; see Fig. 5). While the sources with FRI powers appear to be at lower redshifts, the FRII and FRI/II sources show a similar distribution, suggesting that environmental differences are not crucial in determining the total radio power in these sources (Fig. 6). This ratio does not correlate with jet speeds, suggesting that factors intrinsic to the AGN, or the local parsec-scale enviornment influence the jets speeds, and thereby the extended radio power.

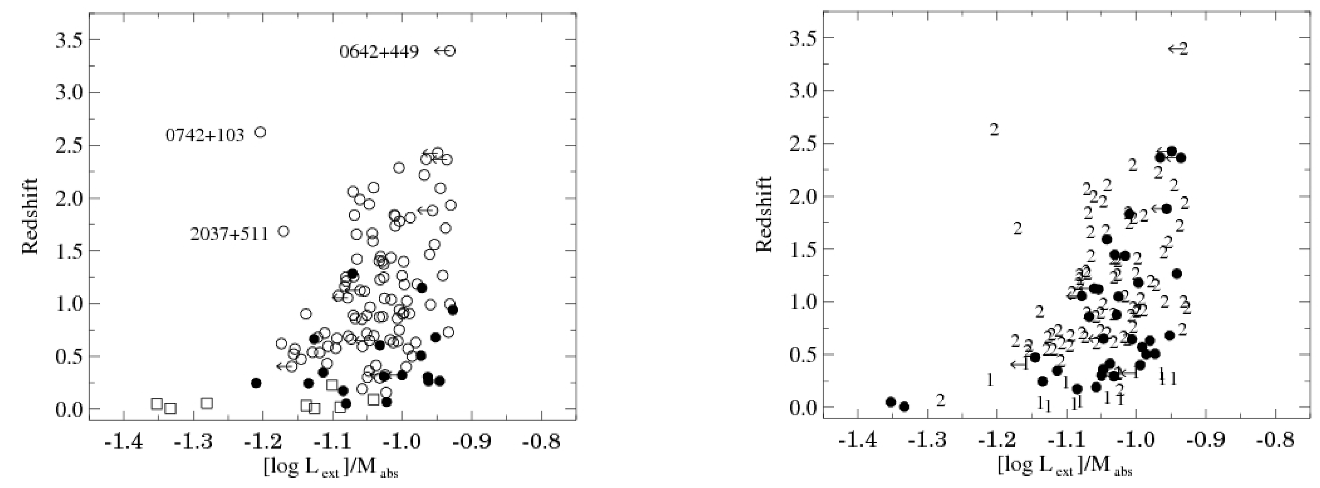

Fig. 5. The environment indicator proxy versus redshift. (Left) Open and filled circles denote quasars and BL~Lacs, respectively, while open squares denote radio galaxies. Core-only sources are represented as upper limits. (Right) Sources divided on the basis of extended radio luminosity into FRI (=1), FRII (=2), and FRI/II (=filled circles), see Fig. 3 above.

