Constraints on the Circumnuclear Disk through Free–Free Absorption in the Nucleus of 3C 84 with KaVA and KVN at 43 and 86 GHz

Kiyoki Wajima1, Motoki Kino2,3, and Nozomu Kawakatu4

1 Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong, Daejeon 34055, Republic of Korea; wajima@kasi.re.kr
2 Kogakuin University of Technology & Engineering, Academic Support Center, 2665-1 Nakano, Hachioji, Tokyo 192-0015, Japan
3 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
4 National Institute of Technology, Kure College, 2-2-11 Agaminami, Kure, Hiroshima 737-8506, Japan

Received 2018 December 26; revised 2020 April 8; accepted 2020 April 9; published 2020 May 21

Abstract

The nearby bright radio galaxy 3C 84 at the center of the Perseus cluster is an ideal target to explore the jet in an active galactic nucleus and its parsec-scale environment. The recent research of Fujita & Nagai revealed the existence of the northern counter-jet component (N1) located 2 mas north from the central core in very long baseline interferometer (VLBI) images at 15 and 43 GHz and they are explained by the free–free absorption (FFA) due to an ionized plasma foreground. Here we report a new quasi-simultaneous observation of 3C 84 with the Korean VLBI Network (KVN) at 86 GHz and the KVN and VLBI Exploration of Radio Astrometry Array (KaVA) at 43 GHz in 2016 February. We succeeded the first detection of N1 at 86 GHz and the data show that N1 still has an inverted spectrum between 43 and 86 GHz with its spectral index $\alpha$ ($5 < \nu < 10^5$) of $1.19 \pm 0.43$, while the approaching lobe component has a steep spectrum with an index of $-0.54 \pm 0.30$. Based on the measured flux asymmetry between the counter and approaching lobes, we constrain the averaged number density of the FFA foreground $n_e$ as $1.8 \times 10^6$ cm$^{-3} < n_e < 1.0 \times 10^7$ cm$^{-3}$. Those results suggest that the observational properties of the FFA foreground can be explained by the dense ionized gas in the circumnuclear disk and/or assembly of clumpy clouds at the central ~1 pc region of 3C 84.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Perseus Cluster (1214); Radio continuum emission (1340); Radio galaxies (1343); Radio lobes (1348); Very long baseline interferometers (1768)

1. Introduction

Active galactic nuclei (AGNs) are widely believed to have an obscuring structure near a central supermassive black hole (SMBH), which is described in the AGN unified model (e.g., Antonucci 1993; Urry & Padovani 1995). Indeed, there is mounting evidence that it has a rich structure within a 10 pc scale from the recent progresses of spatially resolved multi-wavelength observations. At near- to mid-infrared (NIR) to MIR wavelengths thermal dust emission in AGNs supports the existence of compact obscuring structures within 10 pc of the central engine (e.g., Jaffe et al. 2004; Burtscher et al. 2013; Asmus et al. 2014). Recent ALMA observations revealed that multiphase dynamic nature in the circumnuclear disk (CND) region of larger than 10 pc, i.e., the diffuse atomic gas is more spatially extended along the vertical direction of the disk than the dense molecular gas (Izumi et al. 2018). Due to energy feedback from AGNs and nuclear starbursts, coexistence of ionized gas and cold gas is expected on the CND scale (e.g., Wada et al. 2016). Dense molecular gas disks with their sizes of 10 pc, which may be an outer part of a few parsec obscuring structure, have been found around nearby Seyfert nuclei (e.g., Hicks et al. 2013; Davies et al. 2014; Imanishi et al. 2016, 2018; Izumi et al. 2018). Such a CND would be a massive reservoir of molecular gas, which potentially triggers an active star formation. A prominent star formation has been found as a nuclear starburst (e.g., Imanishi & Wada 2004; Davies et al. 2007; Imanishi et al. 2011; Diamond-Stanic & Rieke 2012; Alonso-Herrero et al. 2014; Esquej et al. 2014; Mallmann et al. 2018), which may be related to the CND structure (Kawakatu & Wada 2008; Kawakatu et al. 2020).

