NUCLEAR RADIO JET FROM A LOW-LUMINOSITY ACTIVE GALACTIC NUCLEUS IN NGC 4258

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ABSTRACT

The nearby low-luminosity active galactic nucleus (LLAGN) NGC 4258 has a weak radio continuum component at the galactic center. We investigate its radio spectral properties on the basis of our new observations using the Nobeyama Millimeter Array at 100 GHz and archival data from the Very Large Array at 1.7–43 GHz and the James Clerk Maxwell telescope at 347 GHz. The NGC 4258 nuclear component exhibits (1) an intra-month variable and complicated spectral feature at 5–22 GHz and (2) a slightly inverted spectrum at 5–100 GHz (α ∼ 0.3; Fν ∝ να) in time-averaged flux densities, which are also apparent in the closest LLAGN M81. These similarities between NGC 4258 and M81 in radio spectral natures in addition to previously known core shift in their AU-scale jet structures produce evidence that the same mechanism drives their nuclei. We interpret the observed spectral property as the superposition of emission spectra originating at different locations with frequency-dependent opacity along the nuclear jet. Quantitative differences between NGC 4258 and M81 in terms of jet/corent ratio, radio loudness, and degree of core shift can be consistently understood by fairly relativistic speeds (Γ ≥ 3) of jets and their quite different inclinations. The picture established from the two closest LLAGNs is useful for understanding the physical origin of unresolved and flat/inverted spectrum radio cores that are prevalently found in LLAGNs, including Sgr A*, with starved supermassive black holes in the present-day universe.

Key words: galaxies: active – galaxies: individual (NGC 4258) – galaxies: jets – galaxies: Seyfert – radio continuum: galaxies: submillimeter: galaxies

1. INTRODUCTION

Most of the supermassive black hole activity in the present-day universe is primarily in the lower end of the luminosity function of active galactic nuclei (AGNs) in the form of low-luminosity AGNs (LLAGNs; for reviews, see Ho et al. 1997; Ho 2008) with bolometric luminosities Lbol ≲ 10^{42} erg s^{-1} down to nearly quiescent systems such as Sgr A* at our Galactic center. Most LLAGNs are extremely sub-Eddington systems (L_{bol}/L_{Edd} < 10^{-3}, where L_{Edd} is the Eddington luminosity). The low luminosities and spectral energy distributions (SEDs) of LLAGNs (Ho 1999; Eracleous et al. 2010; Younes et al. 2012) have been modeled by the combination of (1) an inner advection-dominated accretion flow (ADAF; Narayan & Yi 1994), which is a radiatively inefficient, optically thin, and geometrically thick accretion flow at low accretion rates; (2) an outer truncated disk (Quataert et al. 1999) of a standard optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973); and (3) a jet (Falcke & Biermann 1995; Yuan et al. 2005), as proposed by several studies (e.g., Nemmen et al. 2006, 2011; Yu et al. 2011, and references therein).

The ADAF model predicts an SED including a “submillimeter bump” that results from the synchrotron emission of thermal hot (∼10^{8}–10^{10} K) electrons. A highly inverted spectrum (α = 0.4; Mahadevan 1997, in S_{ν} ∝ ν^{α}, where α is the spectral index and S_{ν} is the flux density at frequency ν) is expected in lower-frequency radio bands. However, observed spectra in LLAGNs tend to be flat or slightly inverted (α ≈ −0.2 to +0.2) in the central components (Nagar et al. 2001; Doi et al. 2005b, 2011), as well as the spectrum of Sgr A* at ≲10 GHz (Falcke et al. 1998; An et al. 2005). Furthermore, only the thermal process in the ADAF model cannot provide observed radio luminosities adequately in many cases (Fabbiano et al. 2003; Doi et al. 2005a; Wu & Cao 2005; Wu et al. 2007). Thus, these are the reasons why the jet component is needed in SED modeling for LLAGNs. It is also argued that the entire SED of LLAGNs is practically jet dominated by synchrotron emission and an upscattered inverse Compton component rather than by the accretion flow or disk (in particular at very low luminosities L_X/L_{Edd} ≲ 10^{-6}; Yuan & Cui 2005), according to studies for individual sources (NGC 4258, Yuan et al. 2002a; M81, Markoff et al. 2008) and many samples in the statistical sense (Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006; Yuan et al. 2009; de Gasperin et al. 2011; Plotkin et al. 2012). Thus, the jet component is presumably essential in the energetics at the low state of AGNs.

