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Active Galactic Nuclei: parsec-scale radio structure

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The extreme luminosity of ACTIVE GALACTIC NUCLEI gives us the opportunity to image these objects in tremendous detail. At radio wavelengths (see also RADIOASTRONOMY) we can use the technique of Very Long Baseline Interferometry (VLBI) to obtain parsec-scale resolution images of AGN throughout the observable universe, and sub-parsec-scale resolution in a few nearby systems. These studies have revealed much about the nature of the engines at the center of activity and the spectacular ASTROPHYSICAL JETS they produce by SYNCHROTRON EMISSION. We can also use the radio source as a probe to study the atomic and molecular environment and the magnetic fields in the active centers of QUASARs, Seyfert galaxies, radio galaxies, BL Lacs, and blazars.

The first measurements of parsec-scale radio structure were derived from two antennas seperated by several thousand kilometers, yielding single-baseline VLBI measurements, in 1967 (Broten et al. 1967; and Clarke, Cohen & Jauncy 1967). These observations revealed compact components, often accompanied by more complex structures. With multiple observations, the two relatively equal components of the quasar 3C279 were discovered to be moving apart at velocities 2-3 times the speed of light. This phenomenon of apparent SUPERLUMINAL MOTION is a geometrical consequence of relativistic motion in a direction close to the line-of-sight.

Modern VLBI surveys using the Very Long Baseline Array (VLBA) show that 95% of AGN imaged have an asymmetric, core-jet morphology. The core component, presumed to be coincident with the center of activity, is generally strong, compact, time-variable, and has a flat spectral index, $\alpha \sim 0$ where ($S_\nu \propto \nu^\alpha$). The jet may consist of many components, generally with a steeper spectral index ($\alpha \sim -0.5$) and can exhibit bends, wiggles, and changes in collimation. Straight jets generally line up with larger, kiloparsec-scale jets, hot spots and lobes (see M87: THE NUCLEUS AND JET for a beautiful example), but misalignments do occur. Figure 1 shows three sources from the Caltech-Jodrell Bank Flat-spectrum VLBI survey observed at 5 GHz with full polarimetry (Pollack, Taylor & Zavala 2003). Only the approaching jet is visible due to the strong effects of Doppler boosting on

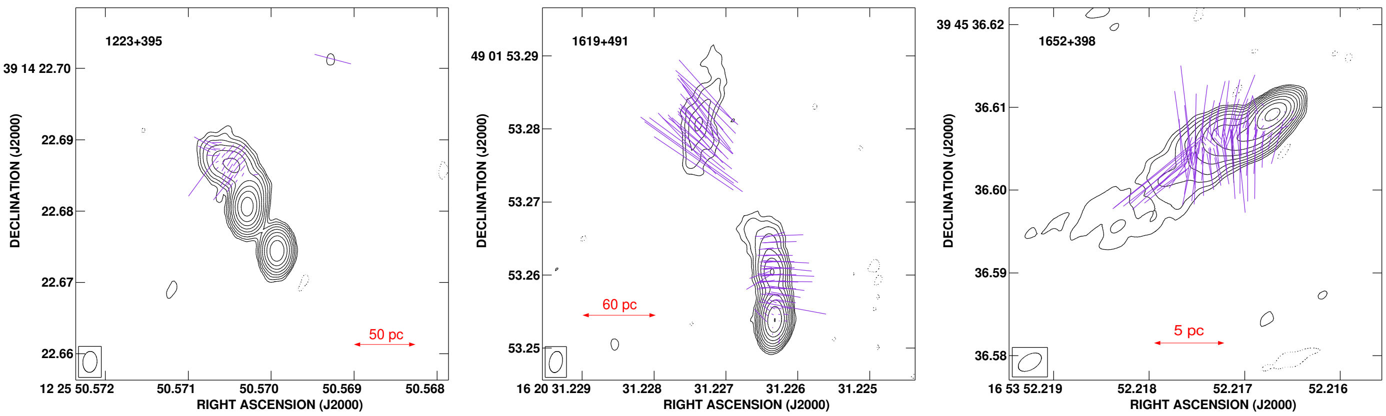

Fig. 1.— Total intensity VLBA images at 5 GHz of the radio galaxy 1223+395, quasar 1619+491, and BL Lac object 1652+398 with electric vector polarization angle (EVPA) vectors overlaid. The measured EVPAs are perpendicular to the intrinsic magnetic field orientation assuming optically thin synchrotron emission. The vector length is proportional to fractional polarization. The core component is the strong compact component at the extreme end of each source. Adapted from Pollack et al. 2003.

intrinsically symmetric jets. The flux density of the approaching jet is increased by $\delta^{2+\alpha}$ where δ is the Doppler factor related to the jet velocity by $\delta = (\gamma(1 - \beta cos(\theta))^{-1}$, while the counterjet side is similarly de-boosted. Estimates of the bulk Lorentz factors for the jets are in the range 3 – 10.