Despite the above-shown progresses on the scale of larger than a few parsecs, it is not yet clear about the physical properties of the obscuring structure on the scale of smaller than 1 pc. There are a number of theoretical models arguing possible origins, e.g., (1) radiation pressure from AGN (e.g., Krolik 2007; Namekata et al. 2014; Namekata & Umemura 2016), (2) radiation pressure from nuclear starburst (e.g., Thompson et al. 2005), (3) high velocity dispersion clouds/ clumps model (Krolik & Begelman 1988; Vollmer et al. 2008), (4) turbulent pressure from SN II explosions (Wada & Norman 2002; Wada et al. 2009), (5) disk winds (e.g., Elitzur & Shlosman 2006; Nomura et al. 2016), (6) outflows driven by AGN radiation pressure (Wada 2012; Chan & Krolik 2016, 2017; Dorodnitsyn et al. 2016; Wada et al. 2016), and (7) chaotic cold accretion within the inner kiloparsec (Gaspari et al. 2013). In order to investigate its physical origin in detail on a <1 pc scale, high-resolution observations of the hot ionized gas around AGNs are essential to understand basic properties of multiphase CNDs. As previous research has been carried out mainly with a very long baseline interferometer (VLBI) at centimeter wavelengths (e.g., Kamen et al. 2000, 2001), the free–free absorption (FFA) is one of the useful tools to explore the ionized gas around AGNs.

The compact radio source 3C 84 (also known as NGC 1275) is one of the nearby ($z = 0.018$) best-studied radio galaxies. Proximity of the object allows us to make detailed observations about the environment around the SMBH on 1 pc scale. Abdo et al. (2009) reported an increase in the radio flux at 14.5 GHz starting in 2005 with long-term monitoring by the the University of Michigan Radio Astronomy Observatory. They claimed that this radio flare could be interpreted as an ejection of new jet components. This was confirmed by
Nagai et al. (2010), who found the emergence of a newborn bright component, designated as C3, with multiepoch VLBI monitoring during 2006–2009. C3 showed a proper motion toward the southern direction with an apparent velocity of 0.2–0.3c (Nagai et al. 2010; Suzuki et al. 2012; Hiura et al. 2018). Walker et al. (2000) conducted multiepoch, multifrequency Very Long Baseline Array (VLBA) observations of 3C 84 with the frequency range of 0.3–43.2 GHz, resulting in detection of free–free absorbed emission in the northern lobe located at \( \sim 8 \) mas from the core. They suggested that the absorption feature is due to the existence of a 3 pc scale absorber.

Fujita & Nagai (2017) first reported the existence of the northern counter-jet component, designated as N1, in 3C 84 at both 15 and 43 GHz with VLBA. This feature is considered to be a counter-jet component corresponding to the approaching jet located at the south. N1 has a strongly inverted spectrum, which indicates that it is absorbed by an ionized plasma around the SMBH via FFA. So far, however, no detection of N1 has been made at higher frequency than 43 GHz. Observations at 86 GHz or even higher frequencies offer a unique view on the environment of the radio jet in 3C 84 since the radio emission would be more transparent at such frequencies.

In this paper we report the results of VLBI observation of 3C 84 at 86 GHz, which focuses on properties of a newly detected northern component, together with the quasi-simultaneous 43 GHz image obtained in our previous work summarized in Kino et al. (2018). By combining the northern counter-jet images at 86 and 43 GHz, we show the spectral index between these frequencies and also discuss properties and geometry of sub-parsec-scale structure and the circumnuclear environment in 3C 84.

Throughout this paper, we define the spectral index, \( \alpha \), as \( S_\nu \propto \nu^\alpha \), where \( S_\nu \) is the flux density at the frequency \( \nu \), and we adopt a \( \Lambda \)CDM cosmology with \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_\Lambda = 0.73 \), and \( \Omega_M = 0.27 \) (Komatsu et al. 2009), corresponding to an angular-to-linear scale conversion of 0.36 pc mas\(^{-1}\) for 3C 84.

### 2. Observations and Data Reduction

Our observations were conducted with the Korean VLBI Network (KVN) and VLBI Exploration of Radio Astrometry (VERA) array (hereafter KaVA) on 2016 February 22 at 43.2 GHz with the total on-source time of 475 minutes, and with KVN on 2016 February 23 at 86.2 GHz with the total on-source time of 737 minutes. The KaVA 7-telescope data was correlated using the Daejeon Hardware Correlator (Lee et al. 2015b) with the output preaveraging time of 1.6 s, whereas the DDX correlator (Deller et al. 2011) was used for the KVN 3-telescope data correlation with the output preaveraging time of 2 s.