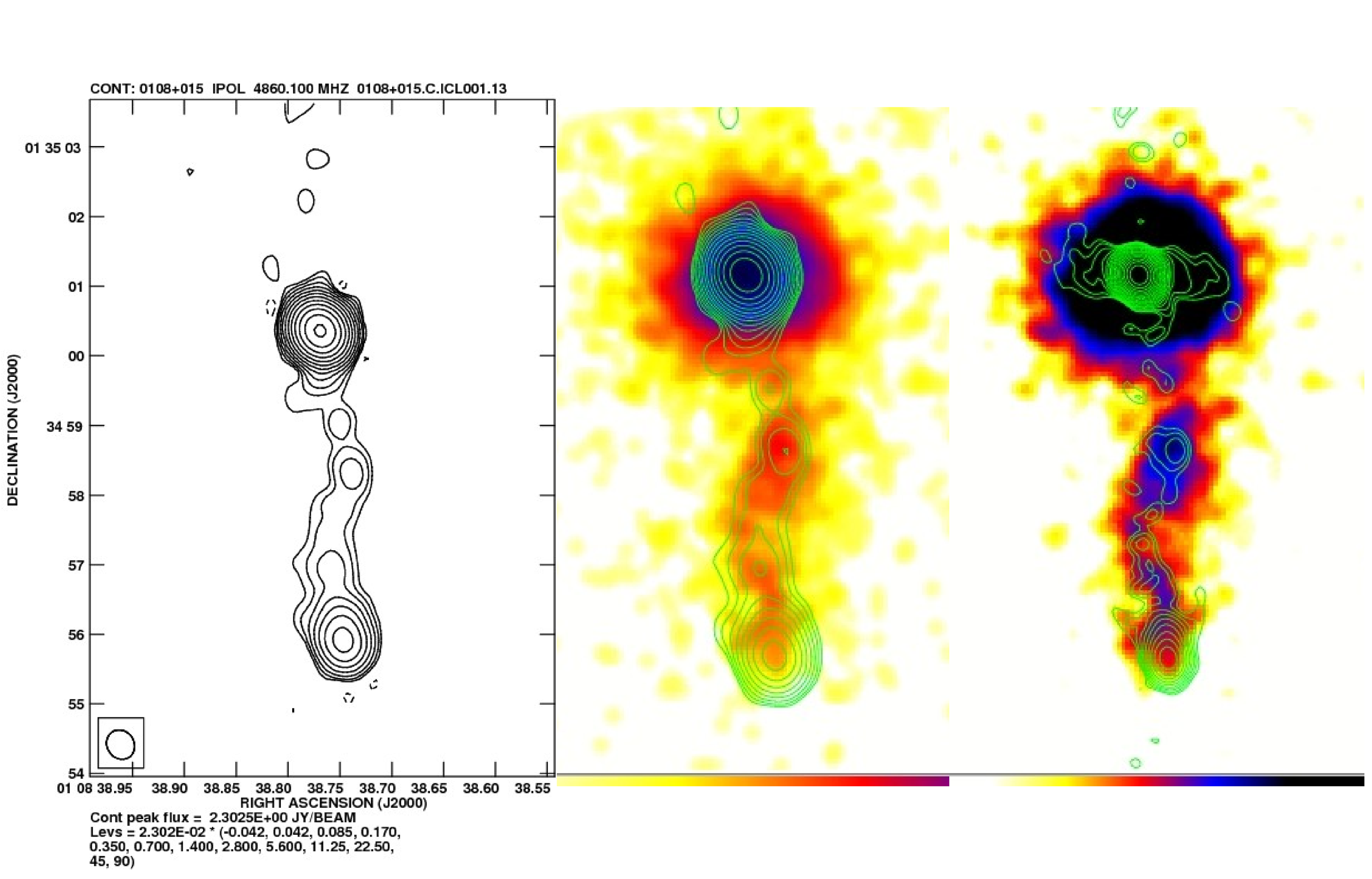

Fig. 6. (Left) The 4.9 GHz radio image of 0106+013. (Center) The Chandra 0.5 - 7 keV filtered image (in colour) with the 4.9 GHz radio contours and (Right) 8.4 GHz radio contours superimposed.

Chandra Observations of MOJAVE blazars

Of the MOJAVE blazars with significant extended radio emission, nearly 80% have revealed X-ray jets in our ~10 ks Chandra observations (*Hogan et al., in preparation*), indicative of the relevance of relativistic bulk motion in producing X-ray emission. As a followup to the pilot X-ray observations, we were awarded ~70 ks of time on the Chandra telescope for observing two MOJAVE blazars, viz., 0106+013, and 1641+399. The observations for 0106+013 took place in November 2008, while 1641+399 is scheduled to be observed next month.

0106+013 - Preliminary Findings

The highly polarized quasar 0106+013 lies at a redshift of 2.099 (1" = 8.44 kpc, H_0 = 71 km/s/Mpc). Its ~38 kpc radio jet is one-sided, suggesting a highly relativistic jet on kpc-scales, oriented close to our line of sight (Fig. 6, Left). Its highest parsec-scale jet component speed is 26.5c, making it one of the few high apparent jet speed source in the MOJAVE sample.

The data were reduced and analysed using the CIAO software version 4.1 and calibration database (CALDB) version 4.1.2. After reprocessing the level 1 events file (to remove the 0.5 pixel randomization) and creating a new level 2 file, we used the CIAO tool "eff2evt" on the energy (0.5 - 7.0 keV) filtered image to get flux estimates. The core and jet flux values are of the order of 2.5E-12 ergs/cm^2/s and 1.5E-13 ergs/cm^2/s, respectively. X-ray spectral fitting results are currently being analysed. As seen in Fig. 6, the X-ray jet follows the radio jet remarkably closely. It even appears to bend just like the radio jet, and seems to terminate just before the radio hot spot.

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