NUCLEAR RADIO CONTINUUM EMISSION OF LOW-LUMINOSITY ACTIVE GALACTIC NUCLEUS
NGC 4258

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ABSTRACT

The nearby low-luminosity active galactic nucleus (LLAGN) NGC 4258 has a weak radio continuum emission at the galactic center. Quasi-simultaneous multi-frequency observations using the Very Large Array (VLA) from 5 GHz (λ6cm) to 22 GHz (λ1.3cm) showed inverted spectra (α > 0, Sν ∝ να) in all epochs, which were intra-month variable, as well as complicated spectral features that cannot be represented by a simple power law, indicating multiple blobs in nuclear jets. Using the Nobeyama Millimeter Array (NMA), we discovered a large amplitude variable emission at 100 GHz (λ3mm), which had higher flux densities at most epochs than those of the VLA observations. A James Clerk Maxwell Telescope (JCMT) observation at 347 GHz (λ850 μm) served an upper limit of dust contamination. The inverted radio spectrum of the nucleus NGC 4258 is suggestive of an analogy to our Galactic center Sgr A*, but with three orders of magnitude higher radio luminosity. In addition to the LLAGN M 81, we discuss the nucleus of NGC 4258 as another up-scaled version of Sgr A*.

Subject headings: galaxies: active — galaxies: individual(NGC 4258) — galaxies:jets — galaxies: Seyfert — radio continuum: galaxies — submillimeter

1. INTRODUCTION

The nucleus of NGC 4258 (7.2 Mpc, Herrnstein et al. 1999) is one of the three closest radio continuum sources as extremely sub-Eddington super-massive black hole (SMBH) systems, following Sgr A* (8 kpc, Reid 1993; Eisenhauer et al. 2003) at the Galactic center and the nucleus of M 81 (3.6 Mpc, Freedman et al. 2001), as shown in Table 1. Their low-luminosities are believed to be caused by the radiative inefficiency of optically-thin accretion inflows in low accretion rates. An advection-dominated accretion flow model (ADAF) can fairly successfully explain the observed broadband spectra of Sgr A* (e.g., Narayan et al. 1995; Mannoto et al. 1997). In this model, synchrotron emission of thermal electrons is responsible for a highly inverted radio spectrum. However, this model has two problems: (1) The observed slightly inverted spectrum means the presence of a significant radio excess compared to the ADAF spectrum. The radio excess requires an additional emitting component. A model of jet + ADAF has been proposed to explain the radio excess (Falcke & Biermann 1999; Yuan et al. 2002). In another model, an inflow of hybrid plasma consisting of both thermal and nonthermal particles is adopted for Sgr A* (Özel et al. 2000). (2) The upper limit of the integrated electron density of accreting plasma, constrained by the detections of radio polarization in Sgr A* (Bower et al. 2003), is much lower than that predicted by the ADAF model. A sufficient mass loss is required before advecting across the event horizon. A radiatively inefficient accretion flow (RIAF) model was also proposed, involving a substantial mass-loss outflow and a non-thermal component of electrons (e.g., Yuan et al. 2003). Thus, an outflow or a jet may be essential for modeling the radio spectrum. However, the presence of an outflow or a jet in Sgr A* has never been established in any observational investigation.

Sgr A* shows a mysterious inverted spectrum (α > 0, Sν ∝ να) over the radio regime (e.g., Falcke et al. 1998; An et al. 2005), which cannot be explained by the simple ADAF model. The intrinsic size is ~ 1 AU at 86 GHz, corresponding to ~ 13 times the Schwaltzschild radius (Shen et al. 2005); there has been no evidence for any radio structure of jet or disk. The M 81 nucleus also shows an inverted spectrum similar to Sgr A* but is a much more powerful radio source; therefore, a so-called “a scaled-up version of Sgr A*” (Reuter & Lesch 1996), or “a bridge source” to help span the gap between Sgr A* and other low-luminosity active galactic nuclei (LLAGNs) (Markoff et al. 2008), has been suggested. The M 81 radio source shows a slightly resolved jet-like structure, with a size of 700–1300 AU at 22 GHz (Bietenholz et al. 1996). However, the jet-like component in M 81 makes only a minor contribution to the total flux; the substantial contribution to the observed inverted spectrum is from an unresolved core.

NGC 4258 is a LLAGN of type 1.9 Seyfert galaxy (Ho et al. 1997) with a weak radio continuum component at its galactic center. Total flux densities at 22 GHz and 1.5 GHz were ~ 3 mJy and 0.5 mJy, respectively, in very-
The nearest three active nuclei.

| Name  | $D$  | $M_{BH}$ | $P_{22}$ | $\Theta_{22}$ | $L_X$ | $L_X/L_{Edd}$ | Ref. |
|-------|------|----------|----------|--------------|-------|---------------|------|
| NGC 4258 | 7.2 | a | $3.9 \times 10^9$ | a | $2 \times 10^{19}$ | 0.4 | 3000 | 3700 | g | $8.0 \times 10^{69}$ | 1.6 $\times 10^{-5}$ |
| M 81 | 3.6 | b | $7.0 \times 10^7$ | e | $1.9 \times 10^{20}$ | 0.18 | 650 | 460 | h | $1.5 \times 10^{69}$ | 1.7 $\times 10^{-6}$ |
| Sgr A* | 0.008 | cd | $4 \times 10^6$ | f | $5.7 \times 10^{15}$ | 0.46 | 4 | 50 | i | $2.4 \times 10^{53}$ | 5 $\times 10^{-12}$ |