The data were reduced using the Astronomical Image Processing System (AIPS) software (Greisen 2003) for amplitude and phase calibration, and the Caltech software Difmap (Shepherd 1997) for imaging and self-calibration. We applied a priori amplitude calibration using the antenna gain factors and system noise temperature measurements with the AIPS task APCAL. We also applied the amplitude correction factor with APCAL, as mentioned by Lee et al. (2015a). Bandpass calibration for both amplitude and phase is employed with the AIPS task BPASS. Fringe fitting was done using the AIPS task FRING with the solution interval of 30 s, resulting in successful fringe detection on all baselines for the whole observing time. Fringe-fitted data were exported to Difmap for imaging. We applied the amplitude and phase self-calibration to KaVA’s data and could reconstruct the source model using the visibility for all baselines with the maximum error of 6%. Although we could not apply the amplitude self-calibration to KVN’s data because of the small number of antennas, we believe that the visibility amplitude of KVN’s data was calibrated well since dense measurement (every 10 s) of the system noise temperature was made at all KVN stations. To estimate the amplitude calibration error of KVN’s data, we compared the observation results of a bright quasar 3C 273 obtained by the KV key science program, iMOGABA (interferometric monitoring of gamma-ray bright AGNs; Lee et al. 2016), and a VLBA observation, both of which were conducted quasi-simultaneously (2014 February 28 and 26 for iMOGABA and VLBA, respectively) at 86 GHz by employing the same amplitude calibration procedure as that of our observation of 3C 84. As a result, we confirmed that the peak intensity and total CLEANed flux of each observation are coincident within the range of 15%. To ensure a better sensitivity, we adopted natural weighting of the data with gridding weights scaled by amplitude errors raised to the power of −1. Details of the image dynamic range (DR) obtained with KaVA at 43 GHz have been reported by Kino et al. (2018), while DR of 100 was obtained for the image at 86 GHz with KVN.

### 3. Results

Figure 1 shows images of 3C 84 with KaVA at 43 GHz and KVN at 86 GHz. Restored KaVA image with the synthesized beam of the KVN 86 GHz image is also shown in Figure 1. The source consists of two bright components, the central core component (hereafter C1) and the southern lobe component (hereafter C3), both of which were identified in the previous VLBI observations (e.g., Nagai et al. 2010, 2012, 2014). On the other hand, we could identify N1 in the north of C1 with the separation angle of 2.5 mas. This is already reported by Fujita & Nagai (2017) as mentioned in Section 1, whereas we could identify N1 at 86 GHz as well as 43 GHz. The detection level of N1 is about 6 times the off-source rms noise (\( \sigma = 13 \) mJy and 65 mJy at 43 and 86 GHz, respectively) at both frequencies.

Figure 2 shows the spectral index map of 3C 84 between KaVA at 43.2 GHz and KVN at 86.2 GHz. Both observations do not employ the phase-referencing technique, resulting in the loss of the absolute position through the self-calibration procedure (Pearson & Readhead 1984; Thompson et al. 2001). We therefore superposed two images with reference to C3 since it shows an optically thin feature at the peak intensity position. To confirm this feature quantitatively, we estimate \( \alpha \) of each component. Table 1 shows peak intensities of each component at 43.2 and 86.2 GHz, corresponding to the center and right panels in Figure 1, and \( \alpha \) between these frequencies. C1 and C3 show its spectral index of \(-0.11 \pm 0.35\) and \(-0.54 \pm 0.30\), respectively, suggesting that C1 is the self-absorbed core and C3 is the optically thin component, whereas N1 has an optically thick spectral feature with \( \alpha \) of \(+1.19 \pm 0.43\) (see also Figure 2). Although an optically thick spectral feature can also be seen in the northeast of C1, we believe that this is not a real one because of lower signal-to-noise ratio in the images at both frequencies at around this area.
compared to that in the central region of the component. To check fidelity of the spectral index map, we examined an effect of registration error between images at each frequency taking into account the expected amplitude error of the peak intensity of 15% shown in Section 2. If we assume that the 15% error of C3 becomes \( \pm 0.32 \) mas in the R.A. and \( \pm 0.19 \) mas in the decl. Assuming the maximum registration error between each image shown above, resultant spectral index maps between 43 and 86 GHz show that \( \alpha \) at the peak position of N1 is inverted for all cases although an optically thick region always appears at the edge of C1, probably due to lower signal-to-noise ratio. We thus do not discuss a physical property at the edge of C1 in this paper.

The measured \( \alpha \) for both C1 and C3 is consistent with previous results by Suzuki et al. (2012), in which C1 is the radio core and C3 is the hot spot component (i.e., a termination shock). Comparison of \( \alpha \) between C1 and N1 clearly indicates that N1 suffers strong absorption from the intervening FFA foreground, which has been already claimed by Fujita & Nagai (2017).

4. Discussion

In this section, we discuss physical properties of the FFA foreground that exists somewhere along our line of sight to N1. The pioneering work of Walker et al. (2000) showed that synchrotron emission from the northern counter radio lobe located at the 5–10 mas from C1 is obscured by an FFA foreground for the first time. In the present work, we investigate the newly emerged northern counter-jet component N1 located around 2 mas from C1. Using the observational properties of N1, here we investigate physical properties of the FFA foreground. While Walker et al. (2000) discussed only a geometrically thin disk as the FFA foreground, we argue for both a geometrically thin CND and assembly of clumpy clouds as the FFA foreground in light of the current understanding of a more realistic picture of AGN nucleus structure (Wada 2012; Wada et al. 2016; Izumi et al. 2018). The considered structure is summarized in a schematic picture shown in Figure 3. Hereafter we assume that the plasma composition of the FFA foreground is a pure hydrogen. Hence, an electron number density equals that of protons.

