A giant radio jet of very unusual polarization in a single-lobed radio galaxy

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Abstract We report the discovery of a very unusual, highly asymmetric radio galaxy whose radio jet, the largest yet detected, emits strongly polarized synchrotron radiation and can be traced all the way from the galactic nucleus to the hot spot located $\sim$ 440 kpc away. This jet emanates from an extremely massive black-hole ($> 10^9 M_\odot$) and forms a strikingly compact radio lobe. To a surface brightness contrast of at least 15 no radio lobe is detected on the side of the counter-jet, which is similar to the main jet in brightness upto the scale of tens of kpc. Thus, contrary to the nearly universal trend, the brightness asymmetry in this radio galaxy *increases* with distance from the nucleus. With several unusual properties, including a predominantly toroidal magnetic field, this Fanaroff-Riley type II mega-jet is an exceptionally useful laboratory for testing the role of magnetic field in jet stabilization and radio lobe formation.

1 Discovery of the largest radio jet and imaging with GMRT and Effelsberg dish

Relativistic jets, which contain highly collimated streams of plasma traveling close to the speed of light, are commonly found in diverse astrophysical environments. They are associated with some extreme relativistic phenomena such as radio galaxies and quasars, microquasars, pulsars, supernovae and gamma ray bursts. Bipolar jets in a radio galaxy or quasar are launched from the central region of an active galaxy, probably from a rotating magnetized accretion disk around a massive spinning black-hole, the “central-engine” [1]. While astrophysical jets have begun to reveal their mysteries, many of their basic properties, such as their ejection, collimation, stability and composition, remain to be understood. Fundamental questions raised by astrophysical jets include the roles of magnetic fields in their survival against internal instabilities out to distances approaching hundreds of kiloparsec from the galactic nucleus and in the formation of the radio hotspot and lobe due to the jet’s termination.

Recently we reported the discovery of a radio source associated with the bright elliptical galaxy CGCG 049-033 (at $z = 0.0446$) and displaying a unique combination of properties, including the largest detected radio jet [2]. This extraordinary object was originally spotted by us serendipitously in the NVSS database [3]. Thereafter, we imaged it with the GMRT (Fig. 1, 1.3 GHz frequency, resolution $3'' - 11''$) and with the Effelsberg radio telescope (Fig. 2, 8.4 GHz frequency, resolution $84''$). We also took its optical spectrum with the 2-meter telescope recently set up by IUCAA near Pune (India). The massive elliptical galaxy hosting this radio source is projected $22'$ (= 1.1 Mpc) away from the (radio-quiet) central elliptical galaxy of the rich cluster Abell 2040 at $z = 0.0456$. The $\sim 8.6'$ (= 440 kpc) long radio jet terminates in an edge-brightened lobe,clearly consistent with a Fanaroff-Riley II (FR II) morphology (Fig. 1).

2 Why the radio source associated with galaxy CGCG 049-033 is extraordinary?

The source is extraordinary for the following reasons:

• Its radio jet is not only the largest detected jet, it is also very strongly polarized (∼20 to 50% at 8 GHz, inspite of the large averaging by the 84″ beam). Furthermore, the inferred magnetic field orientation is predominantly orthogonal to the jet (Fig. 2), contrary to the norm for FR II jets [4]. A very similar magnetic field pattern was found by us from the analysis of the NVSS map of this jet at 1.4 GHz (Fig. 2). Thus, the jet appears to be a truly rare example where an extremely well ordered toroidal/helical magnetic field configuration is able to persist out to several hundred kiloparsecs from the nucleus.

• The radio lobe blown by this jet is strikingly compact (Fig. 1). This could be due to "blocking" of the back-flow of its synchrotron plasma by a toroidal magnetic field [5], as hinted to by the polarization vectors mapped by us.

• The two radio jets appear quite similar upto the initial ∼100 kpc, but thereafter the northern jet undergoes an abrupt fading. Any lobe formed by it has remained undetected even in the Effelsberg single-dish map, as well as GMRT and NVSS maps (Fig. 1,2). This implies an extreme factor (> 20) for the lobe flux asymmetry. Thus, contrary to the nearly universal trend, the brightness contrast between the two opposite sides of this double radio source *increases* with distance from the nucleus.

• The parent galaxy hosts a supermassive black hole of mass $\sim 2 \times 10^9$ $M_\odot$ powering the FR II radio morphology. A strong radio core (AGN) of ∼100 mJy, containing about 50% of the total flux density was found with GMRT (Fig. 1). Yet only stellar absorption lines were seen in the optical spectra of this radio galaxy taken with the 2.4-mt Kitt-Peak telescope and with the 2-mt telescope of IUCAA [2].

3 Outlook for future

We have initiated a more detailed observartion plan with VLA at λ 6cm and 3.6cm wavelengths for mapping the polarization structure of the jet, counter-jet and the radio lobe. Since this giant radio jet appears to be remarkably well collimated and stable upto an unprecedented scale of ∼400 kpc, these detailed observations will reveal what role a toroidal/helical magnetic field might play in stabilizing this remarkable radio jet. We will also search for the 'missing' northern radiolobe (Fig. 2). How abrupt is the end of the counter-jet after sustaining a surface brightness very similar to the main jet over the initial ∼100 kpc (Fig. 1)? Possible clue to this sudden onset of asymmetry (relative to the main jet) may come from determination of the magnetic field orientation in the counter-jet, which is essentially unknown as yet. We are also planning an x-ray imaging study with *Chandra* of the inner ∼100 kpc scale jet and counter-jet region close to the radio core and the associated AGN.