From the morphology alone it is generally difficult to distinguish between classes of AGN. The polarization characteristics are, on average, more telling. The core components are generally polarized at the level of 1-5% for BL Lacs, somewhat less for quasars, and <1% for radio galaxies. Jet components are similarly more strongly polarized for the BL Lacs and quasars (0-30%) than for the radio galaxies and Seyfert galaxies (0-10%). The decreased polarization is likely an orientation effect since the galaxies are seen through a thicker Faraday screen (see below).

Synchrotron emission is intrinsically polarized up to 70%, yet much lower values are typically observed, especially in the cores of AGN. One explanation is that a Faraday rotating screen of thermal gas exists that causes cancellation on scales smaller than the resolution. This predicts fairly high Faraday Rotation Measures, especially toward the cores of AGN. Such high RMs have recently been observed in several AGN, including 3C279 (see Figure 3). These RMs in turn tell us that the magnetic field strength in the nuclear region outside the radio plasma is $\sim 10\mu$G. Within the radio plasma the fields are likely to be much higher

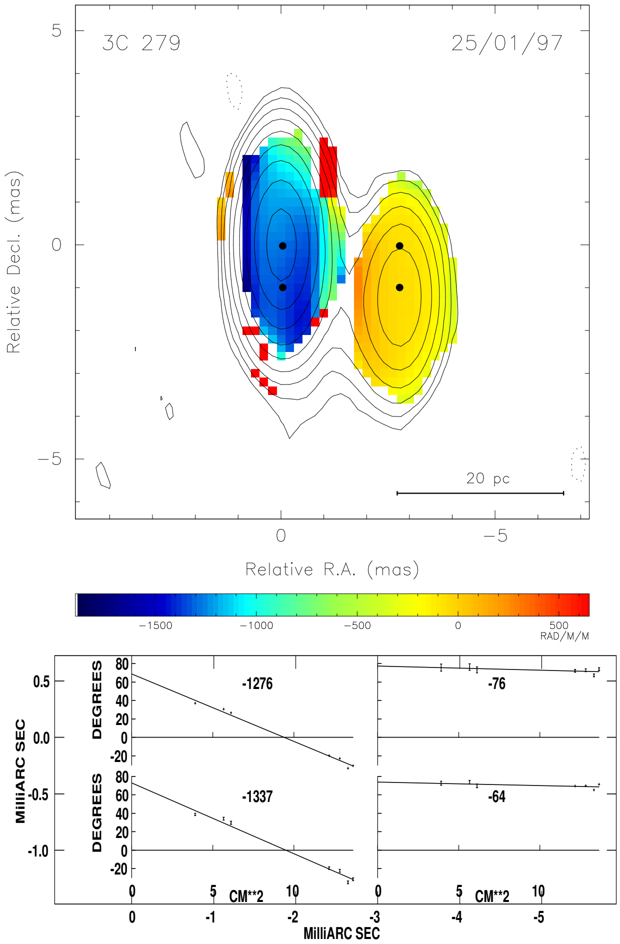

Fig. 2.— The Rotation Measure image for 3C279 in false color. The colorbar ranges from -2000 to 600 rad m^{-2}. At bottom are sample fits to 4 points showing the derivation of the RM using VLBA observations ranging from 8 to 15 GHz. Adapted from Taylor (1998).

($\sim$ 0.1 G).

The other 5% of sources observed in VLBI surveys have very different morphologies from the core-jet majority, with extended emission on both sides of a compact core (see Figure 2) that is not dominated by Doppler boosting. These Compact Symmetric Objects (CSOs) are with few exceptions compact (<1 kpc) in overall extent, and have moderately high luminosities. Other characteristics are very low polarization, identification with a galaxy, low variability, and a faint core component relative to emission from the rest of the source. The study of these objects is of particular interest because the small size of the CSOs is thought to be attributable to the youth of the source itself (ages 10^3 – 10^4 yr), rather than its confinement by a dense medium (Readhead et al. 1996a). Unifying evolutionary models have been proposed (Readhead et al. 1996b, Fanti et al. 1995) whereby these CSOs evolve into large classical radio galaxies like Cygnus A on a timescale of a few million years.