Very long baseline interferometry (VLBI) images at milliarcsecond (mas) resolutions have sometimes revealed elongated radio structures similar to sub-parsec scale jets in LLAGNs (Falcke et al. 2000; Nagar et al. 2005). With the exception
of a handful of well-known nearby galaxies and Seyfert galaxies with jets extending to kpc scales (Wrobel 1991; Ho & Ulvestad 2001), most of the power is concentrated in an unresolved core of $\lesssim 10^3$–$10^4$ Rs (Rs is the Schwarzschild radius) with high brightness temperatures of $\lesssim 10^6$–$10^{11}$ K (Ulvestad & Ho 2001; Anderson et al. 2004; Filho et al. 2004; Krips et al. 2007). Radio flux variability observed in several LLAGNs in total flux on typical timescales of a few days also indicates $\lesssim 1000$ Rs in size (Anderson & Ulvestad 2005). Thus, the radio-emitting origin has still been unknown for most LLAGNs from an observational point of view. One of the rare cases in which a nuclear radio component has been spatially resolved is M81 (Bietenholz et al. 1996), which is the nearest (3.6 Mpc; Freedman et al. 2001) LLAGN in the VLBI-observed sample of Nagar et al. (2005). M81 contains a type 1.5 Seyfert nucleus (Ho et al. 1997) with a 2–10 keV X-ray luminosity of $\sim (1.5–4) \times 10^{40}$ erg s$^{-1}$ (Ishisaki et al. 1996; Markoff et al. 2008) and a black hole with a mass of $7 \times 10^7 M_\odot$ (Devereux et al. 2003). The radio nucleus consists of a bright core plus weak one-sided jet-like elongation with a scale of $\sim 1$ mas ($3 \times 10^3$ Rs) at 1–43 GHz in VLBI images (Bietenholz et al. 2004; Ros & Pérez-Torres 2012). Observed radio properties are characterized by the following: (1) Core shift: the position of radio brightness peak appears shifted depending on observing frequency at 1.7–8.4 GHz; the line of sight toward the putative black hole is opaque at these radio frequencies (Bietenholz et al. 2004; Martí-Vidal et al. 2011). Therefore, almost all radio fluxes should be attributed to AU-scale jets rather than an accretion flow. (2) Flux variability: M81 is the most well-studied LLAGN in total flux as well; a bright radio nucleus ($\sim 70–400$ mJy) exhibits rapid and large-amplitude intra-day fluctuation (Ho et al. 1999; Sakamoto et al. 2001) and on the timescales of several weeks and years (Bietenholz et al. 2000; Markoff et al. 2008; Martí-Vidal et al. 2011). (3) Inverted spectrum: a centimeter to submillimeter (cm to submm) spectrum is slightly inverted on time average ($\alpha \approx 0.3$; Reuter & Lesch 1996; Doi et al. 2011) with a possible turnover frequency at 100–230 GHz (Schödel et al. 2007). (4) Spectral variability: a complexly variable spectral profile is observed at meter to submm wavelengths (235 MHz–345 GHz) in quasi-simultaneous observations over six months (Markoff et al. 2008). Thus, the radio properties (2)–(4) at arcsec resolutions are ascribable to nuclear jets whose structure is spatially resolved as (1). For this reason, M81 may be a Rosetta Stone for understanding the origin of unresolved radio cores in other LLAGNs and Sgr A*.

NGC 4258 contains a type 1.9 Seyfert nucleus (Ho et al. 1997) with a 2–10 keV X-ray luminosity of $(4.2–17.4) \times 10^{40}$ erg s$^{-1}$ (Makishima et al. 1994; Fruscione et al. 2005) and a black hole with a mass of $3.9 \times 10^7 M_\odot$ (Herfst et al. 1999). NGC 4258 is the second nearest (7.2 Mpc; Herfst et al. 1999) LLAGN in the VLBI-observed sample of Nagar et al. (2005). Thereby, NGC 4258 in addition to M81 constitutes rare cases in which a nuclear radio structure is spatially resolved (Miyoshi et al. 1995). VLBI imaging at $\sim 1.5$ GHz showed a two-sided nuclear jet extending in the north–south direction (Cecil et al. 2000) that appears physically connected with the kpc-scale jet-like radio structures (“anomalous arms”; e.g., van der Kruit et al. 1972). The nuclear radio structure has been thoroughly investigated at 22 GHz through VLBI observations of water masers (Herfst et al. 2005; Argon et al. 2007). A two-sided nuclear jet with a scale of $\sim 1$ mas ($9 \times 10^3$ Rs) upwells from the dynamical center of a putative disk of Keplerian rotating water masers in a disk with a nearly edge-on orientation. VLBI images provided a 3$\sigma$ upper limit of 220 $\mu$Jy on 22 GHz at the dynamical center; most of the nuclear radio continuum flux comes from the jet, which is located significantly off the dynamical center (Herfst et al. 1998). The jet exhibits a flux variation of $\sim 100\%$ on the timescales of a few weeks or longer (Herfst et al. 1997; see also the Appendix). Thus, the observed properties in terms of innermost jet structure and flux variability of the nuclear component are very similar to those of M81 ((1) and (2)). However, the radio spectral properties are known in much less detail (see the Appendix): (3) a slightly inverted spectrum? (4) a variable spectral profile? To establish the archetype of LLAGNs by using M81 and NGC 4258, the radio spectral properties of the NGC 4258 nucleus should be investigated and compared with those of M81 at cm to submm wavelengths.