Note. — Col. (1) name source; Col. (2) distance; Col. (3) reference of distance; Col. (4) black hole mass; Col. (5) reference of black hole mass; Col. (6) radio power at 22 GHz; Col. (7) projected size of radio source at 22 GHz in milli-arcsecond. For NGC 4258, the offset of a northern nuclear jet from a dynamical center. For M 81, the major axis of the fitted size of the nuclear component. For Sgr A*, an intrinsic source size estimated by calibrating interstellar scattering, see references in detail; Col. (8) reference of source size; Col. (9) size of radio source at 22 GHz in milli-arcsecond. For NGC 4258, the offset from the dynamical center of a Keplerian disk rotating around a dark mass of $3.9 \times 10^7 M_\odot$ and well established by water maser observations (Miyoshi et al. 1995; Herrnstein et al. 1999). The putative accretion disk on the SMBH has an almost edge-on orientation with the rotation axis pointing almost north ($PA = -8^\circ$) and tipped $82^\circ$ to the line-of-sight. The jet closely aligns in projection on the sky with the rotation axis. The jet extends up to $5 \times 10^5$ AU at 1.5 GHz in a VLBI image (Cecil et al. 2000), which may be physically connected with the kpc-scale jet-like structures ("anomalous arms"; e.g., van der Kruit et al. 1972; Hyman et al. 2001). Thus, the key difference between NGC 4258 and Sgr A* and M 81 is that the jet in NGC 4258 has definitely been identified as the radio emitting origin by VLBI imaging. The peaks of north–south jets are significantly shifted from the putative position of SMBH, implying that the major fraction of total flux is from jets rather than from an innermost accretion flow. If the nucleus of NGC 4258, just like that of M 81, is another scaled-up version of Sgr A*, the radio emitting processes of the mysterious inverted-spectrum radio emission of Sgr A* and M 81 could be responsible for jets. However, an inverted spectrum over the radio regime has not yet been established for the NGC 4258 nucleus.

In the present paper, we report the continuum spectra and flux variability of radio emission of the NGC 4258 nucleus at centimeter to submillimeter bands. Observations and data reductions are described in § 2. Results are presented in § 3, and their implications are discussed in § 4. Finally, we summarize in § 5. At a distance of 7.2 Mpc to NGC 4258, 1″ corresponds to 35 pc.

2. Observations and Data Reductions

We reduced raw data from the archival data of the James Clerk Maxwell Telescope (JCMT) on Mauna Kea at 347 GHz, the data of our observations conducted with the Nobeyama Millimeter Array (NMA) at the Nobeyama Radio Observatory (NRO) at ∼ 100 GHz, and from the archives of the Very Large Array (VLA) at the National Radio Astronomy Observatory (NRAO) from 4.9 to 43 GHz.

2.1. JCMT data

We retrieved archival data for observations of NGC 4258 on March 18, 1998 using the Submillimetre Common User Bolometer Array (SCUBA) (Holland et al. 1999) on the JCMT at 347 GHz (850 μm) in jiggly-map mode. The SCUBA covers a field of view of ∼ 2′, which is two times larger than that covered by the NMA. The data were processed with the SCUBA User Reduction Facility (SURF) package. We applied the standard reduction procedures including flat fielding, flagging of transient spikes, correcting the extinction, pointing correction, sky removal and flux density scaling. An Uranus scan gave us a flux scaling factor, with an uncertainty assumed to be ∼ 15%, and an effective beam size of 15.1′, corresponding to ∼ 530 pc. The measured R.M.S. of the image noise was 10.5 mJyb beam$^{-1}$ on blank sky.

2.2. NMA observations

We observed the nuclear regions at ∼ 100 GHz (λ 33 mm) using the NMA. Array configurations were AB, C, and D with maximum baseline lengths of 351, 163, and 82 m, respectively. Observations were originally conducted for HCN($J = 1 - 0$) and HCO$^+ (J = 1 - 0$) molecular emission lines, except for observations conducted only for continuum between May 13 and 15, 2005. Visibility data were obtained with double-sided receiving systems. In the data for molecular-line observations, we use only line-free data from the upper-side band at a center frequency of 100.777 GHz with a bandwidth of 1 GHz (the emission lines were in the lower-side band at a center frequency of 88.777 GHz). In the data for continuum observations, we use two sidebands at 89.729 and 101.729 GHz, both of which were line-free. The typical system noise temperature was about 140 K in the double-sided band. For gain calibration, we made scans between the target and a reference calibrator, 1150+497, every 20 or 25 min. Flux scales of the calibrator were derived by relative comparisons with the known flux calibrators such as Uranus that were observed quasi-simultaneously at almost the
same elevations in order to avoid a residual error of calibration from differential atmospheric attenuation. The uncertainty in the absolute flux scale is expected to be less than 15%. A scan of around 30 min was performed for bandpass calibration using bright quasars.