### 4.1. FFA Opacity

First, we estimate the FFA opacity for foreground seen at 86 and 43 GHz. It is well known that the theoretically known FFA opacity for the case of uniformly distributed plasma is given by

\[
\tau_{\text{ff}}(\nu) \approx 25 \left( \frac{L}{1 \text{ pc}} \right) \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right)^2 \left( \frac{T_e}{10^4 \text{ K}} \right)^{-1.5} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2} \exp \left( -\frac{m_e c^2}{\nu L} \right),
\]

(1)

where \( T_e \) and \( n_e \) are the temperature and the electron density of absorbing matter, respectively, and \( L \) is the path length along the line of sight (Levinson et al. 1995). Correspondingly, a change in the FFA depth, \( \delta \tau_{\text{ff}} \), for a given frequency can be expressed as

\[
\delta \tau_{\text{ff}} = \left( \frac{\delta L}{L} + 2 \frac{\delta n_e}{n_e} - 1.5 \frac{\delta T_e}{T_e} \right) \tau_{\text{ff}}.
\]

(2)

From this, one can discuss which quantity mainly contributes to the \( \delta \tau_{\text{ff}} \) in different epochs.

Assuming that C3 and the corresponding counter-lobe component N1 have intrinsically the same intensities (Fujita & Nagai 2017), one can obtain \( \tau_{\text{ff}} \) as

\[
\exp \left[ -\tau_{\text{ff}}(\nu) \right] = \frac{I_{\text{N1}}}{I_{\text{C3}}},
\]

(3)
Table 1

| Component | $I_{\text{peak}}$ (Jy beam$^{-1}$) 43.2 GHz | $I_{\text{peak}}$ (Jy beam$^{-1}$) 86.2 GHz | $\alpha_{43}$ |
|-----------|------------------|------------------|-------------|
| C1        | 6.28 ± 0.02      | 5.82 ± 0.08      | 0.11 ± 0.35 |
| C3        | 6.82 ± 0.02      | 4.71 ± 0.08      | 0.54 ± 0.30 |
| N1        | 0.18 ± 0.02      | 0.41 ± 0.08      | 1.19 ± 0.43 |

Note. Column 1: component name; columns 2 and 3: peak intensity of a restored image at 43.2 GHz with KaVA with the restored beam size of 1.36 mas × 0.78 mas and the position angle of the major axis of 82.3°, and at 86.2 GHz with KVN; column 4: spectral index.

where $I_{C3}$ and $I_{N1}$ are the peak intensities of C3 and N1, respectively. Using Equation (3) and the measured $\tau_{N1}$ and $I_{C3}$, we obtain $\tau_{ff} = 2.4 \pm 0.2$ at 86 GHz and $3.6 \pm 0.1$ at 43 GHz, respectively. The ratio of $\tau_{ff}$ between 43 and 86 GHz, which is given by $\gamma = \log(\tau_{ff}(86 \text{GHz})/\tau_{ff}(43 \text{GHz}))$ with $\log 2 = -0.57 \pm 0.10$ is significantly different from $\gamma = -2$ which indicates a nonuniformity of FFA even if the error of $\gamma$ is taken into account. Note that this agrees with that derived between 15 and 43 GHz (Fujita & Nagai 2017). Also note that the spectral index map between the subsequent two frequencies does not provide the turn-over frequency of FFA. For its determination, VLBI observations at higher frequencies would be needed.

4.2. Physical Properties of FFA Foreground

As mentioned in Section 4.1, our observational results suggest the existence of an optically thick, ionized nonuniform plasma foreground, which may be an inner part of the rotational disk of the molecular gas within ~100 pc detected by ALMA (Nagai et al. 2019), although our estimation of $\gamma$ cannot constrain an exact location of the FFA foreground. As for the origin of FFA foreground, there are two possible cases to be realized. One is a CND in which the plasma density changes in the radial direction with its size of 10 pc (see Figure 3). Another one is an assembly of clumpy clouds, which are the main structure of AGNs such as the broad-line region, narrow-line region, clumpy torus, and polar dust (Figure 1 in Ramos Almeida & Ricci 2017). Below we discuss physical properties of CNDs and clumps in Sections 4.2.1 and 4.2.2, respectively.