4 References

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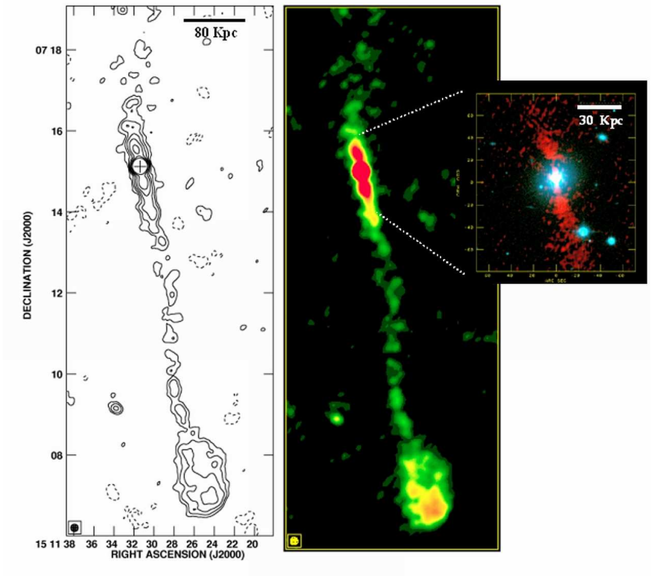

Figure 1: *GMRT maps of CGCG 049-033 at 1.28 GHz [2]* **(left)** *total intensity contours: -0.18, 0.18, 0.36, 0.72, 1.44, 3 and 6 mJy/beam; rms noise:* $\sim 60\ \mu Jy/beam$*, and the pseudo-color image* **(center)***, both with a* $11''$ *beam (FWHM). The inner* $\sim 2'$ *region* **(inset)** *is shown with the* $3''$ *resolution GMRT image (red) overlayed on the optical r-band SDSS image (blue). The '+' marks the radio core position.*

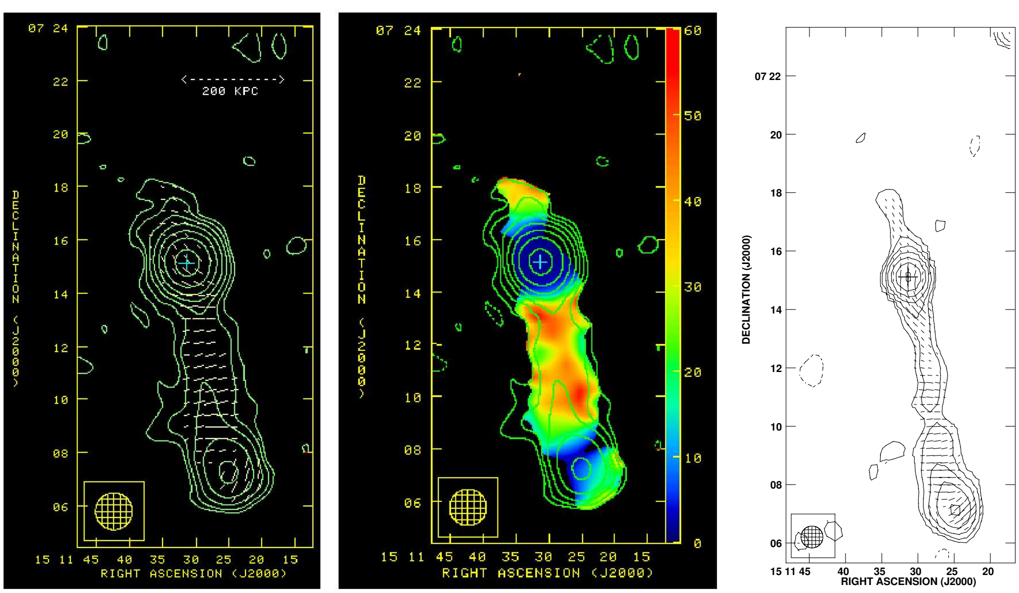

Figure 2: *Effelsberg 8.35 GHz total power contour maps: -0.75, 0.75, 1.5, 3, 6, 12, 24 and 48 mJy/beam, superposed with* **(left)** *rotation-measure corrected magnetic field vectors, having lengths proportional to the local intensity of polarized flux (scale:* $1'' = 47.6\ \mu Jy/beam$*), and* **(center)** *along with pseudo-color map of percentage linear polarization (*$84''$ *HPBW).* **(right)** *The 1.4 GHz NVSS radio map of total power (contours:* ± 1.25*, 2.5, 5, 10, 20, 40 and 80 mJy/beam,* $45''$ *HPBW), along with the scaled vectors of linear polarization (scale:* $1'' = 0.13$ *mJy/beam). The '+' marks the radio core position.*