The data were reduced using the UVPROC-II package (Tsutsumi et al. 1997) by standard manners, including flagging bad data, baseline correction, opacity correction, bandpass calibration, and gain calibration. For the data observed in May 2005, we combined the upper and lower sidebands to obtain a higher sensitivity; the resultant center frequency was 95.729 GHz. Each daily image was synthesized from visibilities in natural weighting and deconvolved using the IMAGR task of the Astronomical Image Processing System (AIPS) developed at the NRAO. FWHMs of the synthesized beams were typically \( \sim 3'' \), \( 5'' \), and \( 7'' \) in the AB-, C-, and D-array configurations, respectively. These resolutions correspond to \( \sim 100, 170, \) and 240 pc. The R.M.S. of image noise was estimated from statistics on blank sky using the IMEAN task of AIPS and was used to determine 3\( \sigma \) upper limits in the cases of negative detection.

### 2.3. VLA data

We retrieved 12 archival data sets from VLA. Our selection criteria for the data were (1) observation toward the nucleus in continuum mode, (2) multi-frequency observation quasi-simultaneously at three or four bands in a range of 4.9–22 GHz or observation including at 43 GHz, and (3) observation with high-spatial resolution (< 1.2\( '' \)) of A- or B-configurations to extract only a nuclear component. We reduced the data using the AIPS by following a standard procedure. 3C 286 scans served as flux scaling factors, with an uncertainty of 3 and 5% that we assumed at <22 GHz and ≥22 GHz, respectively.

In data obtained on January 04, 1997, IF2 at 15 GHz was very noisy, so we used only data of IF1. In data obtained on March 06, 1997 and September 05, 1998, 22-GHz observations had been conducted to set IFs to three frequencies, corresponding to the well-known megamasers of the low-velocity component near the systemic velocity and of high-velocity components red-shifted and blue-shifted relative to the systemic velocity, respectively. However, these observations were done in continuum mode. We used only the blue-shifted maser's band, at which the maser emission is sufficiently weak (Nakai et al. 1993) to not affect our continuum photometry.

All target images were synthesized with natural weighting and deconvolved with the IMAGR task of AIPS. The resultant FWHM of the synthesized beam is 0.1–2''. The typical R.M.S. of image noise estimated from statistics on blank sky using the IMEAN task of AIPS was 0.45, 0.10–0.20, and 0.05–0.10 at 43 GHz, 22–15 GHz, and 8.4–4.9 GHz, respectively.

### 3. RESULTS

The results of the flux measurements are listed in Table 2, and the details are described in the following subsections. An average of flux densities over all epochs at each frequency, a reduced chi-square, and a probability of no variability are also shown at the lowest three lines in the table. Flux variability is found at all frequencies at greater than 95% confidence, except for 43 GHz and 347 GHz, where the number of epochs was inadequate for statistics. At 100 GHz, six upper limits are included. Statistics for the NMA flux densities are performed using only detected data. The spectral plot of all the data is shown in Fig. 1, which apparently shows a global trend of an inverted spectrum over the radio bands.

The JCMT image is shown in Fig. 2, which is the only case in which some radio structure is seen in our images. The light curve plot for measured NMA flux densities is shown in Fig. 3. The spectral evolution obtained by the VLA observations is shown in Fig. 4.

#### 3.1. The upper limit of dust contamination

The JCMT image at 347 GHz (\( \lambda 850 \mu m \)) of the nuclear region (\( \sim 4.3 \times 4.3 \) kpc; Fig. 2) shows a structure elongated along the major axis of the host galaxy and with no nuclear concentration. Such a structure is very similar to that of CO emission (Regan et al. 2001; Helfer et al. 2003; Sawada-Satoh et al. 2007). These suggest that most of the submillimeter emission originated not in the AGN continuum but in interstellar dust associated with the host galaxy. The flux density from the active nucleus, at the point indicated by a cross in Fig. 2, contributes less than the peak intensity. We averaged intensity over the JCMT beam of 15.1'' centered at the nucleus in order to obtain an upper limit of the flux density of AGN emission. The upper limit may be contaminated by the CO(3–2) emission of \( \sim 1 \) mJy in the SCUBA bandwidth of \( \sim 40 \) GHz, considering the velocity-integrated intensity peak of the CO(1–0) map (Helfer et al. 2003) and the intensity ratio CO(3–2)/CO(1–0) (Mao et al. 2010).

In the present study, the JCMT measurement does nothing more than providing the upper limit of AGN continuum emission contaminated by dust emission, as shown by a dashed line in Fig. 1. The gray body spectrum of dust emission is \( S_\nu \propto \nu^{2+\beta} \) in the Rayleigh–Jeans regime at less than about 1 THz, where \( \beta \) is the dust emissivity, which is believed to be between 1 and 2 (Hildebrand 1983); the \( \beta \) value has been determined to be \( 1.3 \pm 0.2 \) by JCMT observations for nearby galaxies (Dunne et al. 2000). In this paper, we adopt \( \beta = 1 \), which is the most influential case in the spectral extrapolation.
to lower frequencies. As a result, the dashed line in Fig. 1 is useful to estimate the upper limit of dust contamination in the millimeter photometry of the nucleus (cf. Doi et al. 2005).