4.2.1. Properties of CNDs

First, we discuss the case in which a CND with a constant half-opening angle ($\phi_{\text{disk}}$) is responsible for FFA (see Figure 3). The CND has a radial profile in $n_e$. The path length ($L$) and its change ($\delta L$) depend on the distance between N1 and C1, $I_N$, and the inclination angle of CND, $\theta$. These are given by

$$L = \frac{\sin \theta \sin 2\phi}{\cos(\theta + \phi) + \cos(\theta - \phi)} I_N, \quad \frac{\delta L}{L} = \frac{\delta I_N}{I_N} \lesssim 0.4.$$ (4)

Therefore, the change of the geometric path length is not likely a main contributor in $\delta \tau_{ff}$ (see Equation (2)) within our observational period. It is known that $I_N = 2.2 (\sin \theta)^{-1} \text{pc}$ and the range of $\theta$ is constrained as $18^\circ < \theta < 65^\circ$ by Tavecchio & Ghisellini (2014) and Fujita & Nagai (2017). Here, the
minimum half-opening angle is assumed as $\phi_{\text{disk}} = 0^\circ 2.5$ (i.e., scale height $h \approx 0.01r$, where $r$ is a radial distance from C1) based on a hydrostatic ionized disk structure (see Section 3 in Levinson et al. 1995). Such a geometrically thin disk is observationally indicated from the large value of the rotation measurement at 230 GHz (Plambeck et al. 2014). As for maximum $\phi_{\text{disk}}$, we set the condition of $\phi_{\text{disk}} < 90^\circ - \theta$, since the radio emission from C1 is not absorbed by the foreground CND (see Figure 2; Plambeck et al. 2014; Kim et al. 2019). Then, we obtain the corresponding allowed range of $L$ in Table 2, i.e., 0.04 pc $\lesssim L \lesssim$ 23 pc. The allowed path length is fairly wide due to the wide range of the allowed $\theta$. For instance, the lower limit of $L \approx 0.04$ pc realizes with the narrowest viewing angle of $\theta = 18^\circ$. This lower limit of $L \approx 0.04$ pc would correspond to the geometrical thickness of the innermost part of CND.

In Figure 4, we show the $n_\text{e}$ of the CND, which satisfies $\tau_{\text{ff}} = 1$ for given $L$ and $T_e$. Hereafter we do not treat the vertical structure of the disk but just discuss an averaged number density ($n_{\text{CND}}$) along the given $L$. The derived number density resides in

$$1.8 \times 10^4 \text{ cm}^{-3} \lesssim n_{\text{CND}} \lesssim 1.0 \times 10^6 \text{ cm}^{-3},$$

properly taking possible uncertainties of the CND’s $L$ and $T_e$ into account. Regarding $T_e$, the ionization condition requires the lower limit of $T_e$ as $T_e \approx 1 \times 10^4$ K. The upper limit of $T_e$ is governed by atomic line cooling in the FFA foreground (Levinson et al. 1995). Since the line cooling function is peaked around $T_e \approx 1 \times 10^4$ K (Sutherland & Dopita 1993), the assumed upper limit of $T_e$ should not be significantly different from $T_e \approx 1 \times 10^4$ K. Following Levinson et al. (1995), we set the upper limit as $T_e \approx 3 \times 10^4$ K in this work.

The column density, $N_H$, is a more convenient quantity than $n_{\text{CND}}$ for comparison of the obtained $n_{\text{CND}}$ with numerical simulations and other observations. In Figure 4, we overlay several lines with its $N_H$ being constant, as given by

$$N_H \approx 3 \times 10^{23} \text{ cm}^{-2} \left( \frac{n_{\text{CND}}}{10^5 \text{ cm}^{-3}} \right) \left( \frac{L}{1 \text{ pc}} \right).$$

Wada et al. (2016) examined the structure and dynamics of molecular, atomic, and ionized gases around an AGN by using three-dimensional radiation-hydrodynamic simulations. They found that inhomogeneous ionized gases are a geometrically thick, while dense molecular gases are distributed near the equatorial plane. If the viewing angle for the nucleus is larger, e.g., $\theta \gtrsim 50^\circ$, the column density is consistent with our observation. Thus, our observation might trace the parts of ionized gas demonstrated by radiation-hydrodynamic simulations. It is also interesting to note that Hitomi Collaboration et al. (2018) reported the detection of the Fe-Kα fluorescence line at 6.4 keV from 3C 84 with the Soft X-ray Spectrometer on board the Hitomi satellite with its equivalent width of ~20 eV. They derived $N_H$ as $N_H f_{\text{cov}} \approx 3.0 \times 10^{22} \text{ cm}^{-2}$, where $f_{\text{cov}}$ is the covering fraction of the fluorescenting material, from the Hitomi observation. They discuss a possible matter distribution in the case of the fluorescent material being located at a distance of 100 pc from the central engine. A small $f_{\text{cov}}$ (~0.02) can be derived if their result accommodates the electron density of the [Fe II] emitters (~4000 cm$^{-3}$) obtained with the NIR observation by Gemini (Scharwächter et al. 2013). When adopting this $f_{\text{cov}} \approx 0.02$, $N_H$ becomes $\approx 1 \times 10^{24} \text{ cm}^{-2}$, which is comparable to our results with $L$ of a few parsecs and $n_e$ of a few $\times 10^5$ cm$^{-3}$ shown in Figure 4. This may indicate a possibility that the Hitomi satellite detected the fluorescence line from a few parsec region of CNDs that absorbed the synchrotron emission from N1.

