



Publication Year	2018
Acceptance in OA	2020-10-28T11:19:12Z
Title	Evidence of Jet-Clump Interaction: A Flip of the Radio Jet Head of 3C 84
Authors	Kino, M., Wajima, K., Kawakatu, N., Nagai, H., ORIENTI, Monica, Giovannini, Gabriele, Hada, K., Niinuma, K., GIROLETTI, MARCELLO
Publisher's version (DOI)	10.3847/1538-4357/aad6e3
Handle	http://hdl.handle.net/20.500.12386/28041
Journal	THE ASTROPHYSICAL JOURNAL
Volume	864

EVIDENCE OF JET-CLUMP INTERACTION: A FLIP OF THE RADIO JET HEAD OF 3C 84

M. KINO^{1,2}, K. WAJIMA³, N. KAWAKATU⁴, H. NAGAI², M. ORIENTI⁵, G. GIOVANNINI^{5,6}, K. HADA², K. NIINUMA⁷,
M. GIROLETTI⁵*Draft version August 28, 2018*

ABSTRACT

Radio jets in active galaxies have been expected to interact with circumnuclear environments in their early phase evolutions. By performing the multi-epoch monitoring observation with the KVN and VERA Array (KaVA) at 43 GHz, we investigate the kinematics of the notable newborn bright component C3 located at the tip of the recurrent jet of 3C 84. During 2015 August–September, we discover the flip of C3 and the amount of the flip is about 0.4 milli-arcsecond in angular scale, which corresponds to 0.14 parsec in physical scale. After the flip of C3, it wobbled at the same location for a few months and then it restarted to propagate towards the southern direction. The flux density of C3 coherently showed the monotonic increase during the observation period. The flip is in good agreement with hydrodynamical simulations of jets in clumpy ambient medium. We estimate the number density of the putative clump based on the momentum balance between the jet thrust and the ram pressure from the clump and it is about 10^{3-5} cm^{-3} . We briefly discuss possible origins of the clump.

Subject headings: galaxies: active radio continuum: galaxies gamma rays: galaxies galaxies: individual (3C 84, NGC 1275)

1. INTRODUCTION

Active galactic nuclei (AGNs) are powered by surrounding gas accretion onto supermassive black holes (BHs) at the center of each galaxy. Since the circumnuclear material plays important roles of a gas reservoir for the accretion flow, its nature, such as the structure, the size, and the mass, has been intensively investigated (e.g., Ramos Almeida and Ricci 2017 for review). While AGNs themselves radiate across the entire electromagnetic spectrum, from the radio and up to γ -rays, circumnuclear material do not emit significant electromagnetic signal. Hence, circumnuclear matter distributions in particular at the central parsec scale regions in AGNs are highly uncertain. Observationally, there are some indications of inhomogeneous matter distribution. VLBI observations of young radio sources reveal that a large fraction of young radio lobes with a two-sided structure show the asymmetry in arm-length ratio and their flux density from a pair of the lobes and the pair of the lobes satisfies a brighter-when-farther behavior (Dallacasa and Orienti 2013; Orienti and Dallacasa 2014; Orienti 2016). This asymmetry can be naturally explained by the inter-

action between the jet and an inhomogeneous environment. At X-ray energy band, time variations in absorbing column density on timescales from months to years have been known, which indicate highly non-uniform circumnuclear material such as clumps on a sub parsec scale (Ives et al. 1976; Malizia et al. 1997; Risaliti et al. 2002). Theoretically, jets are thought to have a strong impact on the interstellar medium of a host radio galaxy. The deposition of jet mechanical energy may affect formation of stars in the host galaxy and the accretion of matter down the gravitational potential onto the central BH, which is so called AGN feedback (e.g., Silk and Rees 1998; Bicknell et al. 2000; King 2003; Croton et al. 2006; Fabian 2012). In the context of AGN feedback, Wagner and Bicknell (2011) ran numerical simulations of AGN jets interacting with a non-uniform medium containing dense clumps, focusing in the effects of the AGN jet on the cold dense clumps in which stars were formed. Intriguingly, Wagner and Bicknell (2011) indicate flips of the jet head caused by the interaction with the clumps, although such a phenomenon has not yet been observed so far. Similar behavior have been also reported in several other studies (e.g., Fragile et al. 2017). However, no direct evidence for such dramatic impact is yet reported so far.

NGC 1275 is a notable nearby giant elliptical galaxy at the core of the Perseus cluster, with an optically luminous nucleus, currently classified as a Seyfert 1.5/LINER (Sosa-Brito et al. 2001). Interestingly, Nagai et al. (2010) found the emergence of newborn bright component so-called C3 during multi-epoch monitoring of 3C 84 using Very Long Baseline Interferometer (VLBI). The component C3 showed a proper motion towards the southern direction with the apparent velocity of $0.2 - 0.3 c$ (Nagai et al. 2010; Suzuki et al. 2012; Hiura et al. 2018). Since various observations of 3C 84 indicate the gas-rich environment such as molecular gas (Krabbe

motoki.kino@nao.ac.jp

¹ Kogakuin University of Technology & Engineering, Academic Support Center, 2665-1 Nakano, Hachioji, Tokyo 192-0015, Japan² National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan³ Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea⁴ National Institute of Technology, Kure College, 2-2-11, Agaminami, Kure, Hiroshima, 737-8506, Japan⁵ INAF - Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy⁶ Dipartimento di Astronomia, Università di Bologna, via Gobetti 103/2, I-40129, Bologna, Italy⁷ Graduate School of Sciences and Technology for Innovation, Yamaguchi University, 1677-1 Yoshida, Yamaguchi, Yamaguchi 753-8512, Japan

et al. 2000; Salome et al. 2006; Lim et al 2008), warm $[H_2]$ gas (Wilman et al. 2005; Scharwachter et al. 2013) and dense ionized plasma surrounding the 3C 84 jet (O’Dea 1984; Walker et al. 2000), 3C 84 is regarded as a quite unique laboratory to explore interactions between the jet and the circumnuclear environment on parsec scale. In this work, we will report the KaVA monitoring observation of 3C 84 during 2015-2016, in which we indeed discover a theoretically predicted a flip of the jet head accompanying the clear increase of the C3 flux density.

In this work, we define the radio spectral index α_R as $S_\nu \propto \nu^{-\alpha_R}$. The cosmological parameters used here are as follows; $H_0 = 71$ km/s/Mpc, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$ (e.g., Komatsu et al. 2011). The redshift of 3C 84 ($z = 0.018$) is located at the distance 75 Mpc and it corresponds to 0.35 pc mas $^{-1}$. The mass of the black hole in NGC 1275 is estimated to be around $M_\bullet \approx 8 \times 10^8 M_\odot$ (Schawachter et al. 2013) and we adopt this value. Corresponding Eddington luminosity is $L_{\text{Edd}} \approx 1 \times 10^{47}$ erg s $^{-1}$. Normalized physical quantity is denoted as $Q = 10^x Q_x$, otherwise stated.

