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Identifying Cores, Jets, and Hot Spots in Compact Symmetric Objects

G. B. Taylor[1], A. C. S. Readhead, and T. J. Pearson

California Institute of Technology, Pasadena, CA 91125, U.S.A.

Abstract. The flux-limited VLBI survey of Pearson & Readhead (1988), along with the First Caltech-Jodrell Bank Survey (Polatidis et al. 1995; Thakkar et al. 1995; Xu et al. 1995) and Second Caltech-Jodrell Bank Survey (Taylor et al. 1994; Henstock et al. 1995) have yielded 34 objects of size < 1 kpc with emission on both sides of the central engine. These Compact Symmetric Objects (CSOs) comprise 5-10% of all high luminosity AGN. To be certain of the CSO classification requires the correct identification of the center of activity between high-luminosity radio emissions. We review the current status of multi-frequency, multi-epoch VLBI observations of the CSO candidates. Based on spectral indices, component motions and source morphologies the core, jets and, in some cases, hot spots are identified. The relative positions of the cores and hot spots are crucially important for understanding the interaction of the jets with the surrounding environment and their evolution in time. Furthermore, observations of bi-directional jet motions can be used to place restrictions on the distance to the radio source, and thereby constrain H_0.

1. Introduction

The only way to confirm the identification of a Compact Symmetric Object (CSO) candidate is by demonstrating two-sided ejection on scales < 1 kpc. This usually requires the positive identification of the central engine, although one object has been identified as a CSO based on bi-directional motion in the central jet components (1946+708: Taylor, Vermeulen, & Pearson 1995). The central engine (or core) component generally has an inverted spectrum, is compact, and is located at the center of symmetry. Given the low flux densities and strongly inverted spectra of most CSO cores (see Section 3), progress in confirming and understanding CSOs has been slow. While Phillips & Mutel (1980, 1982) first drew attention over a decade ago to a class of "Compact Double" sources (CDs), which are almost certainly CSOs, definitive proof that the two components in these objects straddle the central engine has been elusive. Some CDs were even found to be asymmetric core-jet sources in which a compact jet component happened to appear similar to the core component at the discovery frequency (Conway et al. 1994). And in the CSOs 0108+388 (Conway et al. 1994) and 2352+495 (Conway et al. 1992) a strong compact jet component was tentatively

[1]Present address: National Radio Astronomy Observatory, Socorro, NM 87801, U.S.A.

identified as the core. Sensitive, multi-frequency, multi-epoch observations are therefore essential for correctly identifying the core component.

2. Observations

The observations were carried out at 8.4 and 15 GHz using the Very Long Baseline Array (VLBA) telescope. Details of the observations and the reduction procedure are given in Taylor, Readhead, & Pearson (1996).

3. Discussion

In Figure 1 we show the 15 GHz images and spectral index maps for 0108+388. In Figures 2 and 3 we show the 15 GHz images for 0710+439 and 2352+495 respectively. In Table 1 we present a score-card summary of our results for each of the eight objects studied. Our identifications of the centers of activity show that there are substantial jet-to-counterjet brightness ratios ($>$ 10:1) in all five of the confirmed PR CSOs. So far only the one unconfirmed CSO (1031+567) lacks a strong, predominantly one-sided jet. Three possible interpretations for these large ratios are (1) relativistic beaming, (2) different external densities on the two sides and (3) an intrinsic asymmetry in the jets. A problem with significant relativistic beaming is that the "core" components in the CSOs are generally quite weak, making up typically $< 1\%$ of the total source flux density at 5 GHz. If the jets are substantially Doppler boosted then it is reasonable to expect the core flux density to be similarly enhanced. Furthermore, if these jets were strongly Doppler boosted by virtue of a favorable orientation close to the line of sight, then there should exist a much more numerous population of unbeamed sources that would have undetectable jets. The second possibility is that the jet on one side has encountered a denser medium. This denser medium may cause entrainment and/or a greater emissivity of the radio plasma. Some evidence in support of asymmetries in the external medium is that the stronger hot spot is located on the more jetted side in three out of three sources in which hot spots can clearly be identified. And in 2352+495 the bright, broad, and complex B1–B2 jet feature has the appearance of a disrupted jet. A third possibility is that the jets possess an intrinsic asymmetry which causes one side to be brighter than the other.