It is important to verify that the picture described above is consistent with the nondetection of N1 in the last decade. Since $\delta L/L$ is too small to change $\delta \tau_{\text{ff}}$ in our observational period, $n_{\text{CND}}/R_{\text{CND}}$ would be a main contributor of $\delta \tau_{\text{ff}}$. It is expected that $R_{\text{CND}}$ is larger in earlier observational epochs. As an example, we reanalyzed one epoch of VLBA archive data at 43 GHz conducted on 2012 October 29, which showed nondetection of N1 (Jorstad et al. 2017). The data shows the peak intensity of the southern component of 1.94 mJy beam$^{-1}$ with the $1\sigma$ image noise of 4.2 mJy beam$^{-1}$. If we set the detection criterion of N1 as 5 times the image noise, the upper limit of the peak intensity of N1 shall become $21$ mJy beam$^{-1}$, resulting in the lower limit of the opacity being 4.5. Assuming the typical values of $T_e$ of $1 \times 10^4$ K and $L = 0.5$ pc for 2012 October, $n_{\text{CND}} \gtrsim 2.6 \times 10^5$ cm$^{-3}$ is required to accommodate the opacity obtained by VLBA to the result of nondetection of N1. On the other hand, taking the same typical values of $L \approx 0.5$ pc and $T_e \approx 1 \times 10^4$ K and applying $\tau_{\text{ff}} = 3.6$ which was taken by our KaVA observation in 2016, we obtain $n_{\text{CND}} \approx 2.3 \times 10^5$ cm$^{-3}$, which is smaller than $n_{\text{CND}}$ in 2012.

Although the change is too subtle to draw a conclusion, the comparison of two-epoch images obtained in 2012 and 2016 indicates a slightly larger $n_{\text{CND}}$ for earlier epochs, which is consistent with a radial gradient in the disk. To make a clear conclusion, further yearly timescale long-term monitoring of 3C 84 is much awaited.

4.2.2. Properties of Clumpy Gas Clouds

Second, we discuss the case in which clumpy gas clouds are responsible for FFA (the clouds in Figure 3). This idea is motivated by recent observations of 10 pc obscuring structures in nearby AGNs with ALMA (García-Burillo et al. 2014; Imanishi et al. 2016, 2018; Izumi et al. 2018). The detailed

**Table 2**

| $\phi_{\text{disk}}$ (°) | $L$ (pc) | $\theta = 18^\circ$ | $\theta = 40^\circ$ | $\theta = 65^\circ$ |
|-------------------------|----------|---------------------|---------------------|---------------------|
| 0.5                     | 0.042    | 0.065               | 0.22                |
| 5                       | 0.43     | 0.66                | 2.23                |
| 10                      | 0.86     | 1.35                | 5.07                |
| 15                      | 1.31     | 2.12                | 9.85                |
| 20                      | 1.80     | 3.01                | 22.9                |
| 25                      | 2.32     | 4.13                | *                   |
| 30                      | 2.91     | 5.66                | *                   |
| 35                      | 3.59     | 8.02                | *                   |
| 40                      | 4.41     | 12.5                | *                   |
| 45                      | 5.44     | 16.5                | *                   |
| 50                      | 6.82     | 21.2                | *                   |
| 60                      | 12.3     | 30.5                | *                   |

*Note. C1 is hidden by CNDs.*
Figure 4. Estimated electron number density ($n_{\text{CND}}$) in the case of the circumnuclear disk (CND) being the FFA foreground. The color bar represents the estimated $n_{\text{CND}}$ for given $T_c$ and $L$, and the value is in the range of $1.8 \times 10^4 \text{ cm}^{-3} \leq n_{\text{CND}} \leq 1.0 \times 10^8 \text{ cm}^{-3}$. The three dashed lines indicate the cases corresponding to the constant column density, $N_H$, of $1 \times 10^{23} \text{ cm}^{-2}$, $5 \times 10^{24} \text{ cm}^{-2}$, and $1 \times 10^{25} \text{ cm}^{-2}$.

