LIMB-BRIGHTENED JET OF 3C 84 REVEALED BY THE 43 GHz VERY-LONG-BASELINE-ARRAY OBSERVATION

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ABSTRACT

We present a study of the sub-parsec scale radio structure of the radio galaxy 3C 84/NGC 1275 based on the Very Long Baseline Array data at 43 GHz. We discover a limb brightening in the “restarted” jet that is associated with the 2005 radio outburst. In the 1990s, the jet structure was ridge brightening rather than limb brightening, despite the observations being done with similar angular resolutions. This indicates that the transverse jet structure has recently changed. This change in the morphology reveals an interesting agreement with the γ-ray flux increase, i.e., the γ-ray flux in the 1990s was at least seven times lower than the current one. One plausible explanation for the limb brightening is that the velocity structure of the jet is in the context of the stratified jet, which is a successful scenario that explains the γ-ray emission in some active galactic nuclei. If this is the case, then the change in apparent transverse structure might be caused by the change in the transverse velocity structure. We argue that the transition from ridge brightening to limb brightening is related to the γ-ray time variability on the timescale of decades. We also discuss the collimation profile of the jet.

Key words: galaxies: active – galaxies: individual (3C 84, NGC 1275, Perseus A) – galaxies: jets – radio continuum: galaxies

1. INTRODUCTION

The radio source 3C 84 is associated with the giant elliptical/radio galaxy NGC 1275 (z = 0.0176). Its classification by radio luminosity is Fanaroff–Riley type-I (e.g., Chiaberge et al. 1999). Due to its brightness and proximity, this source is one of the best-studied radio sources in history. Recently, increased activity, which started in 2005, has been detected in the radio band (Abdo et al. 2009). The very long baseline interferometry (VLBI) observations revealed that this flux density increase originated within the central parsec-scale core, accompanying the ejection of a new jet component (Nagai et al. 2010, hereafter Paper I). This new component appeared from the south of the core around 2003 and is moving to the position angle ∼160° steadily with slightly changing speed in both parallel and perpendicular directions (Suzuki et al. 2012, hereafter Paper II). The apparent speed ranges from 0.1c to 0.5c (Paper II). The moving direction of the new component is clearly different from the direction of the pre-existing component near the core, separated about 0.5 mas along the position angle of −150°. The flux density of both the new component and the core particularly increased after 2007–2008, and the new component showed a further increase in flux density after 2009 (Nagai et al. 2012, hereafter Paper III).

It is notable that 3C 84 is the best studied γ-ray radio galaxy along with M87 and Centaurus A, and therefore these sources are ideal laboratories for the study of the γ-ray emission mechanism in misaligned active galactic nuclei (AGNs). Strong variability in the γ-ray emission has been detected from 3C 84 by the Large Area Telescope (LAT) on board Fermi. An averaged γ-ray flux during the first four months is (2.10±0.23)×10−7 ph cm−2 s−1 above 100 MeV. This γ-ray flux is seven times brighter than the upper limit estimated by EGRET/CGRO. It was claimed that the innermost jet of 3C 84 is the most likely source of γ-ray emission because of the different γ-ray activity level between EGRET era and Fermi era (Abdo et al. 2009). During the first two years of observation, variations on the timescale of a month were observed by Fermi-LAT in γ-rays: one occurred in 2009 April–May (Kataoka et al. 2010), and the other one occurred in 2010 June–August (Brown & Adams 2011). In particular, photons up to 102.5 GeV were detected during the second flare. The largest increased activity in GeV band was reported on 2013 January 21 (Ciprini 2013). An average daily γ-ray flux is six times greater than the average flux reported in the second Fermi-LAT catalog.

In Paper III, the radio time variability was studied to search for a possible correlation with the γ-ray variability, but no clear correlation was found on the timescale of γ-ray time variation. Neither new component ejection nor change in morphology associated with the γ-ray flares were found by VLBI observations (Paper III). The lack of significant changes in radio band for 3C 84 after the detection of high γ-ray activity leaves the debate on the region responsible for the high-energy emission and its location still open. Besides, the apparent speed detected by VLBI is relatively slower than the jet speed predicted by the one-zone synchrotron-self Compton model or deceleration jet model unless the jet angle to the line of sight is very small (<5°: Paper II). This indicates that the gamma-ray emitting region may have a higher Lorentz factor, and that the emission may be more strongly beamed than would be implied by the Lorentz
factor estimated from the VLBI proper motions. We also performed a spectral energy distribution (SED) fit to the observed broadband spectrum using the estimated apparent speed, but it failed to reproduce the optically thin radio spectrum observed by VLBI (Paper II).

