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, predominantly one-sided radio galaxy CGCG049-033. Its radio jet, the largest detected so far, 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 20 no radio lobe is detected on the side of the counter-jet, which is similar to the main jet in brightness up to 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. Introduction

Relativistic jets, which contain highly collimated streams of plasma travelling 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” (Blandford & Payne 1982). 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.

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2. The remarkable giant radio-jet source CGCG 049-033

Recently we have 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 (Bagchi et al. 2007). This extraordinary object was originally spotted by us serendipitously in the NVSS database (Condon et al. 1998). Thereafter, we imaged it with the GMRT (Fig. 1, at 1.3 GHz frequency, resolution 3\'' to 11\'' ) and with the Effelsberg radio telescope (Fig. 2, at 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) at Girawali Observatory. 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 \( \approx 8.6\'' (= 440 \) kpc) long radio jet terminates in an edge-brightened lobe, similar to a Fanaroff-Riley II (FR II) radio-jet morphology (Fig. 1).
Figure 2. Effelsberg 8.35 GHz total power contour map: -0.75, 0.75, 1.5, 3, 6, 12, 24 and 48 mJy/beam, with (left): rotation-measure corrected magnetic field vectors, having lengths proportional to the local intensity of polarized flux (scale: 1" = 47.6 µJy/beam), and (center): with image of percentage linear polarization fraction (beam: 84" HPBW). (right): Optical spectra of CGCG 049-033 taken with IFOSC on the 2-m telescope of IUCAA and with the 2.4-m Hiltner/KPNO telescope (see Bagchi et al. (2007)).

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

Below we highlight a few striking properties of CGCG 049-033 which, when taken together, set it apart from nearly all the known FR II radio galaxies:

- Its remarkably well collimated radio jet is not only the largest detected jet, it is also very strongly polarized ($p \sim 20$ to 50% at 8 GHz, inspite of the averaging by the large 84" beam). Furthermore, The observed strong linear polarization and its orientation imply a well organized transverse (toroidal) magnetic field for this giant radio jet. The projected magnetic field orientation is predominantly orthogonal to the jet (Fig. 2), contrary to the norm for FR II jets (Bridle et al. 1994). 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 a scale $>100$ kpc from the nucleus.

- The radio lobe inflated by this giant jet is strikingly compact with hardly any back-flow. This could be result of “blocking” of the back-flow of its synchrotron plasma by a toroidal magnetic field (Nishikawa et al. 1997), as hinted to by the polarization map (Fig. 2).

- The two radio jets appear quite similar upto the initial $\sim100$ kpc, but thereafter the northern jet undergoes an abrupt fading. Any lobe formed by it could not be detected even in the Effelsberg single-dish map, as well as GMRT and NVSS maps (Fig. 1 and 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 optical spectrum reveals that the host galaxy harbours a supermassive nuclear black hole of mass $\sim 2 \times 10^9 \, M_\odot$. This is reflected in the very large stellar velocity dispersion $\sigma_* = 375 \pm 35 \, \text{km s}^{-1}$ of absorption lines and large bulge luminosity in K-band ($M_K = -26.22 \pm 0.044$, $L_{K, \text{bulge}} = 6.5 \times 10^{11} L_{K,\odot}$).

The observed core-to-lobe flux density ratio, $f_c = 1.67$ at 1.28 GHz is an extreme value; for FR II radio galaxies with matching radio lobe power to CGCG 049-033, $f_c$ is typically only $\sim 0.1$ (Zirbel and Baum 1995). The large excess in $f_c$, by a factor $F \sim 17$, could be attributed to relativistic beaming which can boost the core flux by a factor $\sim \delta^n$ (usually $n \sim 2$ for compact flat-spectrum jets, and the Doppler factor is $\delta = \left[ \Gamma_j (1 - \beta_j \cos\theta) \right]^{-1}$, where $v_j = c\beta_j$ is the bulk speed of jet and $\Gamma_j$, the bulk Lorentz-factor). The corresponding viewing angle $\theta$ of the nuclear jet (Giovannini et al. 1994): $\cos(\theta) = \left[ 0.5 + (\sqrt{F} - 1)/\beta_j / \sqrt{F} \right]$, is then quite small ($\theta \lesssim 28^\circ$, for $\beta_j \lesssim 1$). Such small angles are jointly disfavored by the projected giant radio size, the apparent symmetry of the inner jets and the identification with a galaxy (Barthel 1989). Jet bending on parsec scale can result in a strongly Doppler boosted nuclear jet (despite the large projected size of source). However, the observed straightness and good alignment of the inner kiloparsec jets disfavor this scenario (Fig. 1).

4. Outlook for future

A higher resolution mapping of the polarization structure of the jets and the radio lobe will reveal what role a toroidal/helical magnetic field might play in stabilizing this remarkable radio jet upto an unprecedented scale of $\sim 400$ kpc. The observed quasi-regularly spaced ($\sim 40$ kpc) sequence of radio knots (Fig. 1) as well as its excellent collimation make this mega-jet a prime target for probing jet confinement mechanisms. A deeper radio imaging of this jet could be used to test viability of the theory of jet stabilization upto $>100$ kpc scales via a spine-sheath type flow (Hardee et al. 2007), or the jet collimation by a surrounding high pressure ambient medium, leading to a sequence of reconfinement shocks (Komissarov & Falle 1998). An X-ray imaging study with Chandra of the inner $\sim 100$ kpc scale jet and counter-jet region, the associated AGN and the hot gaseous halo of the host galaxy is being planned.

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