2. OBSERVATION AND DATA REDUCTION

From 2015 August to 2016 June, we conducted full-track 12 epochs monitoring of 3C 84 at 43 GHz with KaVA, the combination of the Korean VLBI Network (KVN) and the Japanese VLBI Exploration of Radio Astrometry (VERA) radio arrays. The joint array, KaVA, has a total of seven antennas at frequencies of 22 and 43 GHz, resulting in angular resolutions of about 1.2 and 0.6 mas, respectively. Basic imaging capabilities of KaVA has been summarized in detail by Niinuma et al. (2014) and Hada et al. (2017). Left-hand circular polarization was received and sampled with a 2 bit quantization. All the data were recorded at 1 Gbps (256 MHz bandwidth, 16 MHz, 16 sub-bands) and correlated by the Daejeon correlator. As a technical note, we note that in the flux calibration of KaVA one visibility amplitudes of KaVA correlated by the Daejeon hardware correlator (Lee et al. 2015a) should be corrected by multiplying the factor of 1.35 (Lee et al. 2015b).

In Figure 1, we show the visibility amplitude and phase obtained in one of the KaVA monitoring epochs with a typical data quality. On-source time for 3C 84 was about 6-7 hours and that is sufficiently long for obtaining a good uv-coverage. The typical size of the original beam of KaVA at 43 GHz is 0.6-0.7 mas and we restored all of the images with the beam size of 0.75 mas. In Table 1, we show the observation summary dealt in this work. As seen in the second column of the Table 1, some stations were lost (station(s) followed after the minus sign mark in the second column) in some of the KaVA monitoring observations due to system troubles in some of the epochs. Three epochs of the images obtained by the Very Long Baseline Array (VLBA) in the framework of the Boston University (BU) Blazar monitoring program (<https://www.bu.edu/blazars/research.html>) are also included for consistency check purpose. We followed the standard procedures for initial phase and amplitude calibration using the National Radio Astronomy Observatories (NRAO) Astronomical Imaging Processing System (AIPS) (Greisen 2003). *A priori* amplitude calibration was applied using the measured system noise temperature and the elevation-gain curve of each antenna. We

calibrated the bandpass characteristics of phase and amplitude at each station using the auto-correlation data. Following the amplitude calibration, fringe-fitting was performed to calibrate the visibility phases, and finally the data were averaged over each intermediate frequency band. The imaging and self-calibration were performed in the Difmap software (Shepherd 1998) in the usual manner.

3. OBSERVATIONAL RESULTS

3.1. Position of C3 component

Let us estimate the positional accuracy of C3 relative to C1.⁸ The peak positions of the C1 and C3 components are determined based on the standard model-fitting procedure in Difmap. First, we estimate a systematic error in position due to the positional scattering of the peak position of C1 from the origin-point in the difmap during the period when the peak flux density of C1 is brighter than that of C3 (first half of our observation period). From the data, we obtained the positional scattering of C1 about 0.02 – 0.07 mas. Second, we should estimate the systematic error. A deconvolution error is known as a major systematic error and it is possibly caused by some other component such as the C2 component (e.g., Nagai et al. 2010). In our observation, however, the peak flux density of C3 ($\gtrsim 5$ Jy) is more than the factor of ~ 3 brighter than that of C2 (0.9 – 1.8 Jy) and the separation angle of C2 and C3 (~ 2 mas) is larger than the beam size of KaVA at 43 GHz ($\sim 0.6 - 0.7$ mas). Therefore, it is clear that the deconvolution error by C2 is negligibly small. Third, we add to note that a nominal estimate of the position accuracy, i.e., the KaVA beam size divided by the dynamic range (a few 10^3) is even much smaller than the systematic error by the peak position scattering of C1. Based on these error estimations, we conservatively set the positional accuracy of C3 relative to C1 as 0.07 mas. The error bars in the position in Figure 2 correspond to the 0.07 mas. Since both of C1 and C3 are so bright that one can generally obtain a quite high positional accuracy of C3 relative C1, which is clearly reflected in the high values of the dynamic ranges shown in the Table 1.

For consistency check purpose, we have included three epochs of VLBA archival data from the Boston University (BU) Blazar monitoring program. The peak positions of C3 with VLBA (see Appendix) are also shown in Fig. 3 with the triangle mark and these locations are consistent with those measured with KaVA.

Generally, one should be aware that C3 has substructures in it (e.g., Nagai et al. 2014; Giovannini et al. 2018). When we discuss these substructures inside the C3 component, then a higher spatial resolution is required since substructures can not be resolved with the KaVA beam. In the present work, we focus on the kinematics of the spatially-averaged positions of C3 and thus the KaVA beam size is enough for this investigation. We also confirm good agreements of spatially-averaged positions in C3 between KaVA and VLBA images shown in Appendix.

In terms of structures around C3, we should also note

⁸ Since we did not conduct a phase-referencing mode observation but a normal imaging one, the position of C3 is defined as a relative position to C1.

a newly generated temporal structure shortly extending towards the West of C3 in the subsequent three epochs (2015 Dec 6th, 2016 Jan 5th, and Jan 20). We will briefly discuss a possible origin of this substructure in §5.2.

3.2. Flip of the C3 component

In Figure 2, we show the 12 epochs images of 3C 84 at 43 GHz obtained with KaVA during the period from 2015 August to 2016 June. Here we can see the overall propagation of the C3 component towards the south direction, and the change of the flux densities of the C1 and C3 components.⁹ In Figure 3, we show the location of the peak position of the C3 component relative to the peak location of the C1 component. The C3 position on August 1 2015 is well along the extended line of the past trajectory of C3 (Nagai et al. 2010; Suzuki et al. 2012; Hiura et al. 2018). As seen in Fig. 3, we discover the flip of the C3 position during August–September in 2015. After September 2015, all the epochs obtained with KaVA and VLBA show the flip of C3 in relative right ascension. As seen in Figure 2, the motion of the peak position of C3 was decelerated and C3 wobbled for a few months. After that, the peak position of C3 resume to propagate towards the south direction in the sky. Intriguingly, the apparent velocity of C3 temporally seems to reach the velocity comparable to c after September 2015. Hence, doppler boosting could potentially contribute the brightening of C3 in the light curve. Since the number of the observation epochs here is not enough to conclude it, we will separately explore it in our forthcoming paper by adding further observation epochs in 2017–2018.

3.3. Light curves of C1 and C3

In Figure 4, we show the light curves of the C3 and C1 components. The clear monotonic increase of the peak intensity of C3 is found in the overall trend of the light curve. The peak intensity C3 increased more than a factor of ~ 4 . On the other hand, the peak intensity of C1 does not show such a monotonic increase in the flux density and it was in the range of $\sim 5 - 6$ Jy/beam during the observation period. The peak intensity of C3 finally exceeded that of C1 during 2016 winter. In the last epoch, i.e., 2016 June 12, the peak intensity of C3 became more than 4 Jy brighter than that of C1. As shown in In Figure 4 and Table 1, the peak flux density measured by VLBA on 2015 Dec 5th and the one measured by KaVA on 2015 Dec 6th show a good agreement to each other. This agreement of the independent VLBI arrays of KaVA and VLBA well guarantees the robustness of the flux measurements of these two arrays.

It is intriguing to see that the onset of the C3 flux density increase was seen about MJD 57350. It means that the brightening of C3 realized with ~ 100 days delay from the date of the flip around MJD 57250. As explained in § 3.2, the propagation of C3 suspended for a few months. After around MJD 57350, it restarted to advance to southward. The onset of the C3 flux density increase is coincide with this restart timing of the C3

propagation towards the south direction rather than the moment of the flip of C3.