While several possible scenarios to reconcile the discrepancy between radio and \( \gamma \)-ray properties have been discussed in earlier works (Papers I, II, and III), it is of great interest to investigate the presence of stratified structure with a velocity gradient (Ghisellini et al. 2005) in the jet of 3C 84. According to this scenario, the radio emission is mostly coming from the slower sheath, while the emission from the spine is beaming away from the line of sight. Therefore, the limb brightening can be observed along the jet if the spine-sheath structure is present. Clear evidence of limb brightening is found in several AGNs such as M87 (Junor et al. 1999), Mrk 501 (Giroletti et al. 2008), Mrk 421 (Piner et al. 2010), and 1144+35 (Giovannini et al. 1999), but no clear signature of limb brightening has been found in 3C 84 thus far. To detect the limb brightening, high spatial resolutions that can resolve the transverse direction of the jet and high dynamic range images are required. In this paper, we report a new Very Long Baseline Array (VLBA) observation at 43 GHz to investigate the transverse structure of the jet in 3C 84. We mainly focus on discussing the origin of limb brightening, but we also present the collimation profile that can be obtained by resolving transverse direction.

The redshift of 3C 84 corresponds to the angular scale of 0.344 pc mas\(^{-1}\) assuming \( H_0 = 70.7 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.27\), and \( \Omega_\Lambda = 0.73\). The mass of the central super massive black hole was estimated to be \( 3.4 \times 10^9 M_\odot \) (Wilman et al. 2005), which yields \( 10^7 r_g = 9.5 \times 10^{-2}\) mas, where \( r_g \) is Schwarzschild radius.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were carried out using 10 VLBA stations at 43 GHz on 2013 January 24. The data consists of eight intermediate frequencies (IFs) with a 32 MHz bandwidth for each IF. Total bandwidth is 256 MHz per polarization. Both right-hand and left-hand circular polarizations were obtained, and only parallel-hand correlations (RR and LL) were obtained in the correlation process because the polarization information is outside the scope of this observation. We performed a phase-referencing mode observation by switching the pointing between the target source and the calibrator, J0313+4120. The observation consisted of many different scans for 3C 84 and the calibrator as well. The integration time for each scan is 10 s. Total observing time for 3C 84 is about 45 minutes, and the overall observations, including calibrator scans, were spanned over 8 hours. The scans for 3C 84 were spread evenly over different hour angles, and therefore we obtained good \( \nu \tau \)-coverage. In this paper, we do not present the phase-referencing image but focus on the self-calibrated image. The purpose of phase-referencing analysis is to measure the core-shift effect (e.g., Hada et al. 2011). This will be reported in a forthcoming paper (T. Haga et al., in preparation).

The data reduction was performed using the AIPS developed by the NRAO. An a priori amplitude calibration was performed using the aperture efficiency and system noise temperature provided by each station. The opacity correction for the atmospheric attenuation, fringe fitting, and bandpass calibration were applied. For the deconvolution of the synthesized image, we used CLEAN and the self-calibration technique. Final images were obtained after a number of iterations with CLEAN as well as both phase and amplitude self-calibrations using the DIFMAP software package (Shepherd et al. 1994).

3. RESULTS

Figure 1 shows the self-calibrated image of 3C 84. In previous studies it was shown that the parsec-scale structure mostly consisted of three components. We have detected the same structure, but a finer scale structure is visible from our image. The bright core and one-sided jet structure is clearly seen. The jet position angle is \(-170^\circ\) up to 1.2 mas from the core and then slightly changes to the position angle \(-180^\circ\). At the end of the jet, there is a bright knot-like feature. While this feature was represented by a single Gaussian component (labeled C3 in Figure 1) in the previous studies, multiple subcomponents are seen from this image. The changing pattern of the jet direction is approximately consistent with the previously detected path of C3 motion (Paper II). There is an elongated feature (C2) toward the west from the C3 region, which invokes the backflow from C3. However, C2 was already been present before the emergence of C3. Therefore, the origin of C2 and its connection with C3 is not very clear. We did not detect any significant emission from the counter-jet side.