3.2. Flux variability at λ3 mm

In NMA images at 100 GHz (λ3 mm) of a field of view of ~1', which is roughly two times smaller than the JCMT image area, only a point-like single emission component was found at the nucleus. We detected the emission for 9 out of 15 epochs with NMA's sensitivities. Flux densities were measured in the image domain by fitting and the flux scaling (15%). In our previous study (Doi et al. 2002), fitting the root sum square of errors of the Gaussian component was found at the nucleus. We detected the centimeter (beam size), indicating that the de-
tecting limit of nuclear emission. The upper limit of millimeter continuum emission tends to be significantly stronger than the centimeter emissions. The upper limit of dust contamination was estimated to be <2.2 mJy at 100 GHz, within a 15.1″ region at the nucleus (§ 3.1). The upper limit of the contamination from low-frequency anomalous arms was estimated to be <0.5 mJy at 100 GHz on the basis of a spectral extrapolation using a flux density of 3.4 mJy at 4.9 GHz for the nuclear region of 14″ (Hummel et al. 1989) and a spectral index of −0.65 (Hyman et al. 2001). Therefore, the contamination both from dust and anomalous arms was almost negligible for our NMA photometry with beams of ~3–7″.

Flux variability was detected at greater than 95% confidence. The variability showed no correlation with the array configuration (beam size), indicating that the detected variability did not result from a resolution effect. The NMA flux decreased from 18.1 ± 3.5 mJy at maximum to 4.6 ± 1.7 mJy at minimum in three years, indicating L < 0.7 (pc). A flux increase from 10.0 ± 1.3 mJy on December 21, 2001 to 18.1 ± 3.5 mJy on March 21, 2002 (three months) results in L < 0.13 (pc). We derive the size by the equation, L < c |d ln S/dt| −1, where L is size, S is flux density, and t is observation time difference, assuming an exponential light curve (Burbidge et al. 1974;
at 850 µm. Contour levels are \( \sigma_{\text{rms}} (4, 5, 6, 7, 8, 9) \), where \( \sigma_{\text{rms}} = 10.5 \text{ mJy beam}^{-1} \) is R.M.S. of image noise. Cross symbol represents the position of the NGC 4258 nucleus, and its positional accuracy is described by the length of the cross. Beam size, 15.1\( \text{''} \), is described in the lower left-hand corner of the image.

Valtaoja et al. (1999). Slight diffuse contamination and the variability strongly demonstrate that almost all NMA fluxes originated in only a nuclear component rather than in any galactic components. Hence, our NMA photometry is substantially responsible for the active nucleus. This is the first insight into the nuclear radio emission at a millimeter band for NGC 4258.

3.3. Spectral evolution at VLA wavelengths

In VLA images at 5–43 GHz (\( \lambda 6–0.7 \text{ cm} \)), a single emission component was identified at the nucleus in all cases we analyzed. Flux densities were measured with the JMFIT task of the AIPS. The total errors were determined from the root sum square of errors of the Gaussian fitting and the flux scaling. In all cases, emissions were almost unresolved: they were not extended beyond half of the FWHM of the synthesized beams. To estimate the contribution of diffuse components to our photometry, we also made images with uniform weighting, resulting in a slightly smaller beam (but in a less sensitive image). The resultant ratios of the measured flux densities with uniform weighting to that with natural weighting were between 0.80 and 1.10: 0.93 on average. The ratios indicate that almost all fluxes were from a region of \( < 0.1'' \), corresponding to \( < 3.6 \text{ pc} \) at a distance of 7.2 Mpc. We, therefore, successfully carried out photometry without a significant resolution effect for the nucleus with the VLA-A and -B beams.

The VLA spectrum for each epoch is shown in Fig. 4. Variability is apparently seen, compared to a power-law spectrum (\( \alpha = 0.32 \)) represented by dashed lines, which is determined by the least-square fit to all the data from 5 to 22 GHz. For each epoch, we also derived a power-law spectral index by least-square fitting to quasi-simultaneously obtained data from 5 to 22 GHz (column [10] in Table 2), resulting in from \( \alpha = 0.06 \) to \( \alpha = 0.64 \); the average is \( \langle \alpha \rangle = 0.21 \pm 0.04 \). The variation of indices is significant at greater than 99.99\% confidence. Note that the fitted power-law spectral indices remain inverted, \( \alpha > 0 \), in all the epochs.

The spectral features and their evolutions were apparently complicated. Several data points show significant departures from a simple linear trend. Highly inverted spectra are locally observed, for example \( \alpha > 0.7 \) at 8.4–15 GHz on January 04, 1997 and September 05, 1998 and at 15–22 GHz on January 05, 1997. On the other hand, flat and marginally steep spectra are also locally observed. This indicates that the spectrum is made from multiple components. The first six epochs show spectral features rapidly changing in only a month, which suggests that the sizes of emitting sources should be restricted by these light-crossing times. There is a gradual increase at 22 GHz, from 2.2 ± 0.2 to 3.6 ± 0.4 in two weeks from December 22, 1996 to January 05, 1997, deriving \( L < 0.02 \text{ pc (}\ < 4000 \text{ AU}) \). In addition, a flux decrease at 22 GHz in 13 days between March 06 and 19, 1997, resulting in \( L < 0.02 \text{ pc} \). The trend of the inverted spectrum might continue into higher frequencies, which is inferred from the larger flux densities at 100 GHz at several epochs, although we have no simultaneous observation with VLA and NMA. A two-point spectrum between 15 GHz (\( \lambda 33.6 \text{ cm} \)) and 43 GHz (\( \lambda 7 \text{ mm} \)), \( \alpha = 0.59 \pm 0.30 \), observed on December 21, 2000 shows a sign that the trend of an inverted spectrum continues into millimeter wavelengths. The upper limit at 347 GHz (\( \lambda 850 \text{ µm} \)) from the JCMT data is too high to constrain whether the trend of the inverted spectrum continues into submillimeters.