4. NUMBER DENSITY OF THE CLUMP

To change the direction of jet propagation, there may be two possible mechanisms. One is the precession of jet axis, while the other is the collision with obstacles. As for the precession, Falceta-Gonçalves et al. (2010) proposed a scenario that the observed morphology of 3C 84 on 10–100 kpc-scales can be well explained by a precessing jet with a period of $\sim 10^7$ years, using three-dimensional numerical simulations considering the jet precession evolution. Recently, an indication of the precession of the 3C 84 jet has been reported by Hiura et al. (2018) based on VERA monitoring of 3C 84 at 22 GHz during the period of 2007–2013. The VERA data revealed that the relative position of C3 against C1 showed a smooth sinusoidal curve with a period of about 6 years, which can be explained by the jet precession. The relative position of C3 detected by KaVA during in 2015 reported in the present work, however, is clearly different from the sinusoidal curve but a flip and wobbling motion, which can be naturally explained by a collision between the jet and surrounding non-uniform/clumpy medium. The recent detection of the enhanced linearly-polarized emission of the C3 component in 3C 84 has been found in the same period and this enhancement can also support the interaction between the jet and clumpy medium (Nagai et al. 2017, see also § 5). Because of these reasons, we assume that the flip of C3 is caused by the dense clump and hereafter we estimate the number density of the clump.

If the 3C 84 jet thrust completely overwhelms the ram pressure by the clump, then the clump is dynamically negligible. Then the jet would continue to propagate along the same direction without any flip of the jet head. On the other hand, too dense clump should completely intervene jet propagations. To realize the flip of the jet head, the jet thrust would be comparable the ram pressure by the clump (e.g., a numerical simulation shown in Figure 6 of the paper Wang et al. 2000). From this condition, one can obtain

$$\frac{L_j}{c} \approx \rho_{cl} v_h^2 A_{cross}, \quad (1)$$

where L_j , ρ_{cl} , v_h , and $A_{cross} \equiv \pi(D_L \theta_{flip})^2$ are the total kinetic power of the jet, the mass density of the clump, the jet-head advancing velocity and the effective cross sectional area of the jet-clump interaction, respectively (Begelman and Cioffi 1989; Kino and Kawakatu 2005). In sub-Sec 5.2, we will present a consistency check about this assumption of Eq. (1). According to recent VLBI observations, the averaged velocity of the jet after the emergence of the C3 component is known as

$$0.2 c \lesssim v_h \lesssim 0.3 c, \quad (2)$$

(Nagai et al. 2010; Suzuki et al. 2012; Hiura et al. 2018). Here we set the effective cross sectional area as

$$A_{cross} \approx 1.9\pi \times 10^{35} \left(\frac{\theta_{flip}}{0.4 \text{ mas}} \right)^2 \text{ cm}^{-2}. \quad (3)$$

In principle, the cross sectional area of the clump $A_{cl} \equiv \pi R_{cl}^2$ can be larger than this effective cross sectional one A_{cross} since there may exist a remaining part of the clump

⁹ The apparent extended structure on the south-west side of the image in the epoch 2015 September in Figure 2 is not a real structure. It was an artifact by the poorer uv coverage because of the lack of three stations in KaVA on this epoch (see the second column of Table 1).

on the west side of the jet-head flip region. Hence, we introduce a numerical factor $\eta \equiv A_{\text{cl}}/A_{\text{cross}}$. Therefore, we take into account of such cases and hereafter we mainly examine a case of $\eta \approx 1$. The corresponding radius of the clump (R_{cl}) can be given by $R_{\text{cl}} \approx 0.14\eta^{1/2}$ pc. In the sub-section 5.2, we will briefly address the case of $\eta \gg 1$ as well.

The total kinetic power of the jet L_j has been also constrained in the literatures. Heinz et al. (1998) argued that the time-averaged total power of the jet in NGC 1275 probably exceeds $L_j \sim 1 \times 10^{46}$ erg s $^{-1}$. They derived the conclusion based on the observed properties of X-ray cavities in the central region of the Perseus cluster, which is supposed to be inflated by relativistic particles of the shocked jet. Hence, the minimum value of the jet power can be nominally $L_j \sim 1 \times 10^{46}$ erg s $^{-1}$.¹⁰ As for the maximum value of L_j , Tavecchio et al. (2014) employed the largest jet power $L_j = 2.3 \times 10^{47}$ erg s $^{-1}$ based on their model fitting against the non-thermal emission spectrum observed in 3C 84. This value suggested by Tavecchio et al. (2014) is comparable L_{Edd} . We adopt this value as the maximum value of L_j . Summing up, we set the range of L_j as

$$1 \times 10^{46} \text{ erg s} \lesssim L_j \lesssim 2 \times 10^{47} \text{ erg s} \quad (4)$$

in the present work.

In Figure 5, we show the estimated range of the clump density n_{cl} based on Eq. (1), i.e., simply based on the momentum balance relation. By substituting the allowed values of L_j and ρ_{cl} shown in Eqs. (2) and (4), one can obtain the allowed value of n_{cl} and it is given by

$$4 \times 10^3 \text{ cm}^{-3} \lesssim n_{\text{cl}} \lesssim 2 \times 10^5 \text{ cm}^{-3}. \quad (5)$$

The bottom right part of the allowed region in Figure 5 corresponds to the case of a denser clump, while the left side region represents the case of a thinner clump. We add to note that an enclosed total mass of the clump ($M_{\text{cl,obs}} = 4\pi R_{\text{cl}}^3/3$) can be estimated as $M_{\text{cl,obs}} \approx 3 M_{\odot} n_{\text{cl},4} (R_{\text{cl}}/0.14 \text{ pc})^3$.

5. DISCUSSIONS

5.1. Origin of the clump

In the previous section, we constrain the number density of the clump located at 1 pc from the central engine of 3C 84 via the simple dynamical argument of jet-clump interaction. Here, we will discuss possible origins of the clump based on its location and number density. Since typical density and location of a cloud in a broad line region (BLR) (e.g., Osterbrock 1989; Perterson 1997; Maiolino et al. 2010; Bentz et al. 2013; Czerny et al. 2017) are obviously different from those for the clump in 3C 84, we will not further discuss the possibility of clouds in BLR below.

5.1.1. A cloud in narrow line region?

Let us discuss a possibility of a cloud in narrow line region (NLR) as the origin of the clump. A typical

¹⁰ However, they also suggested that the jet power in a quiescent state (corresponding to off-state mentioned in the paper of Reynolds and Begelman 1997) may be lower than $L_j \sim 10^{46}$ erg s $^{-1}$.

number density is known as $\sim 10^{2-5} \text{ cm}^{-3}$ (e.g., Osterbrock 1989) and thus it is obvious that a typical number density of cloud in NLR well agree with the estimated number density of the clump (n_{cl}) in 3C 84. In this subsection, we further discuss whether the radial dependence of n_{cl} in 3C 84 has a similar trend with those in other AGN sources. Typically, NLR clouds in moderately luminous AGN such as Seyfert galaxies are expected to be located in the broad radial range of 10^{1-3} pc distance from the central engine (e.g., Ramos Almeida and Ricci 2017). Some of NLRs expand large enough to be partially resolved on the sky (e.g., Pogge 1988; Tadhunter and Tsvetanov 1989; Schmitt et al. 1994; Fischer et al. 2013).

