Detection of the VLBI-Scale Counter Jet in NGC 6251

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Abstract

Mapping the central 5 pc region of the nearby radio galaxy NGC 6251 with a 0.2 pc resolution using VLBI at two radio frequencies, 5 GHz and 15 GHz, we have found the sub-pc-scale counter jet for the first time in this radio galaxy. This discovery allows us to investigate the jet acceleration based on the relativistic beaming model (Ghisellini et al. 1993).

1   Introduction

The genesis of powerful radio jets from active galactic nuclei is one of the long standing problems in astrophysics (Bridle & Perley 1984). Although global morphological properties give us very important information, the very inner regions in the radio jets also provide hints to understanding the genesis of radio jets. In order to investigate radio galaxies at sub–milli-arcsecond angular resolution, we have performed new high-resolution VLBI observations of NGC 6251 using HALCA (Hirabayashi et al. 1998). We use a distance to NGC 6251 of 94.4 Mpc (for a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}). Note that 1 mas (milli-arcsecond) corresponds to 0.48 pc at this distance.

2   Observations

NGC 6251 was observed at 5 GHz using VSOP on 30 April 1998 and at 15 GHz using VLBA on 2 June 1998. Details of the observations are summarized in Table 1. In order to perform beam-size-matched comparison between 5 GHz and 15 GHz, we restored the two images with a same spatial resolution of 0.50×0.50 mas.

Table 1: Observations.

Epoch	ν (GHz)	Stations	Peak Int. (Jy/beam)	RMS noise (mJy/beam)	DR[1]
1998.33	5	VLBA, HALCA, EB[2]	0.13	0.50	260
1998.42	15	VLBA	0.34	0.25	1400

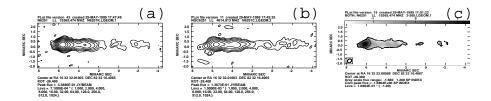[1]DR : Dynamic range; [2]EB : Effelsberg 100-m telescope

Figure 1: The images of NGC 6251 at 15 GHz (a) and at 5 GHz (b). The images are rotated clockwise on the sky by 28°. The spectral index map is shown in (c). Here the spectral index α is defined as $S_\nu \propto \nu^\alpha$.

3   Results

Our final maps at 15 GHz and 5 GHz are shown in Figure 1a and 1b, respectively. Although the secondary peak is seen at both frequencies, its angular distance from the 15 GHz brightest peak is larger by 0.3 mas (0.14 pc) than that at 5 GHz. This difference may be attributed to the different opacity toward the central engine at 5 GHz and 15 GHz.

Here we apply two new methods for the registration using correlation functions between intensity profiles and between wiggling patterns of the radio jet at the two frequencies. The correlation function of intensity profiles exhibits the maximum correlation coefficient $\simeq 0.98$ at an offset of 0.30 ± 0.11 mas, indicating that the peak at 5 GHz is shifted to the jet direction from that at 15 GHz. Analysis of wiggling patterns gives an offset of 0.60 ± 0.36 mas with a correlation coefficient of $\simeq 0.66$. Since these two offsets were obtained using two independent methods, we adopt a weighted average of the two offsets. Thus the best offset of 0.42 ± 0.14 mas is obtained. Using this offset, we register the two images and obtain a spectral index image of the radio jet as shown in Figure 1c. An optically thin component on the opposite side of the jet can be seen. We conclude that this is the real counter jet.
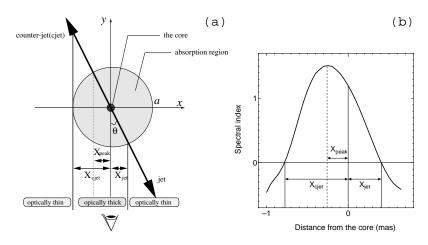
Figure 2: A schematic illustration of the spherical-absorption model (a), and spectral index variation along the radio jet of NGC 6251 (b).

4   Discussions

We assume for simplicity that the core is surrounded by a plasma sphere with a radius of a and the radio emission from the inner part of the jets (i.e., both the jet and the counter jet) suffer from free-free absorption. The approaching jet escapes from the plasma sphere at a projected distance of $x = a \times \sin\theta_{\mathrm{jet}}$ and thus the spectral index is its intrinsic value here. The counter jet suffers the effect of free-free absorption until $x = -a$. It is also noted that the path length is longest at $x = -a \times \sin\theta_{\mathrm{jet}}$. As shown in Figure 2a, we define the following projected distances; $X_{\mathrm{jet}} = X_{\mathrm{peak}} = a \times \sin\theta_{\mathrm{jet}}$ and $X_{\mathrm{cjet}} = a$. Then we are able to estimate $\theta_{\mathrm{jet}} = \sin^{-1}\left(\frac{X_{\mathrm{jet}}}{X_{\mathrm{cjet}}}\right)$. We adopt the 15 GHz brightest peak as the core, because the optical depth at 15 GHz is sufficiently small in the case of free-free absorption. In Figure 2b, we show the observed spectral index variation along the radio jet. We estimate $X_{\mathrm{peak}} \approx 0.24\,\mathrm{mas}$, $X_{\mathrm{jet}} \approx 0.41\,\mathrm{mas}$, and $X_{\mathrm{cjet}} \approx 0.80\,\mathrm{mas}$. Then we obtain $\theta_{\mathrm{jet}} \simeq 31°$.

Adopting the so-called Doppler beaming model, the jet–to–counter-jet intensity ratio R can be written as a function of projected distance x, $R(x) = \left[\frac{1+\beta_{\mathrm{jet}}(x)\cos\theta_{\mathrm{jet}}(x)}{1-\beta_{\mathrm{jet}}(x)\cos\theta_{\mathrm{jet}}(x)}\right]^{2-\alpha(x)}$, where $\beta_{\mathrm{jet}}(x) = v_{\mathrm{jet}}(x)/c$. In Figure 3a, we measured R as a function of x. It is shown that R is estimated to be systematically larger at 5 GHz than those at 15 GHz. This is probably due to stronger absorption at 5 GHz than at 15 GHz. It is shown that
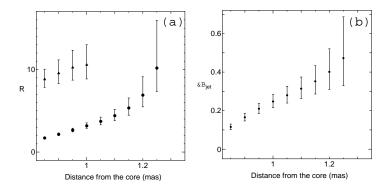
Figure 3: The jet/counter jet flux density ratio R as a function of the projected distance from the brightest peak at 15 GHz for the 5GHz data (filled triangles) and for the 15 GHz data (filled circles) (a), and jet velocity β_{jet} as a function of projected distance from the brightest peak at 15 GHz (b).

R at 15 GHz increases from 1.7 at 0.85 mas (0.4 pc) to 10 at 1.25 mas (0.6 pc) with projected distance from the core. If this increase is just caused by the Doppler beaming, it is suggested that β_{jet} increases with distance, because θ_{jet} does not appear to vary significantly. Figure 3b shows that the jet is accelerated from $\beta_{jet} \approx 0.1$ at 0.4 pc to $\beta_{jet} \approx 0.5$ at 0.6 pc. This provides the first direct evidence for the acceleration in the sub-pc-scale radio jet.

References

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