3.4. Comparisons to previous radio observations for NGC 4258

3.4.1. Flux variability

We discovered variable 100-GHz (\( \lambda 3\text{mm} \)) nuclear emissions at the nucleus. These millimeter emissions seem to be significantly brighter than those at centimeters, which can also be seen in 43 GHz (\( \lambda 7\text{mm} \)) flux densities, although only two epoch data points are presented (Table 2). These millimeter emissions cannot represent the dust contribution because of the variability and the upper limit of the expected dust spectrum based on the SCUBA/JCMT image (§ 3.1).

The significant flux variability at 22 GHz has been previously suggested: the continuum component in VLBA images seems to vary several times (\( S_{\nu \text{GHz}} = 0.7–4.0 \text{ mJy} \)) during 15 epochs in the period 1997–2001, although these measurements are based on a limited range of baseline lengths (Argon et al. 2007). Herrnstein et al. (1997) also showed flux variability of the continuum component at 22 GHz (from \( < 1 \text{ mJy} \) to 6 mJy, based on both VLA and VLBA), which are correlated with the averaged flux density of maser emission in a systemic velocity range: the continuum emission is variable by up to 100\% over timescales of a few weeks. This range of flux densities and timescale of variability are consistent with our measurements at 22 GHz (§ 3.3). We have definitely confirmed the presence of continuum flux variability in the NGC 4258 nucleus at high frequencies, even at 100 GHz.

3.4.2. Continuum spectra

Ho & Ulvestad (2001) reported a slightly resolved core
Fig. 3.— Results of flux monitor for the NGC 4258 nucleus at 3 mm. The three plots on May 2005 are from measurements at 95.725 GHz; the others are from those at 100.777 GHz. Symbols with arrows indicate 3σ upper limits. Flux variation is significant at greater than 95% confidence.

Fig. 4.— Radio spectra for the NGC 4258 nucleus at 5–43 GHz obtained with the VLA A- or B-array. Dashed lines represent a fitted linear spectrum \( S_\nu = S_\nu^{1GHz} \nu^{+\alpha} \) for all data from 5 to 22 GHz.
of $S_{1.4\text{GHz}} = 2.73$ and $S_{5\text{GHz}} = 2.18$ (mJy), $\alpha = -0.18$, in matched angular resolutions of $\sim 1''$, in agreement with previous observations at a similar resolution (Vila et al. 1990); Hyman et al. (2001) reported varying spectral indices between $-0.18$ and $-0.41$ between 1.4 and 5 GHz, i.e., slightly steep spectra, at the nucleus (on the other hand, the spectral index map shows relatively uniform distribution of a steep spectrum of $\alpha = -0.65 \pm 0.10$ throughout “the anomalous arms”). An inverted spectrum had been seen at higher frequencies: $S_{23\text{GHz}} = 2.4$ and $S_{5\text{GHz}} = 3.2$ (mJy), $\alpha = +0.4$ in matched resolutions of $\sim 3''$ (Turner & Ho 1994). Thus, at 1.4 GHz, the extended emission of “the anomalous arms” possibly contaminates a nuclear flux density even with the A-configuration. Our observations at frequencies higher than 5 GHz of an extracted core emission (see, § 3.3) show inverted spectral indices in terms of power law fitted spectra in all epochs (Col. (10) in Table 2) and an inverted spectral feature based on flux densities averaged through our observation epochs.

Not only flux densities but also VLA spectral features are significantly variable in our measurements (Col. (10) in Table 2). Furthermore, the VLA spectral features cannot be represented with a simple power-law spectrum model (Fig. 4). Previously, Hyman et al. (2001) also showed variable spectral indices (slightly steep) between 1.4 and 5 GHz toward the nucleus; Nagar et al. (2001) reported a folded spectral feature (2.1, 1.9, and 2.8 mJy at 5, 8.4, and 15 GHz, respectively) from VLA observations at matched resolutions of 0.5′′. Thus, the continuum spectrum of the nucleus of NGC 4258 is definitely inverted, but not simple or stable. The physical origin of the spectral evolution is discussed in § 4.

4. DISCUSSION

4.1. Inverted spectra and a turnover frequency

In this study, inverted radio spectra at centimeter wavelengths, probably up to millimeter wavelengths, were found for NGC 4258, and have properties similar to that found in Sgr A* and M 81. The fitted VLA spectra were always inverted but complicated and variable (§ 3.4.2), implying the presence of multiple emitting components. Such complicated and variable radio spectra are also seen in M 81 (Markoff et al. 2008). On the other hand, the simultaneous spectrum at $\sim 1–100$ GHz of Sgr A* seems to be relatively simple with only a fold of the spectral index at $\sim 10$ GHz from $\alpha = 0.11 \pm 0.03$ to $\alpha = 0.43 \pm 0.04$ (An et al. 2005): this is consistent with the result of other epochs (e.g., Falcke et al. 1998). We discuss later (§ 4.2) its physical origin as the outer region of nuclear components.