First, let us begin with an estimate the size of NLR (R_{NLR}) for NGC 1275. The $L_{H\beta}$ luminosity is estimated by the luminosity of the $H\alpha$ and $H\beta$ emission line luminosities has the empirical relation of $3L_{H\beta} \approx L_{H\alpha}$ (Figure 5 in Greene and Ho 2005) and we have $L_{H\alpha} \sim 1 \times 10^{42}$ erg s $^{-1}$ in NGC 1275 by KANATA observation (Yamazaki et al. 2013; Kino et al. 2016). Therefore, the size of NLR in NGC 1275 can be estimated as $R_{\text{NLR}} \approx 0.6 \times 10^2 \text{ pc} L_{H\beta,41}^{1/3} \epsilon_{\text{fill},-2}^{-1/3} n_4^{-2/3}$ where the filling factor of the NLR, and the number density of electrons are ϵ_{fill} , and n , respectively. The derived R_{NLR} value is comparable to typical values in other sources (e.g., Osterbrock 1989).

Next, let us compare the location and n_{cl} of the clump in 3C 84 with those in other AGN sources. Interestingly, Walsh et al. (2008) conducted the imaging spectrograph observations of nearby low-luminosity AGNs with the Space Telescope Imaging Spectrograph (STIS) aboard the the Hubble Space Telescope (HST) and they find the electron number density measurements are characterized by a similar slope with the normalization of the electron number density $5 \times 10^3 \text{ cm}^{-3}$ at ~ 1 pc distance from the core for five low-luminosity AGNs of NGC 1052, NGC 3227, NGC 3998, NGC 4278, and NGC 4579 (see Figure 7 in Walsh et al. 2008). Murayama and Taniguchi (1998) also indicate the radial dependence of the electron number density distribution in NLR via detection of coronal lines, which is known as an indicator of denser clump. Regarding the location of the clump, i.e., 1 pc distance from the central engine, the Figure 7 of Walsh et al. (2008) indicates the electron number density as $n_{\text{cl}} \sim 10^{3-5} \text{ cm}^{-3}$, which well agrees with our estimate. Therefore we conclude that the clump in 3C 84 can be understood as a cloud located deep inside (i.e., ~ 1 pc) the NLR with a normal number density.

5.1.2. Self-gravitating molecular cloud?

As alternative case which also agrees with the estimated n_{cl} , here we discuss the case when an intergalactic cloud such as a dark cloud, a circum-stellar cloud, with its typical sizes, masses, and temperatures $0.1 - 3$ pc, 10^{2-7} cm^{-3} , and $10 - 100$ K (Goldsmith 1987) is the origin of the clump. Interactions between galactic jet sources and such cold clumps are indeed suggested in some observations (e.g., Fukui et al. 2009). Here we briefly discuss when the clump can be a self-gravitating one since intergalactic molecular clouds are quite important in the context of star formations. The radius and mass of a self-gravitating clump in the context of

AGNs have been estimated in literatures (e.g., Krolik and Begelman 1988; Honig and Berkert 2007, Kawaguchi and Mori 2011) and we follow those arguments. The two conditions required for self-gravitational clumps are as follows. The first requirement is (1) the free-fall time for spherical clump ($t_{\text{ff}} = \sqrt{3\pi/(32\rho_{\text{cl}}G)}$) is shorter than the sound crossing time ($t_{\text{crs}} = R_{\text{cl}}/c_s$). The second requirement is (2) these clump should be stable against the tidal force in the gravitational field of the central black hole ($F_{\text{tidal}} \approx 2GM_{\bullet}M_{\text{cl}}R_{\text{cl}}/r^3$) by the self-gravity force ($F_{\text{sg}} \approx GM_{\text{cl}}^2/R_{\text{cl}}^2$) where r is the distance from the central black hole to the clump. The second requirement comes down to the relation $(R_{\text{cl}}/r)^3 \lesssim M_{\text{cl}}/2M_{\bullet}$. From these conditions, we have $R_{\text{cl}} \lesssim \frac{\pi}{\sqrt{16G}} \frac{c_s r^{3/2}}{M_{\bullet}^{1/2}} \approx 1.6 \times 10^{-2} c_{s,5} (r/1 \text{ pc})^{3/2} (M_{\bullet}/10^8 M_{\odot})^{-1/2} \text{ pc}$ and $M_{\text{cl,crit}} = \frac{\pi^2 c_s^2}{8G} R_{\text{cl}} \approx 0.5 M_{\odot} c_{s,5}^3 (r/1 \text{ pc})^{3/2} (M_{\bullet}/10^8 M_{\odot})^{-1/2}$. From this, it is clear that the clump can become self-gravitating one only when the clump is cold (i.e., slow sound speed of order of $c_s \lesssim 10^5 \text{ cm/s}$), although there are no direct evidence for cold clump in 3C 84 so far. Therefore, observational explorations of cold clumps are essential to test this scenario. Further discussions on cold gas will be made in the sub-section 5.3.2.

5.1.3. A giant cloud?

Here we briefly discuss a possibility of the existence of a clump with its cross sectional area A_{cl} larger than that of A_{cross} (i.e., $\eta > 1$). If a giant molecular cloud with its size larger than a few parsec scale (Goldsmith 1987) known in our Galaxy exists in NGC 1275, then it may be one of the possible candidates for it. A remaining part of such a large cloud may probably hold back on the western side of the radio lobe made of the shocked material escaped from C3 and produce a remnant structure (see details in Sec 5.2). Do we find such a remnant feature? Here we speculate that the diffuse component C2 may be identical to the remnant of the exhausted jet produced by the interaction of the jet and a large clump. Although little attention has been paid to C2, its existence was well known in literatures (e.g., Venturi et al. 1993; Dhawan et al. 1998) and C2 does not show a systematic motion but shows random wobbling behavior. Such behaviors could be explained by the collision with the large clump, which may cause a back-flows of the exhausted jet (Asada et al. 2006; Mizuta et al. 2010). This scenario could be investigated through high energy γ -ray emissions caused by strong shocks (e.g., Kino et al. 2011, 2017), although detailed investigations of such high energy γ -ray spectra is beyond the scope of this paper.

5.2. Comparison with hydrodynamical simulations

In this sub-section, we will make comparisons of the observational results with hydrodynamical simulations of jet propagations in surrounding ambient matter.