We also find that four of these objects: 0108+388, 0710+439, 1946+708, and 2352+495, all display a remarkable "S"-symmetry about the center of activity. This may be explained by precession of the central engine. Precession has been invoked to explain the morphologies of several kpc-scale radio sources, e.g., Hydra A (Taylor et al. 1990), 3C 315, 3C 388, NGC 326 (Gower et al. 1982). Begelman, Blandford, & Rees (1980) describe the precession resulting from two orbiting black holes. Readhead et al. (1996) have applied this model to 2352+495 and found a wide range of black hole masses and separations that can feasibly produce precession periods of $\sim$ 7000 yr.

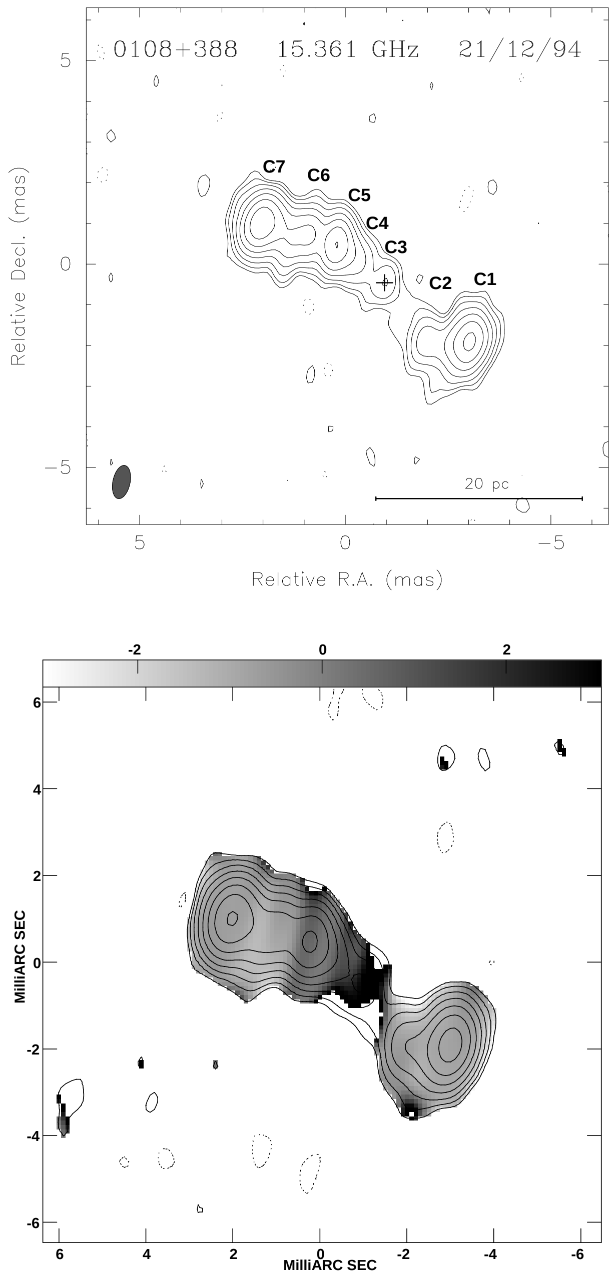

Figure 1. *Top:* The uniformly weighted 15 GHz VLBI image of 0108+388. Contours are drawn at -1, 1, 2, 4, ..., 64 mJy/beam. The cross marks the location of the center of activity. The beam size is 0.83 $\times$0.42 mas in p. a. $-12°$. *Bottom:* The spectral index map ($S_\nu \propto \nu^\alpha$) between 15 and 8 GHz at a resolution of 1.05×0.58 mas in p. a. $-10°$. The grey scale range is from -3 to 3.

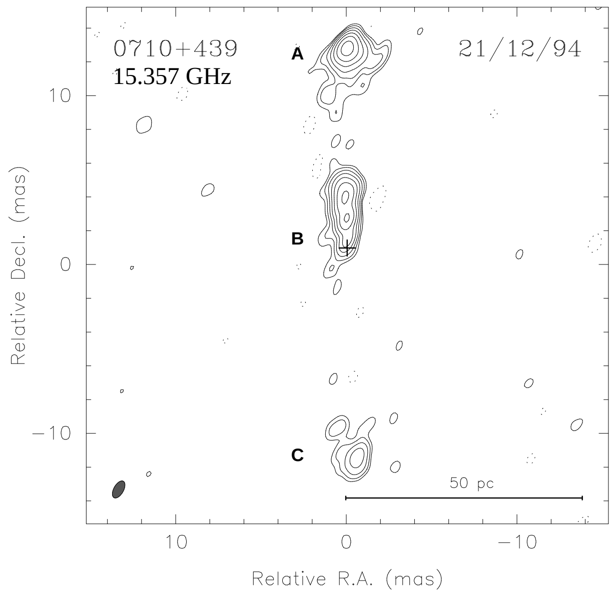

Figure 2. The naturally weighted 15 GHz VLBI image of 0710+439. Contours are drawn at -1.5, 3, 6, 12, ..., 96 mJy/beam. The cross marks the location of the center of activity. We identify components A and C as hot spots. The synthesized beam FWHM is drawn in the lower left-hand corner and has dimensions 1.12×0.57 mas in position angle $-29°$.