The most remarkable finding is that the limb brightening is evident along the approaching jet, which is the “restarted” jet associated with an ongoing activity started in 2005. Similar quality of images have been available from the Web site of Boston University’s blazar monitoring program\(^\footref{9}\) since 2010.

\[ \Omega_\Lambda = M_\odot / 2 \]

\[ r_g = 9.5 \times 10^{-2} \]
November 1. At that time, the morphology of the 3C 84 jet was limb-brightened, and all images available up to 2013 July 28 are in very good agreement with the image presented here. In the VLBA 43 GHz images during the period 2002–2008 (Paper II), the transverse structure was not very clear. This is probably due to the lack of dynamic range. Dhawan et al. (1998), Romney et al. (1995), and Lister (2001) reported the 43 GHz VLBA images of 3C 84 as of 1990s. From those images, no clear limb brightening was seen, though similar angular resolution was achieved. One might also think that this is due to the lack of dynamic range. However, we note that the most sensitive observation by Dhawan et al. (1998) achieved better image noise than our observation, thanks to a much longer integration time (73% duty cycle for 14 hr) and the participation of one Very Large Array antenna. We also created an image with the same contour levels and convolved beam as the image presented in Dhawan et al. (1998), but the limb brightening is still visible (see Figure 2). Therefore, the apparent transverse structure of the jet has indeed changed recently, and this change has occurred at least before 2010 November (first epoch of Boston program) and after 1999 April (the observation epoch of Lister 2001).

The resolved jet in transverse direction allows us to study the jet width profile. We produced the slice profiles of the total intensity across the jet at different cross-sections along the jet. The slices were made at every 0.15 mas step (roughly the same size as the synthesized beam) from the core along the position angle $-10^\circ$ up to 1.5 mas and along the position angle $0^\circ$ beyond. Examples of the slice profiles are shown in Figure 3. The slice profiles are well represented by two Gaussian components. To evaluate the jet width, we fitted two Gaussians to the slice profiles and measured the separation between the peaks of the Gaussians. In some cases an additional Gaussian component between two Gaussians was required, and we regarded the separation between two outer components as the jet width. The slice at 0.15 mas from the core is represented by a single Gaussian due to the lack of resolution. We regard the FWHM as the upper limit of the jet width. Figure 4 shows the jet width as a function of the distance from the core. The power-law fit yields a power-law index of $0.25 \pm 0.03$. The change in the jet width as a function of the distance indicates the collimation profile of the jet, which is a key quantity in the study of the jet formation mechanism. This will be discussed in Section 4.2. The issue of how to determine the jet width may be controversial. We also evaluated the jet width by the separation between the outer

![Figure 2](image2.png) Same map as Figure 1, but the contours are plotted at $-20, 20, 28, 40, \ldots, 640$ mJy beam$^{-1}$ with the convolved beam, FWHM $0.20 \times 0.15$ mas, at the position angle $0^\circ$. These are the same contour levels and beam size as those reported in Dhawan et al. (1998).

![Figure 3](image3.png) Transverse slice profile of the jet. The left and right figures show the profiles along (a) and (b), indicated by the dashed lines in Figure 1, respectively.

![Figure 4](image4.png) Jet width profile. The open squares and open circles represent the measurement for LL and RR maps, respectively. The filled triangle indicates the upper limit constrained by the FWHM of a single Gaussian component. The error of jet width is smaller than the size of each symbol. The horizontal axis is shown in the deprojected distance, assuming the viewing angle of $25^\circ$. Both vertical and horizontal axes are shown in the unit of Schwarzschild radius. Here, we adopt $3.4 \times 10^8 M_\odot$ for the black hole mass (Wilman et al. 2005). The dashed and dotted lines are the power-law fits for LL and RR data, and the resultant power-law indices are $0.25 \pm 0.03$ for both cases.
sides of the half-maximum points of the two Gaussians. The resultant power-law index is ~0.31, which shows no significant difference from the case where the width is defined by the peaks of the two Gaussians. In this paper, we adopt the former case for the definition of the jet width.