5.2.1. Jet confinement condition in a uniform ambient matter

First of all, it is important to check the availability of Eq. (1) based on hydrodynamical simulations of jet propagations. To this end, simulations of jet propagations in a uniform ambient matter provide us a criterion

for the availability of Eq. (1). A propagation of a jet in a uniform ambient matter is essentially governed by the momentum balance between the jet thrust and the ram pressure from the ambient matter. Hence, the physical quantity L_j/n_a is the key to understand the jet propagations where n_a is the number density of the ambient matter. It practically corresponds to the case of $\eta \gg 1$. Hereafter, we discuss the comparison of the obtained n_{cl} in 3C 84 with hydrodynamical simulation of De Young (1993) by focusing on the quantity L_j/n_a . Let us begin with a brief summary of the hydrodynamical simulation of De Young (1993), which thoroughly examine the various combinations of L_j and n_a and investigated the condition of jet-confinement by uniform ambient matter. They examined the case of jet propagations with the total kinetic power $L_j \approx 1 \times 10^{45} \text{ erg/s}$ and changing n_a and they found no jet confinement below $n_a \lesssim 3 \text{ cm}^{-3}$ (Fig. 9 of De Young 1993). They also tested the case of $L_j \approx 1 \times 10^{44} \text{ erg/s}$ and the jet is still "confined" when $n_a \gtrsim 1.6 \text{ cm}^{-3}$ (Fig. 9 of De Young 1993). Therefore, the condition for realizing the jet confinement by the uniform ambient medium based on the simulation of De Young (1993) can be written as

$$\frac{L_j}{n_a} \lesssim (6 \times 10^{43} - 3 \times 10^{44}) \text{ erg cm}^3/\text{s}. \quad (6)$$

The estimate of n_{cl} together with the adopted L_j shown in Eq. (4) in 3C 84 in the present work shows a good agreement with the result of De Young (1993), i.e., the estimated upper limit of L_j/n_{cl} is almost the same as the criterion value inferred from the numerical result of De Young (1993). Thus, the flip of the jet head of 3C 84 is well justified as a consequence in this jet clump collision.

It is worth to add that the condition of confinement shown in Eq. (6) is almost consistent also with the previous work of Kawakatu et al. (2009), which shows that a hot spot, which corresponds to the reverse shock at the tip of the jet, is generated when

$$\frac{L_j}{n_a} \gtrsim 1 \times 10^{44} \text{ erg cm}^3/\text{s}. \quad (7)$$

based on a Mach number value at the hot spot (termination shock) region.

5.2.2. More realistic case: inhomogeneous ambient matter

Next, we discuss the case of an inhomogeneous ambient matter, which would provide us with an insight for more realistic situation. The work of Wagner et al. (2012) indeed made a comprehensive work of jet propagation in two-phase interstellar medium (ISM), which consists of a warm and hot phases. The warm phase has a density perturbation and it produces the clumps with the upper limit temperature $\sim 10^4 \text{ K}$. This situation qualitatively corresponds to the case of $\eta \sim O(1)$. In Wagner et al. (2012), no lower temperature limit is enforced and temperatures in the core of cloud (i.e. clump) may initially be less than 100 K. They have found that the acceleration of the dense embedded clouds (clumps) is realized by the ram pressure of the high-velocity flow through the porous channels of the warm phase. This process transfers 10% to 40% of the jet kinetic energy to the cold and warm gas, accelerating/blowing it to velocities that match those observed radio jets in AGNs.

That is so-call AGN feedback in mechanical energy form. The key feature seen in the simulation of is a mixture of the flip of the jet head and blown out of clumps (Figure 9 of Wagner et al. 2012). Because of the significant non-uniformity of ambient matter, dynamics of clumps cannot be purely determined by the head-on collision between the jet and a single clump alone. Perhaps, such a hybrid case of the jet flip and AGN feedback may be more realistic in actual AGN jet sources. Wagner et al. (2012) show that the AGN Feedback is efficient for $10^{43} \text{ erg s}^{-1} \lesssim L_j \lesssim 10^{46} \text{ erg s}^{-1}$, with the number density of the clump as $30 \text{ cm}^{-3} \lesssim n_{\text{cl}} \lesssim 10^3 \text{ cm}^{-3}$. Since there is an overlap in these parameter ranges, we can expect a hybrid phenomena in 3C 84. Indeed, as mentioned in §3.1, we have detected a short-lived extended structure at the West of C3 from 2015 December to 2016 January. This structure is similar with a substructure at the collision site between the jet and a clump demonstrated in the Figure 9 of Wagner et al. (2012). As for the cloud/clump velocity, Wagner et al. (2012) predicted a typical velocity of the clumps after the collision as from a few 100 km/s to 1000 km/s. Therefore, this clump velocity will be one of the key observational quantities towards testing AGN feedback process in 3C 84 in the future.

5.3. Other signatures of clumpy medium

Lastly, we briefly discuss other signatures of clumpy medium in 3C 84.

5.3.1. Enhancement of linear polarization emission

Nagai et al. (2017) recently reported the detection of a significant polarized emission at the C3 component by VLBA observation data in the BU blazar monitoring program. Faraday rotation is also detected within an entire bandwidth of the 43 GHz band. The obtained rotation measure is $\sim 6 \times 10^5 \text{ rad m}^{-2}$ at a maximum. Similar RM values were also reported at 210-345 GHz by Plambeck et al. (2014) using CARMA and SMA while the 210-345 GHz emissions are likely to originate in the compact region at the close vicinity of the black hole. Nagai et al. (2017) claimed that a simple spherical accretion flow cannot explain the RM observed with the VLBA and SMA/CARMA consistently. To reconcile it, Nagai et al. (2017) proposed a local clumpy/inhomogeneous ambient medium being responsible for the observed RM. When an equipartition condition between magnetic field and accreting gas holds, the electron density is estimated as $\sim 10^4 \text{ cm}^{-3}$, which is comparable to the estimate of n_{cl} in this work. These results also strongly support the existence of the clump near the C3 component.

5.3.2. Searching for cold gas

Observationally, direct detections of cold gas within 10 pc scale from central BHs are challenging and such explorations have just begun for other nearby active galaxies. In this context, Imanishi et al. (2018) made a first detection of cold gas on this scale (what they detected was a rotating dusty molecular torus) in radio band by using the benefit of ALMA's high spatial resolution. First VLBI detection of HCN molecular absorption line features in NGC 1052 has been reported by Sawada-Satoh et al. (2016). We add to note that there are some detections

of absorption lines by such clumps for ultra-luminous IR galaxies (e.g., Geballe et al. 2006, Sajina et al. 2009). We further add to note that a large fraction of X-ray selected Seyfert 2 galaxies indeed show significant variations in the X-ray absorbing column density of N_{H} on the typical timescale less than 1 yr, which clearly suggests the presence of clumpy circumnuclear material on a scale below a parsec (Risaliti et al. 2002).

Although a cold gas has not yet detected at the circumnuclear region of NGC 1275, ALMA can potentially probe the cold molecular gas in the region. We proposed ALMA observations to study the morphological and kinematical properties of the cold molecular gas in the central a few ten parsec (PI: H. Nagai), and the observations were partially completed. We also performs KVN observations to look for absorption line caused by the cold molecular gas in the central a few ten parsec (PI: K. Wajima). Such high resolution observations towards NGC 1275 will definitely accelerate our understanding on a cold gas at the center of nearby radio galaxies.

6. SUMMARY

By performing the multi-epoch monitoring observation with KaVA at 43 GHz in the period from 2015 August to 2016 June, we explore the kinematics of the notable newborn bright component C3 located at the tip of the radio jet 3C 84. Here we summarize our main findings.