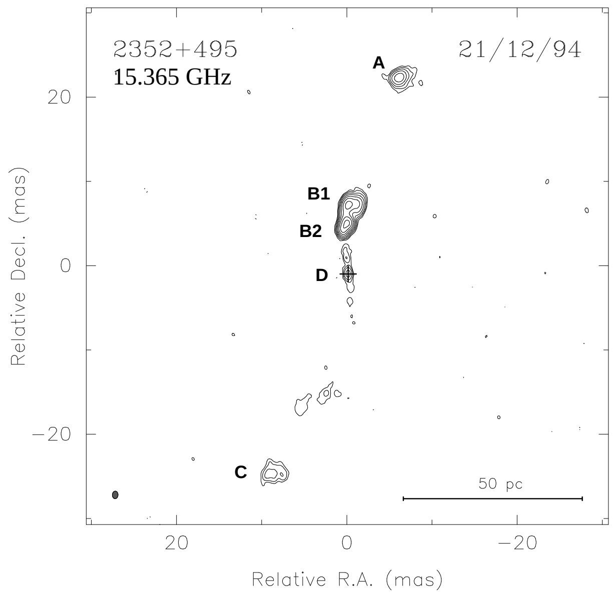

Figure 3. The naturally weighted 15 GHz VLBI image of 2352+495. Contours are drawn at -0.75, 0.75, 1.5, 3, 6, ..., 96 mJy/beam. The synthesized beam is drawn in the lower left-hand corner and has dimensions 0.91×0.67 mas in p. a. $-3°$. We identify component D as the core and components A and C as hot spots.

Table 1. Summary of Identifications

Source	Twin Lobes	Twin Jets	Twin Hot-Sp.	Invert. Core	Compact Core	Relative Motions	"S" Sym.
0108+388	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
0404+768	$\surd$			$\surd$	$\surd$		
0710+439	$\surd$		$\surd$	$\surd$	$\surd$		$\surd$
1031+567	$\surd$		$\surd$				
1242+410	$\surd$	$\surd$		$\surd$	$\surd$		
1358+624	$\surd$			$\surd$	$\surd$		
1946+708	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
2352+495	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

4. Motions in the Jet

Observations of motion in a source where the intrinsic velocity can be determined provide a direct measure of the distance to that source. Lynden-Bell (1977) first suggested that Hubble's constant could be determined from observations of superluminal extragalactic radio sources. He assumed a light-echo model in which oppositely directed components moved away from a common origin at a velocity of c. These ideas were extended to two sided jets with an intrinsic velocity $\beta = v/c$ by Pelletier & Roland (1989). The first measurements of bi-directional motion in an extragalactic radio jet were observed in the CSO 1946+708 (Taylor, Vermeulen, & Pearson 1995). In the CSOs 0108+388 (Figure 1), 0710+439 (Figure 2), and 2352+495 (Figure 3) components in the jet have been measured to be moving away from the center of activity at projected velocities of $\sim 0.6h^{-1}c$. Counterjets are apparent in 0108+388 and 2352+495 and observations to determine their velocities are in progress.

5. Conclusions

We have located the center of activity in five out of six CSOs from the Pearson-Readhead sample (see also Taylor, Readhead, & Pearson 1996), and in two objects from the CJ1 and CJ2 surveys. The core fraction tends to be low (< 0.1) even at frequencies as high as 15 GHz. This low core fraction and the complex morphologies of CSOs have hindered the identification of the center of activity and even led to misidentifications in the past. We have shown that a reliable identification of the center of activity requires sensitive, multi-frequency, multi-epoch VLBI observations. Further monitoring of all the CSOs reported on here would be useful to confirm our identifications of the centers of activity, and to obtain velocities for the jets and hot spots. In the future, phase referenced observations of CSOs to nearby objects could be used to determine the absolute motions of the components in CSOs.

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