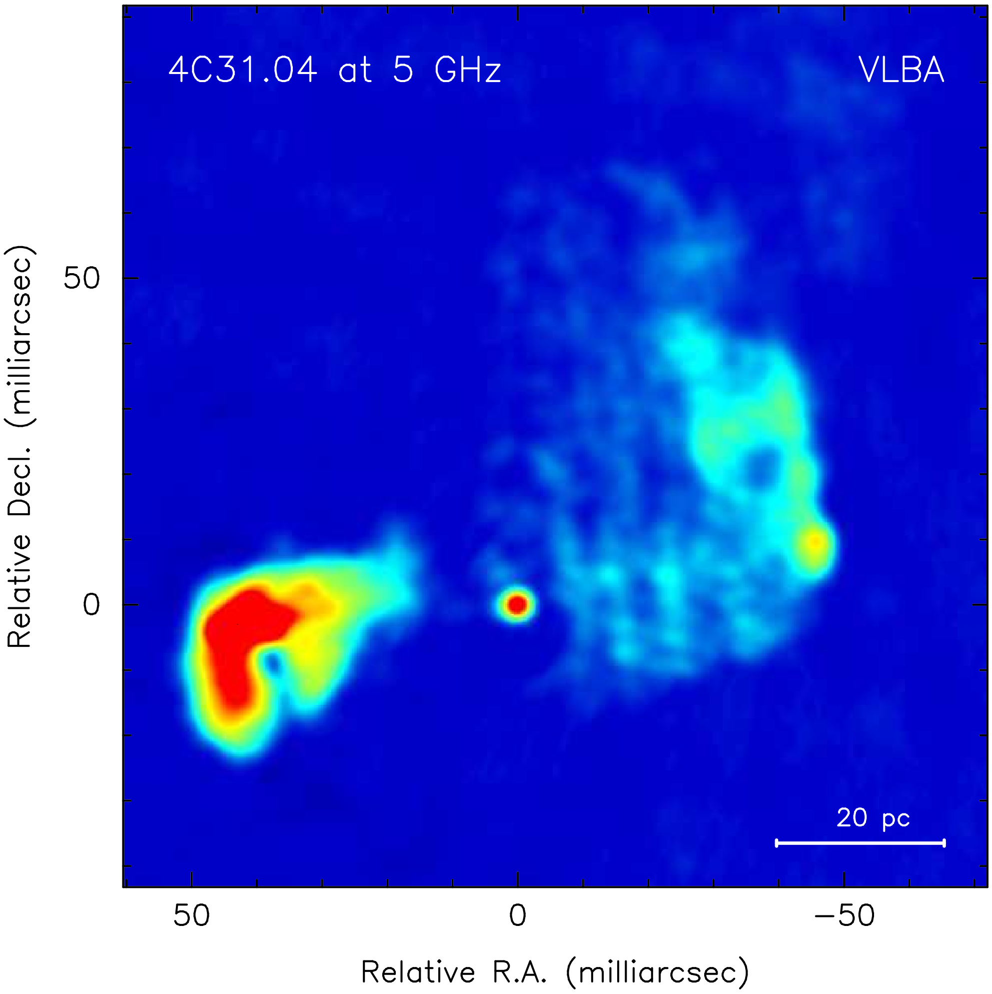

Fig. 3.— Total intensity VLBA image at 5 GHz of the Compact Symmetric Object (CSO) 4C31.04. Adapted from Giroletti et al. (2003).

Measurements of the hotspot advance speeds can provide a kinematic age estimate for CSOs. Typical velocities reported are of order 0.3c (for $H_0 = 71$ km s^{-1} Mpc^{-1}), and yield kinematic age estimates of between 200 and 2000 years.

CSOs have proved useful for testing unified schemes of active galactic nuclei, in which the differences between various classes of AGN are ascribed to orientation (e.g., quasars are viewed more nearly pole-on, while galaxies are viewed such that their jets lie closer to the sky plane). These unified schemes require an obscuring region of atomic or molecular gas surrounding the central engine and effectively shielding the inner few parsecs of the source from view if the radio axis lies at a large angle to the line-of-sight. This model is supported by observations of a few symmetric radio sources which exhibit very broad HI absorption lines, and free-free absorption (*e.g.* Peck et al. 1999). It is reasonable to assume that if CSOs are young, this circumnuclear material is accreting onto, and "feeding", the central engine, and that this process will lead to steady growth.

This discussion so far has concentrated on high luminosity sources. Only recently have unbiased, volume-limited surveys begun to take place to characterize the nature of low power sources (Giovannini et al. 2001). In general the morphologies and jet velocities are similar to those of the high power sources, suggesting that the relativistic jet velocities do not correlate with radio power. The fraction of CSOs may be somewhat higher, but more work needs to be done in this area. There are also a few sources (e.g. 3C236, 3C338) in which the radio emission appears to have self-similar expanding lobes on small and large scales, suggesting perhaps an episodic nature for the radio emission.

New observing techniques have opened up vast numbers of fainter sources that can now be studied with VLBI. Advances to shorter wavelengths and to longer baselines using spacecraft are also opening up new avenues of study. The future should bring many exciting discoveries about the parsec-scale structure of AGN. For more images of AGN on a range of scales see `http://www.nrao.edu/imagegallery/php/level1.php`.

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