- We discovered a flip of the peak position of the C3 component during 2015 August-September. The amount of the positional shift in the angular scale was about 0.4 mas, which corresponds to 0.14 parsec in physical scale. After the flip, the C3 wobbled at the same location for a few months and then it restarted to propagate towards the southern direction. For consistency check purpose, we have analyzed three epochs of VLBA archival data of 3C 84 at 43 GHz and the obtained position of C3 showed good agreement with those measured by KaVA.
- We find the clear monotonic increase of the peak intensity of the C3 component during the observation period. The peak intensity of C3 increased more than a factor 4 at the end of the observation period. On the other hand, the peak intensity of C1 remained almost constant within the range of 5-6 Jy/beam during the period. The flip of C3 together with this monotonic enhancement of its flux density can be explained by a collision between the jet and a dense clump. The onset of the C3 flux density increase was seen about MJD 57350, which is not coincide with the timing of the flip happened on around MJD 57250. The onset of the C3 flux density increase was coincide with the restart timing of the C3 propagation to southward rather than the moment of the flip of C3.
- We estimate the density of the presumable clump based on the momentum balance between the jet thrust and the ram pressure from the clump and we find that the clump number density is estimated about $4 \times 10^3 \text{ cm}^{-3} \lesssim n_{\text{cl}} \lesssim 2 \times 10^5 \text{ cm}^{-3}$. The clump's location and estimated number density are in good agreement with a cloud located deep in

side the NLR or a dense portion of an intergalactic molecular cloud.

- The estimated value of L_j/n_{cl} for the jet-clump collision in 3C 84 satisfies the criterion for the jet confinement derived by the hydrodynamical simulation done by De Young (1993). It guarantees the availability of Eq. (1) and the jet flip by the clump can be naturally expected. Further comparison with the hydrodynamical simulation by Wagner et al. (2012) provides us predictions about more realistic case of the jet propagation in an inhomogeneous ambient gas. Accelerations of clumps by the jet momentum can be realized through the porous channels in the inhomogeneous ambient gas. Since there is an overlap in the parameter ranges of Wagner et al. (2012), similar phenomena in 3C 84 may be expected. We will further perform observations exploring such phenomena in the future.

Acknowledgment

This work is mainly based on KaVA observations, which is operated by the the Korea Astronomy and Space Science Institute (KASI) and the National Astronomical Observatory of Japan (NAOJ). We thank K. Sugiyama for useful discussion. This work is partially supported by JSPS KAKENHI Grant Numbers JP18K03656 (MK) and JP18H03721 (KN, MK, KH). NK acknowledges the financial support of MEXT KAKENHI (16K17670). HN is supported by MEXT KAKENHI Grant Number 15K17619. This study makes use of 43 GHz VLBA data from the VLBA-BU Blazar Monitoring Program (VLBA-BU-BLAZAR; <http://www.bu.edu/blazars/VLBAproject.html>), funded by NASA through the Fermi Guest Investigator Program. VLBA is an instrument of the Long Baseline Observatory. The Long Baseline Observatory is a facility of the National Science Foundation operated by Associated Universities, Inc. This work was supported by the National Research Council of Science & Technology (NST) granted by the International joint research project (EU-16-001).

APPENDIX

VLBA ARCHIVAL DATA ANALYSIS

For consistency check, we used the VLBA archival data taken as a part of Boston University Blazar Program. The observations were done on 2015 August and 2015 September at 43 GHz with all ten VLBA stations. The data consists of 4 intermediate frequencies (Ifs) with a 64-MHz band width for each IF. Total bandwidth is 256 MHz per polarization. Both right-hand and left-hand circular polarizations were obtained. The data calibration procedure is the same as the one performed against KaVA data. Hence, we do not repeat it here. In order to compare the VLBA and KaVA images, we restore the VLBA images with the gaussian beam size of 0.75 mas. Overall structures and fluxes obtained in the two epochs are well consistent with those obtained by KaVA.

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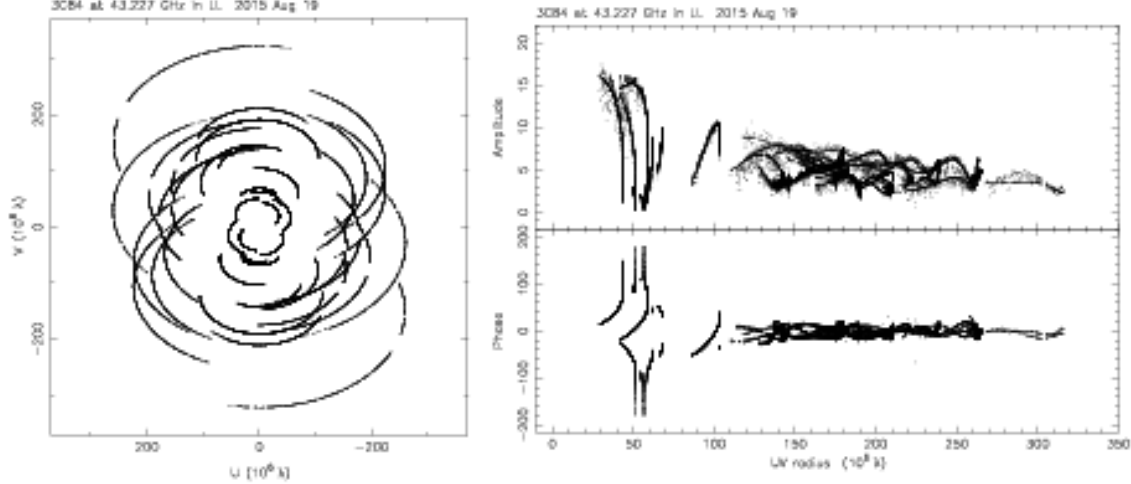


FIG. 1.— The uv coverage and the visibility amplitude and phase obtained on 2015 August. This is one of the epochs in this KaVA monitoring of 3C 84 at 43 GHz.

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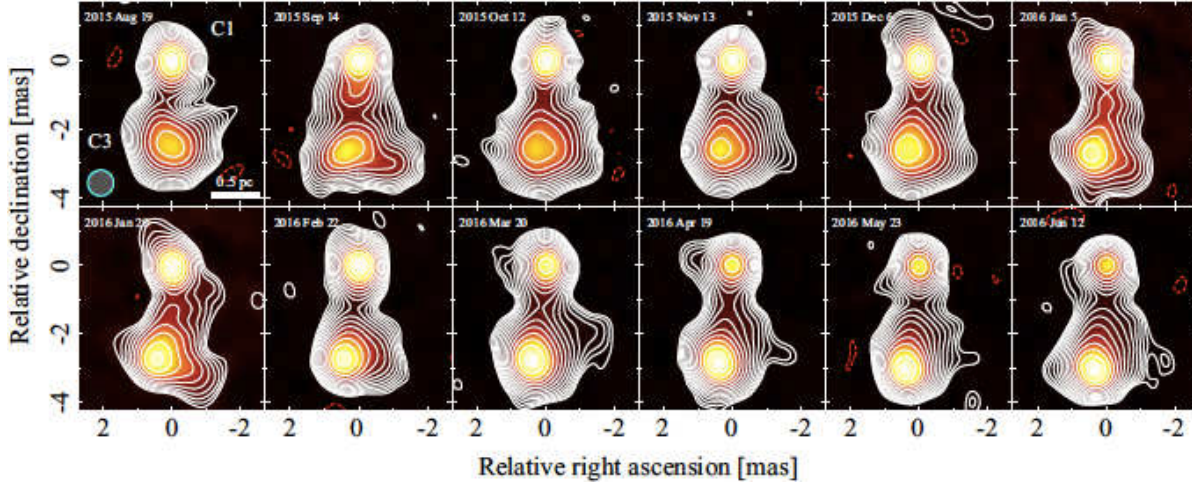


FIG. 2.— Multi-epoch KaVA images of 3C 84 at 43 GHz. Twelve-epoch VLBI images of 3C 84 obtained by KaVA at 43.2 GHz from 2015 August 19 (top left) to 2016 June 12 (bottom right). All images are restored with the circular Gaussian beam of $0.75 \text{ mas} \times 0.75 \text{ mas}$, which is indicated in the lower left corner of the first-epoch image. The lowest contour is three times the off-source rms noise (σ). The dashed and solid curves show negative and positive contours, respectively, and the contour levels are $-3\sigma, 3\sigma \times (\sqrt{2})^n$ ($n = 0, 1, 2, \dots$).