In this paper, we present the radio continuum spectrum and its variability for the NGC 4258 nucleus in the cm to submm bands at arcsecond resolutions. This study also includes imaging of extended components, such as extended synchrotron jets and dust emission in a host galaxy, for the purpose of estimation of contamination. The observations and data reductions are described in Section 2. The results are presented in Section 3. The physical origins of observed radio properties and comparisons with M81 are discussed in Section 4. Finally, we summarize in Section 5. For the distance of 7.2 Mpc to NGC 4258, 1” corresponds to 35 pc.

2. OBSERVATIONS AND DATA REDUCTIONS

For the purpose of revealing radio spectral variability and its average nature for this variable radio nucleus in NGC 4258, we obtained multi-epoch data. We carried out new observations of 15 epochs using the Nobeyama Millimeter Array (NMA) at the Nobeyama Radio Observatory (NRO) at $\sim 100$ GHz (Section 2.1). We retrieved the 1.7–43 GHz archival data of the Very Large Array (VLA) at the National Radio Astronomy Observatory (NRAO) for 13 epochs in total (Section 2.2). The list of these observations is presented in Table 1. We reduced the 347 GHz archival data of the James Clerk Maxwell Telescope (JCMT) on Mauna Kea (Section 2.3), which was, as a result, devoted to estimation of dust contamination in photometry toward the active nucleus because the nuclear region was dominated by dust emission at this frequency (Section 3.1).

2.1. NMA Observations

We observed the nuclear regions at $\sim 100$ GHz ($\lambda$3 mm) by using the NMA. Array configurations were AB, C, and D with maximum baseline lengths of 351, 163, and 82 m, respectively. The visibility data were obtained with double-sided receiving systems. We use only the upper sideband at a center frequency of 100,777 GHz with a bandwidth of 1 GHz, which was practically line free; the emission lines such as HCN($J = 1–0$) and HCO$^+$(J = 1–0) were in the lower sideband at a center frequency of 88,777 GHz. For the data acquired in 2005 May, we use two sidebands centered at 89.729 and 101.729 GHz, both of which were practically line free. The typical system noise temperature was about 140 K in the double-sided band. For gain calibration, we scanned between the target and a reference calibrator, 1150+497, every 20 or 25 minutes. The flux scales of the calibrator were determined from relative comparisons with known flux calibrators such as Uranus. In general, the uncertainty in the flux scale is expected to be 10%–20% as a result of accumulating the differences of residual errors between a reference calibrator and a flux
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Table 1 Data List of VLA and NMA Observations