Figure 4. Estimated electron number density ($n_{\text{CND}}$) in the case of the circumnuclear disk (CND) being the FFA foreground. The color bar represents the estimated $n_{\text{CND}}$ for given $T_c$ and $L$, and the value is in the range of $1.8 \times 10^4 \text{ cm}^{-3} \leq n_{\text{CND}} \leq 1.0 \times 10^8 \text{ cm}^{-3}$. The three dashed lines indicate the cases corresponding to the constant column density, $N_H$, of $1 \times 10^{23} \text{ cm}^{-2}$, $5 \times 10^{24} \text{ cm}^{-2}$, and $1 \times 10^{25} \text{ cm}^{-2}$.

observing structures revealed by ALMA consist of not only a dusty disk, but also clumpy gas clouds with high velocity dispersion implied by supernovae and/or AGN radiative feedback (e.g., Wada et al. 2016; Izumi et al. 2018; Kawakatu et al. 2020). Hence, we consider the case in which clumpy gas clouds dominantly absorb the synchrotron radio emission from N1. In the clouds-dominated case, the FFA optical depth can be written as

$$\tau_{\text{ff}} = \frac{N_c}{10} \left( \frac{r_c}{0.1 \text{ pc}} \right) \left( \frac{\bar{n}_c}{10^4 \text{ cm}^{-3}} \right)^2 \times \left( \frac{T_c}{10^4 \text{ K}} \right)^{-1.5} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2},$$

(7)

where $\tau_{\text{ff}}$, $N_c$, $r_c$, and $\bar{n}_c$ are the average FFA optical depth of each cloud, the total number of clouds in the line of sight and the size of a cloud, and the number density of each cloud, respectively. Here, we note that $\tau = \alpha_{\text{ff}} r_c$ where $\alpha_{\text{ff}}$ is the FFA coefficient. Assuming $N_c$ is comparable to the mean number of clouds along the radial equatorial ray for Seyfert galaxies derived by the IR SED fitting (e.g., Alonso-Herrero et al. 2011; Ramos Almeida et al. 2011; Ichikawa et al. 2015; Audibert et al. 2017), i.e., $N_c \approx 3\text{--15}$, we find that $\tau_{\text{ff}}$ at 86 GHz becomes $\approx 0.2\text{--1.2}$, which is of the order of unity and agrees with observational properties of N1.

To constrain the number density of the clump, getting the size of the clump ($r_c$) should be required. The size of the self-gravitating clump in the context of AGNs has been estimated in the literature (e.g., Kroll & Begelman 1988; Höning & Beckert 2007; Kawaguchi & Mori 2011). According to the authors of these works, we have $r_c \lesssim 0.05 \text{ pc}$ at 1 pc from the central SMBH with $M_{\text{BH}} = 8 \times 10^8 M_{\odot}$ (Scharwächter et al. 2013). On the other hand, the size of clumps can be constrained by the observations of transient X-ray absorption events in nearby AGNs, i.e., the typical size is 0.002 pc (e.g., Markowitz et al. 2014; Tanimoto et al. 2019). By adopting $N_c$ and $r_c$, taking into account their uncertainties of $3 \lesssim N_c \lesssim 15$ and $0.02 \text{ pc} \lesssim r_c \lesssim 0.05 \text{ pc}$, the lower limit of number density of each ionized cloud $\bar{n}_c$ can be given by

$$3 \times 10^4 \text{ cm}^{-3} \lesssim \bar{n}_c \lesssim 4 \times 10^6 \text{ cm}^{-3}. \quad (8)$$

In the case of ionized gas clumps, the typical Thomson scattering opacity of each cloud can be estimated as $\tau_T \approx 1.5 \times 10^{-2}$ since the optical depth is given by $\tau_T = \sigma_T \bar{n}_c r_c$, where $\sigma_T$ is the Thomson cross section. If we adopt the opacity ratio of the dusty gas and the ionized gas is $\approx 10^3$ at the UV band for the AGN radiation (e.g., Umemura et al. 1998; Ohsuga & Umemura 2001; Wada 2012), the optical depth of each cloud is $\tau_{UV} = 10^3 \times \tau_T \approx 15$, which is consistent with the lower value for nearby Seyfert galaxies (e.g., Table 10 in Ramos Almeida et al. 2011). This might indicate that the ionized gas is also clumpy within the 1 pc region of 3C 84. Wada et al. (2018) examine properties of the ionized gas irradiated by less luminous AGN such as Seyfert galaxies based on their “radiation-driven fountain” model (Wada 2012). They found that the ionized region show nonuniform internal structures, corresponding to the clumpy fountain flows caused by the radiation pressure on dusty gas, although the typical density ($\bar{n}_c \approx 10^3 \text{ cm}^{-3}$) is smaller than our estimate. In addition, by the optical/NIR observations, the existence of dense clumps with $\bar{n}_c \approx 10^5 \text{ cm}^{-3}$ has been reported from the detection of coronal lines within NLR
(e.g., Murayama & Taniguchi 1998). These high density clouds in NLRs might contribute the absorption feature of N1.