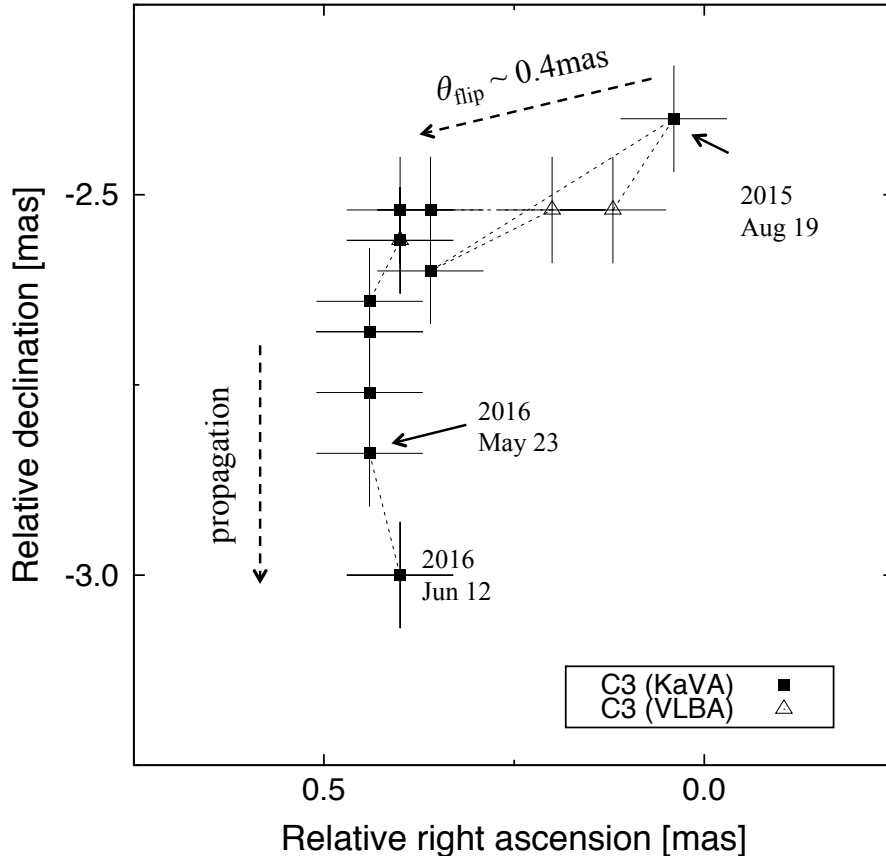


FIG. 3.— Relative peak intensity position of the component C3 with respect to C1 assuming as an origin (0, 0). The filled squares and open triangles represent the peak intensity position obtained with KaVA and VLBA observations, respectively.

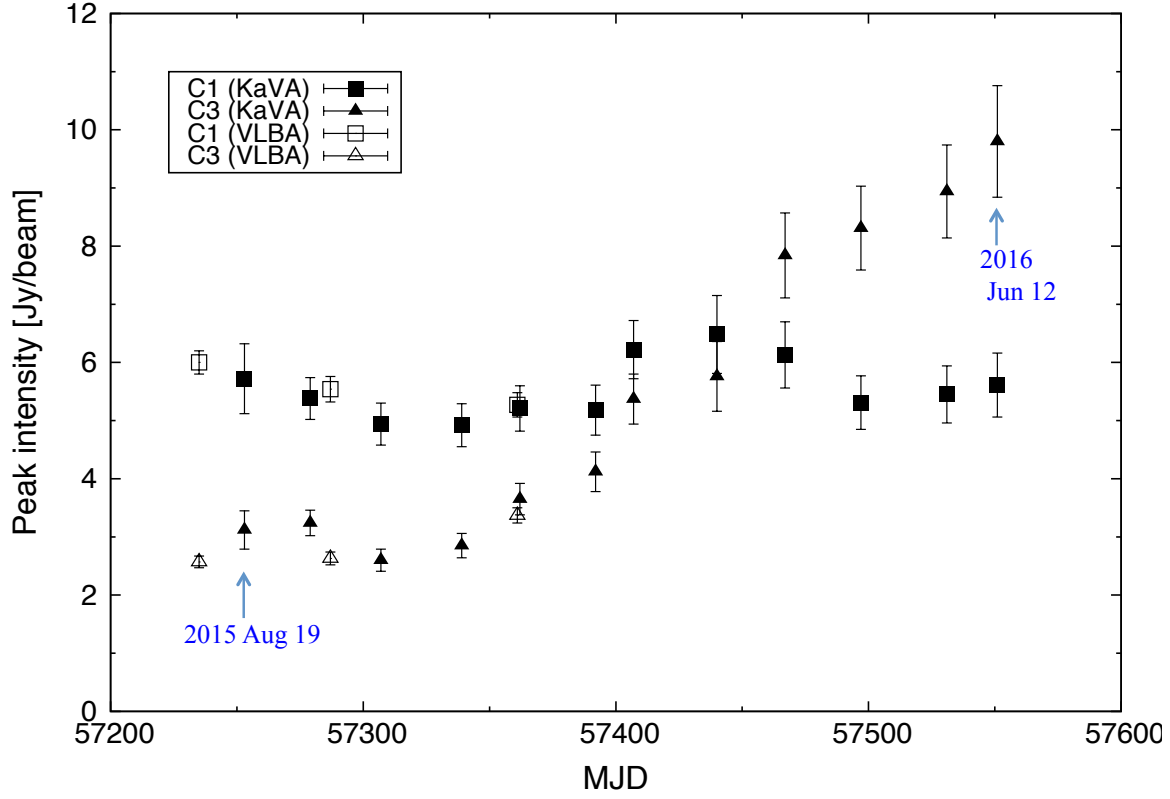


FIG. 4.— Light curve of the components C1 and C3 measured by KaVA and VLBA at 43 GHz from 2015 August to 2016 June. The filled and open points correspond to the peak intensity of C1 (square) and C3 (triangle) measured by KaVA and VLBA, respectively. All data points are obtained from the restored images shown in Figures 2 and 6.