The spectral turnover at a higher frequency, where the inverted spectrum becomes steep, cannot be determined for NGC 4258 using the available data, because of non-simultaneous observations among centimeter, millimeter, and submillimeter bands. The spectral turnover would provide important information about the innermost radio emitting regions in the vicinity of the black hole. Turnover frequency is relevant to a radius where radiation becomes optically thin due to the extraction of accreting material via outflow (e.g., Di Matteo et al. 2000) or the inner edge of an accretion disk in the framework of accretion-flow models. In the framework of jet models, the shock radius at the base of the jet is a major parameter that is responsible for a turnover frequency (Yuan et al. 2002). The observed spectral energy distribution (SED) of Sgr A* suggests the presence of a turnover between the submillimeter and infrared regime, which has been explained by the radiation spectrum from the radius of the innermost edge of accretion flow (Narayan et al. 1995; Mannoto et al. 1997). The simultaneous observations of M 81 at 100 GHz ($\lambda$3mm) and 230 GHz ($\lambda$1mm) present a turnover frequency of between these frequencies (Schödel et al. 2007), which is in good agreement with the data presented by Reuter & Lesch (1996); however the data were not acquired simultaneously. The turnover frequency of M 81 is much lower than that of Sgr A*, suggesting that an effectively radiating site would be present at relatively outer region for M 81; the difference of Schwarzschild radii between them may be responsible for the difference of the turnover frequencies. On the other hand, Yuan et al. (2002) proposed that the SED of NGC 4258 can be modeled as a synchrotron jet dominated spectrum having a spectral peak in the infrared in order to satisfy both the weak radio and relatively strong infrared emissions (the infrared–optical spectral index indicates nonthermal emissions, $\alpha = -1.4\pm0.1$; Chary et al. 2000) by the base of jets with a shock diameter of 5$R_{\text{Sch}}$ ($R_{\text{Sch}}$ is the Schwarzschild radius; Yuan et al. 2002).

In the SED modeling for NGC 4258, observed radio emissions cannot be attributed to the same origin as the infrared peak by the base of jets; the outer component of nuclear jets is required (Yuan et al. 2002), because the emission of the base of jets that should come from the location of the dynamical center of the maser disk is suppressed to be $< 220 \mu$Jy in VLBI images (Herrnstein et al. 1998). Thus, the determinations of turnover frequencies are crucial to reveal the physical origin of radio emissions from innermost regions.

4.2. Physical origin of nuclear radio emissions

The presence of jets has not been definitively confirmed or ruled out for Sgr A*. M 81 shows structures consisting of a core and jet-like elongation at 1–43 GHz (Bietenholz et al. 2004; Ros & Perez-Torres 2008), and the core contributions dominate total radio flux in VLBI images. The location of the core (brightness peak) moves southwest with increasing frequency (1.7–15 GHz), and this trend continues up to the stationary position of a putative black hole (Bietenholz et al. 2004). The line of sight toward the nucleus is opaque at these radio frequencies. Hence, the core emissions cannot be responsible for an accretion disk except due to jets. Thus, the observed inverted spectrum in total flux definitively comes from jets for M 81 at these frequencies. The size of the emitting region inferred from the time scales of observed millimeter variability is $< 25 R_{\text{Sch}}$ (Schödel et al. 2007, see also Sakamoto et al. 2001), which is possibly consistent with the radio emitting size of the accretion disk predicted by the ADAF model. The spectral turnover at 100–230 GHz (Schödel et al. 2007) implies that millimetric observations could see through to the vicinity of the black hole.

The NGC 4258 nucleus has a similar situation in terms of the physical origin of nuclear radio emission. Jet structures whose brightness peaks are significantly shifted from a dynamical center are clearly seen in VLBI images at 1.5 and 22 GHz (Cecil et al. 2000; Herrnstein et
The observed radio luminosity of NGC 4258 at 5 GHz is higher than the maximal luminosity expected from the ADAF model and black hole mass, implying that the radio emission is predominantly from jets, although its optical luminosity could be provided by the ADAF (Wu & Cao 2005); M 81 is also in the same situation. Hence, the observed VLA spectra and their time evolution in our study for NGC 4258 should be caused by jets; we discuss the spectral evolution in detail in § 4.3.

The emission from the location of the dynamical center is < 220 µJy at 22 GHz (Herrnstein et al. 1998), implying higher frequencies are needed to see through. A spectral turnover at a higher frequency, where the source is expected to become optically thin, cannot be determined using available data. The observed millimeter variability during three months in our study suggests a size of < 0.17 pc (§ 3.2), which is too large to give a constraint for the emission from the scale of the accretion disk. Multi-frequency millimeter observations aiming to investigate intra-day spectral evolution are crucial to determine a spectral turnover and the contribution of emission from the scale of the accretion disk.