For the consistency check, we performed the calibration and subsequent imaging for RR and LL correlations independently. The Gaussian fit to both RR and LL images shows a good agreement (see Figure 4).

4. DISCUSSION

4.1. Limb Brightening

Limb brightening is expected to be detected as if there is a velocity gradient across the jet and the beaming-cone angle of the emission from the “spine” is smaller than the jet viewing angle (e.g., Giroletti et al. 2004; Kataoka et al. 2006). So far, we have not detected a clear correlation in light curve between the radio and γ-ray in 3C 84 on the timescale of days to months. Also, the observed apparent motion is relatively slower than the jet velocities expected from the γ-ray emission models. Yet, such a lack of correlation between radio and γ-ray is expected as the radio emission is dominated by the synchrotron radiation from the slow sheath and the γ-ray emission is dominated by the comptonization of both the spine and sheath photons by the electrons in the sheath (see bottom panel of Figure 5 in Ghisellini et al. 2005). Such a “spine-sheath” structure is also favored to explain the γ-ray luminosity. The observed γ-ray luminosity of 3C 84 by Fermi-LAT is of the order of $10^{44}$ erg s$^{-1}$. This is already comparable to the typical observed γ-ray luminosity of low-frequency, peaked BL Lac objects (LBLs), which are the small-viewing angle counterparts of FRI radio galaxies in the context of the unification scheme (Urry & Padovani 1995). However, the Doppler factor of radio galaxies would be smaller than that of LBLs. This problem would be eased if the 3C 84 was dominated not by the fast spine but by the slow sheath (Kataoka et al. 2010).

Here, we roughly estimate the outflow velocity of the limb-brightened region. For simplicity, we assume an intrinsically uniform brightness across the jet in the transverse direction and the observed transverse brightness is only affected by the transverse velocity structure that results in the varying Doppler enhancement of different jet axisymmetric layers. With this assumption, the limb-brightened structure corresponds to a layer where the Doppler factor becomes maximum. Assuming the viewing angle (θ) of 25° adopted in Abdo et al. (2009), the Doppler factor reaches its maximum where the bulk Lorentz factor (Γ) is about 2.4 ($β ∼ 0.9$). Thus, for having a limb brightening morphology, as observed in 3C 84, we require the velocity of the limb-brightened region (sheath) and the inner dim region (spine) to be $Γ ∼ 2.4$ and $Γ \gg 2.4$, respectively. The estimated Lorentz factor of the limb-brightened region seems somewhat faster than the VLBI-measured velocity of C3 in Papers I and II. This may indicate that C3 is the terminal hotspot and its motion does not reflect the jet flow itself.

Apparent velocity constraints depend on the viewing angle. In principle, it is possible to give a constraint on the viewing angle from the jet/counter-jet intensity ratio argument. However, in the case of 3C 84, non-detection of counter jet is not only due to the Doppler effect but also due to the free-absorption effect as reported in Walker et al. (2000). This makes it difficult to obtain a robust constraint on the viewing angle. The detection of counter jet by a higher dynamic range observation would be useful to get a constraint on the viewing angle, providing us with an indication of whether this value changed with respect to previous estimations (Walker et al. 2000; Asada et al. 2006; Lister et al. 2009).

Dhawan et al. (1998), Romney et al. (1995), and Lister (2001) reported the 43 GHz VLBA images of 3C 84 as of the 1990s. From those images, no clear limb brightening was seen despite the fact that similar angular resolution was achieved. One possible explanation for this difference, assuming a constant jet viewing angle and intrinsically uniform brightness distribution across the jet, is a change in the transverse velocity structure. If the flow velocity in the spine has become faster, such a change can be produced.