Alternatively, since the density is comparable to number density \( n_e \approx 10^{-3} \text{ cm}^{-3} \), based on the momentum balance between the jet thrust and the ram pressure from the clump (Nagai et al. 2017; Kino et al. 2018), these ionized clumps may contribute not only the absorption of counter jet but also the feedback on jets. Since the dust sublimation radius of 3C 84 is \( \sim 0.1 \text{ pc} \), the dust components and the clump might be survived. If this is the case, the clumpy clouds might be related to the polar elongation in MIR continuum emission distributions revealed by high-resolution observations in nearby Seyfert galaxies (e.g., Tristram et al. 2014; Asmus et al. 2016; López-Gonzaga et al. 2016).

Lastly, it is worth mentioning that the size of clumpy clouds may be constrained by the multiphase observation of FFA, which is left for future work, since the typical timescale of head speed of jets which is left for future work, since the typical timescale of head speed of jets which is left for future work, since the typical timescale of head speed of jets which is left for future work. Since the dust sublimation radius of 3C 84 is \( \sim 0.1 \text{ pc} \) by assuming \( r_c = 0.05 \text{ pc} \) and the head speed of jets \( v_h \approx 0.2c \) (e.g., Nagai et al. 2010; Suzuki et al. 2012; Hiura et al. 2018). If we detect the flux variability with a few years, it may clarify whether the clumpy clouds are main absorbers rather than the CNDs.

5. Summary

By conducting quasi-simultaneous VLBI observations at 43 and 86 GHz with KaVA and KVN, we explore sub-parsec-scale structure of a nearby bright radio galaxy 3C 84 via the optically thick FFA features. Here we summarize our main findings.

1. We conducted a new quasi-simultaneous observation of 3C 84 with KVN at 86 GHz and KaVA at 43 GHz in 2016 February. We succeeded the first detection of N1 at 86 GHz and the data show that N1 still has an inverted spectrum between 43 and 86 GHz with its spectral index \( \alpha (\nu_0 \propto \nu^{-0.5}) \) of 1.19 \( \pm 0.43 \), while the approaching lobe component C3 has the steep spectrum with \( \alpha \) of \( -0.54 \pm 0.30 \).

2. The opacity of FFA is less dependent on frequency than the case for uniform absorbers, i.e., \( \tau_{\text{ff}} \propto \nu^{-0.5} \pm 0.10 \). Thus, it suggests that an absorbing medium would be a highly inhomogeneous structure and it is consistent with the previous work of Fujita & Nagai (2017).

3. Based on the measured flux asymmetry between the counter and approaching lobes, we constrain the number density of the FFA foreground \( n_{\text{CND}} \) as \( 1.8 \times 10^5 \text{ cm}^{-3} \), considering the uncertainties of temperature and path length of CNDs having gradual change in the plasma density. We also discuss the case of nonuniform CNDs containing clumpy clouds. By considering the size of clouds with subparsec, we constrain the number density of clouds with \( 3.0 \times 10^5 \text{ cm}^{-3} \leq n_c \leq 4.0 \times 10^6 \text{ cm}^{-3} \). In both cases, the derived electron number density is higher than the typical value \( \langle n_e \rangle = 10^{-2}-4 \text{ cm}^{-3} \) seen in the narrow-line region, suggesting that such dense ionized clumps might be located at a parsec-scale central region of 3C 84.

We are grateful to the anonymous referee for valuable comments that improved the manuscript. We acknowledge all staff members and students at KVN and VERA who supported the operation of the array and the correlation of the data. KVN is a facility operated by the Korea Astronomy and Space Science Institute. VERA is a facility operated by National Astronomical Observatory of Japan in collaboration with associated universities in Japan. This work is partially supported by JSPS KAKENHI grant Nos. JP18K03656 and JP18H03721 (MK). N.K. acknowledges the financial support of Grant-in-Aid for Young Scientists (B:16K17670) and Grant-in-Aid for Scientific Research (C:19K03918).

**ORCID iDs**

Kiyoiaki Wajima @ https://orcid.org/0000-0003-3823-7954

Motoki Kino @ https://orcid.org/0000-0002-2709-7338

Nozomu Kawakatu @ https://orcid.org/0000-0003-2535-5513

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