4.3. An interpretation of observed spectral evolution

Radio light curves of Sgr A* at 22 and 43 GHz for a low level of flare activity can be interpreted by considering the ejection and adiabatic expansion of a self-absorbed plasma blob, showing a spectral evolution that a spectral peak frequency shifts toward lower frequencies (Yusef-Zadeh et al. 2006). In this scheme, spectral evolution involving multiple blobs is predicted to propagate from a high frequency to lower frequencies. Similar apparent spectral changes are also seen in M 81 (Markoff et al. 2008). On the contrary, the observed VLA spectra of NGC 4258 seem to include an apparent spectral evolution of a flare-up propagating from 8.4 to 22 GHz in the first four epochs (Figure 4), which cannot be explained by the simple model of an expanding blob; this event began in the period December 07–22, 1996 and ended in the period December 29–31, 1996, i.e., during 7 < t < 24 days. In this paper, for NGC 4258, we propose the model of a series of self-absorbed blobs affected by external absorption (free–free absorption), as described below.

The intensity peak of jets of NGC 4258 at 22 GHz is located about 0.4 mas (corresponding to 0.014 pc) north of the dynamical center of the disk, which is viewed almost edge-on (inclination of 82°; Herrnstein et al. 1999). The relative faintness of the southern jet component may arise because of free–free absorption due to an intervening layer of ionized atomic gas above the molecular disk (Herrnstein et al. 1997). The emission from the location of the dynamical center is suppressed to < 220 µJy, which has been discussed as an ADAF-emitting radius smaller than 100R_{\text{Sch}} (Herrnstein et al. 1998) or as the opake nozzle of a relativistic plasma flow (Blandford & Königl 1979; Herrnstein et al. 1997). In this paper, we consider another case that possibly the disk inflates to be thicker due to higher temperatures at the inside of the maser orbits and could be an absorber toward the root of the northern jet in addition to the nucleus and the root of the southern jet. The thickness of outer (0.13–0.26 pc in radii) maser disk is 5 μarcsec (40 AU) (Argon et al. 2007); we consider the thickness of the putative inner (< 0.13 pc) disk to be ~ 0.2 mas (~ 1400 AU).

We assume that the observed spectral evolution is a composite of a series of emerging synchrotron emitting blobs of spectral-peak flux densities of ~ 0.4, ~ 0.5, and ~ 0.7 mJy at 8.4, 15 and 22 GHz, respectively; these components are supposed to provide residual fluxes between December 07–31, 1996. Under the equipartition condition between the energy densities of particles and magnetic fields in a uniform spherical plasma, the diameters of these blobs are ~ 90, ~ 50, and ~ 40 AU (~ 110, ~ 70, and ~ 60R_{\text{Sch}}) at 8.4, 15 and 22 GHz, respectively; the total extent of the jet consisting of three blobs would be > 180 AU unless they overlapped each other. If these blobs get away from the absorption region while advancing north from the dynamical center, in order of the 8.4-, 15-, and 22-GHz blobs, then the observed spectral evolution propagating from 5 to 22 GHz can be explained. The advancing speed should be > 0.044c (c is the speed of light), because of the total extent of jets of > 180 AU and a duration of the event of < 24 days. The flare up of 22 GHz seems to begin before December 22 and to end after December 29; the duration of 22-GHz flaring up seems to be > 7 days, which means an advancing speed of < 0.12c to pass over the diameter of the 22-GHz blob. Consequently, the putative jet speed would be sub-relativistic, 0.044c–0.12c.

Our model requires no spectral evolution of each individual blob during the event, i.e., no adiabatic expansion. Using the model of an adiabatically expanding synchrotron blob (van der Laan 1966) to avoid the decrease of spectral peak frequency from 15 to 8.4 GHz during the event of 7 < t < 24 days, an expansion speed should be limited to 0.002c < v < 0.006c, which is much smaller than the putative bulk speed. Thus, our model described above is valid only in a dynamical situation dominated by the time scale of bulk advancing jets rather than by expansion.

A moving absorber in front of emitting blobs is another idea to explain the spectral evolution propagating to higher frequencies. A Kepler rotation velocity of the maser disk is 1140 km s$^{-1}$ (0.0038c) at the radius of the innermost maser disk of 0.13 pc (e.g., Miyoshi et al. 1995; Argon et al. 2007). To provide the rotation speed of the required > 0.044c, a rotation radius should be < 200 AU, which is close to the same as or less than the size of the emitting region. Thus, a moving absorber cannot be responsible for the observed spectral evolution.

4.4. NGC 4258 another scaled-up version of Sgr A*

We found inverted radio spectra in the NGC 4258 nucleus, analogous to Sgr A* and M 81. We discuss the analogy and differences on the NGC 4258 as another scaled-up version of Sgr A*, in addition to M 81, in reference to Table 1.

The NGC 4258 is a radio source with a linear scale 800 times larger (80 times larger in R_{\text{Sch}} unit) than that of Sgr A*. The black hole mass of NGC 4258 is upscaled with reference to Sgr A*, in the same order as that of M 81. However, several differences are seen between NGC 4258 and M 81.