Alternatively, the apparent change of jet structure from ridge brightening to limb brightening could be explained by a change in the jet viewing angle with constant jet physical properties. If the jet viewing angle was very small in the 1990s while the recent viewing angle is moderate, the ridge brightening could appear only in the 1990s because of the strong beaming of the spine emission toward the observer. However, we feel that this possibility is very unlikely. If the viewing angle was small and the physical properties of the jet (such as magnetic field and electron energy distribution) were similar to the current ones, 3C 84 should have been detected as a bright γ-ray source because of the strong beaming effect. Contrary to this, the upper limit of γ-ray flux estimated by EGRET in the 1990s was at least seven times weaker than the recent flux level.

The ridge brightening appeared in a low γ-ray state and the limb brightening appears in an on-going high γ-ray state, revealing an interesting agreement. In the spine-sheath structure, the external Compton in the sheath is the dominant contribuor to γ-ray emission at large viewing angles (Ghisellini et al. 2005; Tavecchio & Ghisellini 2008). Thus, we speculate that the origin of the γ-ray high state might be the result of an increase in the energy of the seed photons from the spine, related to a possible increase of the spine flow velocity as well as in a brightness increase of the sheath region. How such a change in the transverse velocity can occur is an open question, but the restarted activity of 3C 84 may be tied to this change. Yet, the sheath Doppler factor of 2.4 ($δ ∼ 2.4$, where $δ$ is the Doppler factor) could be problematic for the synchrotron peak position. Recent SED modelings, including very high energy γ-ray data in 2009 October–2010 February and 2010 August–2011 February, show that $δ = 2$ shifts the synchrotron bump to lower frequencies and the resultant SED disagrees with the observed optical, UV, and X-ray data. Higher Doppler factor ($δ ∼ 4$) is favored to reproduce those data (MAGIC Collaboration 2013). However, we note that this SED modeling does not fit to the radio data. This may require an additional emitting component to reproduce the whole electromagnetic spectrum. In any case, the limb-brightened structure in the 3C 84 jet suggests that the jet property in transverse direction is not uniform and this should be taken into account for the broadband SED modeling.

The transverse velocity structure is just one possible explanation for the limb brightening and we cannot exclude other possibilities. Here, let us briefly comment on them. The limb brightening can result from the helically wrapped magnetic field structure as discussed in the explanation of the limb brightening of M87 (Owen et al. 1989). More recently, Clausen-Brown et al. (2011) analyzed in detail the transverse intensity profile of a cylindrical jet with a helical magnetic field for various conditions. It is shown that a limb brightening is evident in the
case of $\theta_{ob} \sim 1$ rad, where $\theta_{ob}$ is the jet viewing angle in the observer frame. It should be noted that the observed brightness ratio between eastern and western limbs in 3C 84 is not constant. The western limb is brighter near the core ($\sim$0.5 mas from the core) while the eastern limb is brighter between $\sim$0.5 mas and $\sim$1.5 mas from the core (see Figure 1). Then, the western limb becomes brighter again beyond $\sim$1.5 mas from the core. This side-to-side change of brightness pattern is similar to a filament cutting diagonally across the jet, invoking the helically wrapped side-to-side change of brightness pattern is similar to a filament & Duffy 2004. With this framework, the coincidence of the ∼core) while the eastern limb is brighter between ∼0.5 mas and ∼1.5 mas from the core.

5. CONCLUSION

While the jet structure was rather ridge brightening in the 1990s, clear limb brightening has been discovered in the sub-pc scale jet of 3C 84, which was formed by the restarted activity observed since 2005. Although several possibilities are considered, we propose that the change from ridge brightening to limb brightening may be attributed to a change in the transverse velocity structure on the basis of a “spine-sheath” scenario. This is compatible with the lack of the radio counterpart of short-term $\gamma$-ray flares reported in Paper II. The jet width profile in the $\sim10^{-5} - 10^{-3}$ mas scale is rapidly collimated rather than parabolic shaped and differs from the trend in M87, which might reflect the different circumnuclear environment between M87 and 3C 84. Higher resolution studies are important to probe whether the limb brightening is present in the innermost region of 3C 84 and study the collimation profile as well. Future high-resolution instruments, such as (sub)millimeter VLBI including phase-up ALMA, will give us a hint of the jet physics in connection with the $\gamma$-ray emission and jet formation theory.

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