TABLE 1
OBSERVATION SUMMARY

UT date (MJD)	Stations	Image rms (mJy/beam)	Peak intensity (Jy/beam)	Dynamic range
2015 Aug1	VLBA (Boston U. monitor)	0.90	6.00	6.70×10^3
2015 Aug 19 (57253)	KaVA	3.97	5.72	1.44×10^3
2015 Sep 14 (57279)	KaVA - MIZ, IRK, OGA	4.95	5.38	1.09×10^3
2015 Sep 22	VLBA (Boston U. monitor)	0.86	5.54	6.44×10^3
2015 Oct 12 (57307)	KaVA - IRK	3.56	4.94	1.39×10^3
2015 Nov 13 (57339)	KaVA - MIZ	10.21	4.92	4.80×10^2
2015 Dec 5	VLBA (Boston U. monitor)	0.97	5.27	5.43×10^3
2015 Dec 06 (57362)	KaVA	2.28	5.21	2.29×10^3
2016 Jan 05 (57392)	KaVA	3.49	5.18	1.48×10^3
2016 Feb 22 (57440)	KaVA -KUS	4.93	6.48	1.31×10^3
2016 Mar 20 (57467)	KaVA	2.60	7.84	3.02×10^3
2016 Apr 19 (57497)	KaVA	3.52	8.31	0.90×10^3
2016 May 23 (57531)	KaVA-MIZ	9.95	8.94	0.90×10^3
2016 Jun 12 (57551)	KaVA	6.67	9.80	1.47×10^3

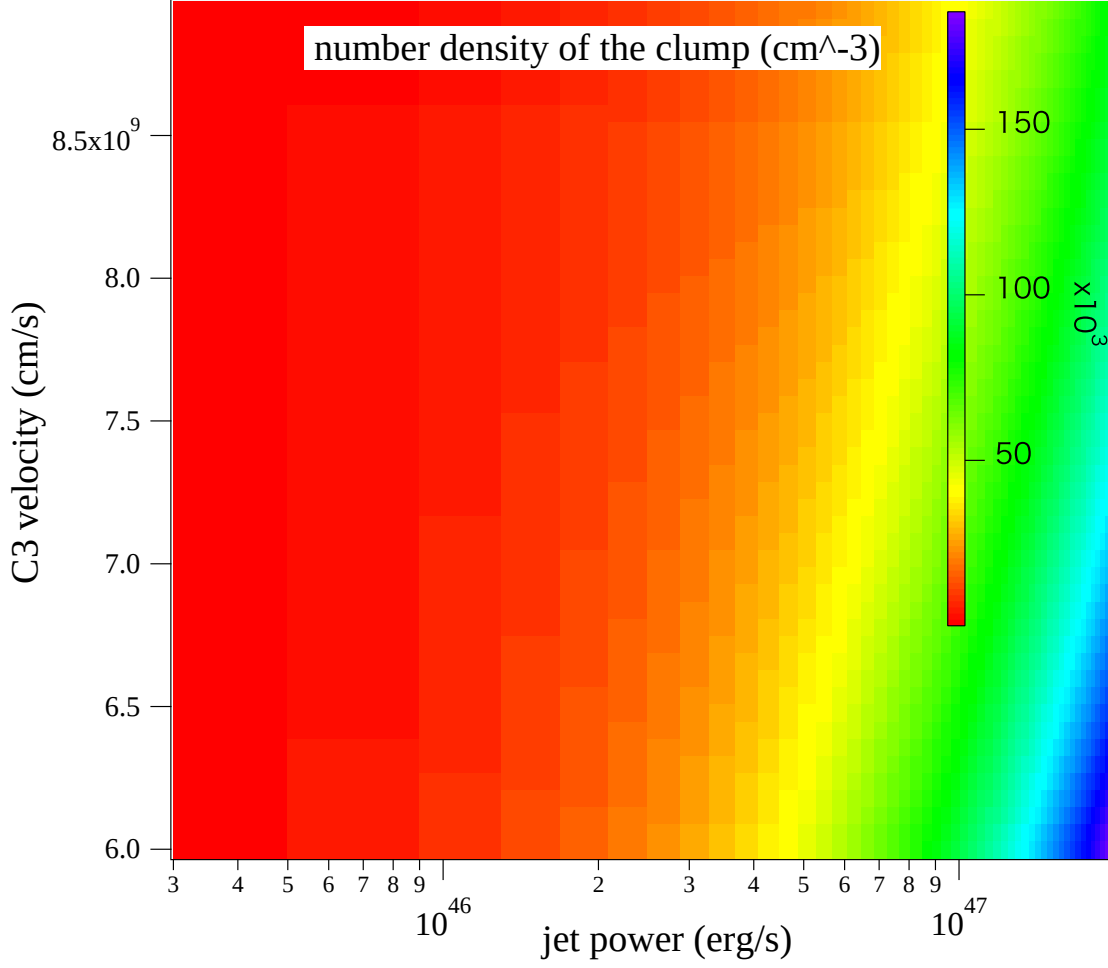


FIG. 5.— The estimated number density of the clump (n_{cl}) based on Eq. (1). The color contour indicates n_{cl} in the unit of 10^3cm^{-3} . The vertical axis shows the advancing velocity of the C3 component (v_h), while the horizontal axis represents the total jet power (L_j).

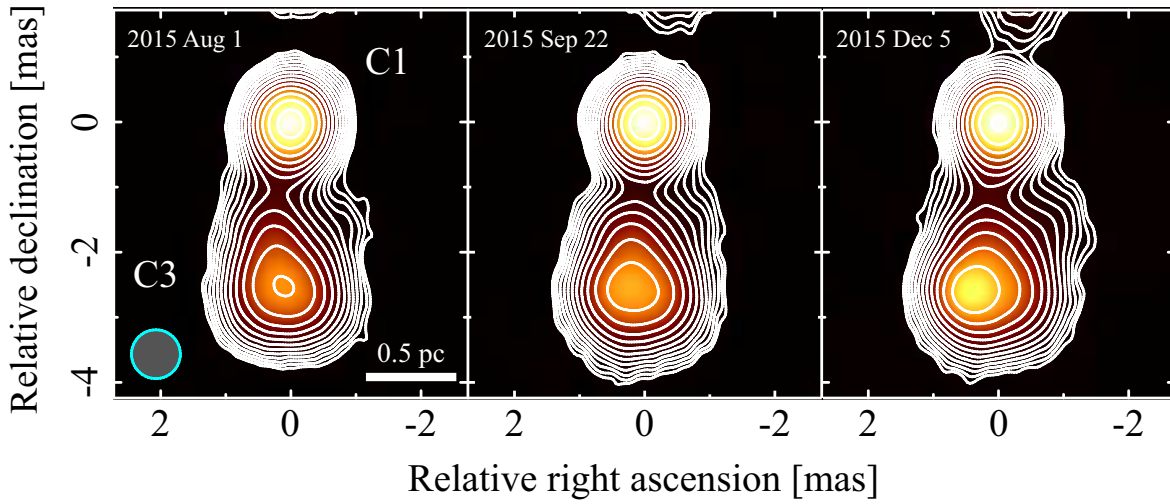


FIG. 6.— Three-epoch VLBI images of 3C 84 obtained by VLBA at 43 GHz from 2015 August 1 (left) to 2015 December 5 (right). All images are restored with the circular Gaussian beam of $0.75 \text{ mas} \times 0.75 \text{ mas}$, which is indicated in the lower left corner of the first-epoch image. Definition of the curves and contour levels are identical to that shown in Figure 2.