The X-ray luminosity of NGC 4258 is five times larger than that of M 81, and its 10 times higher L_x/L_{\text{Edd}}, which is thought to be proportional to the Eddington ratio L_{\text{bol}}/L_{\text{Edd}} that is defined as the ratio of bolometric...
to Eddington luminosities, indicates a higher accreting system compared to M 81. However, the radio power is 10 times smaller. According to “a fundamental plane of black hole activity” (Merloni et al. 2003, see also Falcke et al. 2004), radio luminosity seems to depend on the relationship of $L_{5\text{GHz}} = 10^{7.33} f_X^{0.9} M_{\text{BH}}^{0.78}$, where the 5-GHz core luminosity $L_{5\text{GHz}}$ and the 2–10 keV X-ray luminosity $L_X$ in ergs s$^{-1}$, and the black hole mass $M_{\text{BH}}$ in $M_{\odot}$, with a scatter of $\sigma(L_{5\text{GHz}}) = 10^{0.88}$. The radio luminosities the relation predicts are $\sim 1/100$ and 1/5 of the observed ones for NGC 4258 and M 81, respectively, assuming $\alpha \sim 0.2$ at 5–22 GHz. Therefore, the radio emission of the NGC 4258 nucleus is very weak. On the other hand, the linear scale of the radio source is four times larger than that of M 81 (also eight times larger scaled in $R_{\text{Sch}}$ unit). Hence, NGC 4258 has significantly lower-brightness jets. The core shift of NGC 4258 is eight times larger than the expected core shift of $\sim 0.09$ mas at 22 GHz for M 81$^9$. This is contrary to commonsense: a core shift tends to be larger in a higher radio luminosity. The difference of inclinations ($i = 82^\circ$ for NGC 4258; Miyoshi et al. 1995; Herrnstein et al. 1999, and $i = 14^\circ$ for M 81; Devereux et al. 2003) can account for half of the factor of 8, and thus another parameter providing a large factor may be required. A possible parameter is the jet Lorentz factor $\gamma$ (or jet speed $\beta$): $\sim 2.5–3$ times smaller $\beta$ could be responsible for the larger core shift of NGC 4258, considering the radio luminosities and inclinations under a sub-relativistic regime (Eq. (11) in Lobanov 1998). Thus, compared to that of M 81, the jets of NGC 4258 may be less accelerated, which is consistent with the picture of significantly lower-brightness jets as pointed out above. Otherwise, free–free absorption would contribute the larger core shift of NGC 4258. Such a situation can be relevant to the discussion of the VLA spectral evolution with an absorber at the inner disk ($\S$ 4.3).

We discussed above the differences of the resolved jets of NGC 4258 and M 81. On the other hand, the presence of jets has not been definitively confirmed or ruled out for Sgr A*, and the physical scales of radio emitters are quite different (a factor of $\sim 1000$ in linear scale, or $\sim 100$ in $R_{\text{Sch}}$). Although Sgr A* is a $\sim 10^6$ times lower Eddington ratio system compared to NGC 4258 and M 81, it is in good agreement with the fundamental plane (the expected radio luminosity is $6.4 \times 10^{15}$ W Hz$^{-1}$ at 5 GHz). This is suggestive of the jet origin in a radiatively inefficient accreting system (Merloni et al. 2003). However, Sgr A* seems to have no ability to emanate jets up to kpc scales, unlike NGC 4258 (anomalous arms; Hyman et al. 2001) and M 81 (Kauffman et al. 1996). Such great distinctions of physical scales of jets might be relevant to the difference between the relatively simple radio spectra of Sgr A* and complicated spectra of NGC 4258 and M 81. Thus, in addition to M 81, NGC 4258 is possibly an up-scaled version of Sgr A* and shows some apparently different radio properties, which might be related to physical scale.

5. SUMMARY

We investigated the radio properties of the continuum emission from the nucleus of the nearby LLAGN NGC 4258, and discussed analogies to Sgr A* and M 81 as a scaled-up version of Sgr A*. The summaries are described below:

- We discovered a large amplitude variable emission at 100 GHz ($\lambda 3\text{mm}$) using the NMA. The emission was detected at 9 out of 15 epochs. The detected flux densities were higher than those at centimeters (not simultaneous). Significant contamination from dust emission is ruled out by the variability and the estimation using JCMT data at 345 GHz.

- Quasi-simultaneous multi-frequency observations using the VLA at 5–22 GHz showed inverted spectra in all ten epochs. The spectra were complicated and variable, indicating the presence of multiple blobs in nuclear jets. The observed spectral evolution cannot be explained by the model of an adiabatically expanding blob that is expected to show a spectral peak propagating to lower frequencies, while a propagation to higher frequencies was apparently seen in less than one month. We proposed partially absorbed advancing components to explain the spectral evolution.

- The observed radio property of a highly variable and inverted spectrum for the NGC 4258 nucleus is similar to that of Sgr A* and M 81, even with more than three orders of magnitude larger radio power, 10 times larger black hole mass, and a more than six orders of magnitude higher Eddington ratio compared to Sgr A. In addition to the LLAGN M 81, NGC 4258 is possibly another up-scaled version of Sgr A*.

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On the basis of astrometric measurements at 1.7–15 GHz, the stationary position of a putative black hole coincides with the 50% of contour levels of brightness distribution of each frequency (Bietenholz et al. 2004).

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