| Date       | Project Code | Array Config. | ν (GHz) | θmaj (″) | θmin (″) | P.A. (°) | σ (mJy beam⁻¹) |
|------------|--------------|---------------|---------|----------|----------|----------|----------------|
| 1996 Dec 7 | AH594A       | VLA-A         | 22.460  | 0.10     | 0.09     | 34       | 0.12           |
| 1996 Dec 22 | NMA-C        | VLA-A         | 22.460  | 0.11     | 0.09     | 28       | 0.11           |
| 1997 Jan 4 | BR0043       | VLA-A         | 15.365  | 0.16     | 0.14     | 87       | 0.20           |
| 1997 Mar 6 | BM0056a      | VLA-B         | 22.265  | 0.35     | 0.31     | 66       | 0.10           |
| 1997 Mar 19 | AH594F       | VLA-B         | 22.460  | 0.43     | 0.32     | 82       | 0.20           |
| 1998 Feb 28 | AG0527       | VLA-A         | 43.340  | 0.05     | 0.04     | 13       | 0.41           |
| 1998 Sep 5 | BM0112a      | VLA-B         | 22.265  | 0.40     | 0.33     | 87       | 0.16           |
| 2000 Dec 21 | AN0097       | VLA-A         | 43.340  | 0.09     | 0.04     | 76       | 0.51           |
| 2001 Dec 21 | NMA-D        |                | 100.777 | 7.5      | 6.2      | 72       | 0.89           |
| 2002 Mar 21 | NMA-C        |                | 100.777 | 8.8      | 4.7      | 36       | 3.00           |
| 2003 Dec 22 | NMA-C        |                | 100.777 | 4.3      | 3.5      | 2        | 0.94           |
| 2004 Jan 14 | NMA-AB       |                | 100.777 | .        | .        | .        | .              |
| 2004 Apr 1  | NMA-D        |                | 100.777 | 6.6      | 5.7      | 76       | 0.93           |
| 2005 Apr 5  | NMA-C        |                | 100.777 | 3.8      | 3.0      | 33       | 0.83           |
| 2005 Apr 8  | NMA-C        |                | 100.777 | 4.4      | 3.6      | 30       | 1.49           |
| 2005 May 13 | NMA-D        |                | 95.729  | 7.5      | 6.2      | 88       | 0.87           |
| 2005 May 14 | NMA-D        |                | 95.729  | 9.5      | 7.9      | 70       | 1.93           |
| 2005 May 15 | NMA-D        |                | 95.729  | 9.9      | 6.8      | 76       | 0.94           |
| 2006 Mar 25 | NMA-D        |                | 100.777 | .        | .        | .        | 3.12           |
| 2006 Mar 29 | NMA-D        |                | 100.777 | .        | .        | .        | 3.12           |
| 2006 Mar 31 | NMA-D        |                | 100.777 | .        | .        | .        | 2.37           |
| 2006 Apr 1  | NMA-D        |                | 100.777 | .        | .        | .        | 2.86           |

Notes. Column 1: observation date; Column 2: project code; Column 3: telescope and array configuration; Column 4: observing frequency; Columns 5–7: FWHMs in major and minor axes for synthesized beam and position angle of the major axis; Column 8: image rms noise.

A VLA participated in VLBI observation as a phased-up element, and the VLBI results have been published (Agron et al. 2007).

calibrator. These residual differences can be due to pointing error, seeing effect, calibrations of atmospheric attenuation and elevation-dependent antenna efficiency, and temporal variations in polarization and flux density of calibrators. To avoid the residual errors of calibration from differential atmospheric attenuation and antenna efficiency, we observed 1150+497 and a flux calibrator at almost the same elevations within 1 hr. These observations were made within a few days of each other, typically, or were separated by up to 10 days in worst cases (from observations for NGC 4258); 1150+497 is a quasar with a large amplitude but gradual light curve on the timescale of years, which is much longer than the intervals between NGC 4258 and flux calibration observations. In the present study, we assume a 15% error in the flux scaling factor. We observed bright quasars for about 30 minutes for bandpass calibration.

The data were reduced using the UVPROC-II package (Tsutsui et al. 1997) by standard means, including flagging bad data, baseline correction, opacity correction, bandpass calibration, and gain calibration. Each daily image was synthesized from visibilities in natural weighting and deconvolved using IMAGR task of the Astronomical Image Processing System (AIPS) developed at the NRAO.

2.2. VLA Data

In the VLA archive, we searched data sets of observations carried out in the continuum mode using multi-frequency bands with high spatial resolutions of A or B configurations. We retrieved (1) all available data sets consisting of three or four bands in the range of 5–22 GHz (λλ1.3–6 cm) for revealing spectral time evolution, (2) all available data sets including the 43 GHz (λλ1.7 cm) band for the probe of millimeter spectrum, and (3) a data set including a deep imaging with A-array configuration at 1.7 GHz (λλ18 cm) to evaluate the contamination from extended components of “the anomalous arms” in the photometric measurements at higher frequencies. Observations of each data set were carried out at multi-frequency quasi-simultaneously within 3 hr typically, or longer (but within one day at most) for VLA data obtained as part of VLBI observations (BR0043, BG0062, BM0056, and BM0112).

We reduced the data using the AIPS by following the standard procedure. 3C 286 scans served as flux scaling factors. We followed the guidelines for accurate flux density bootstrapping (Perley & Taylor 2003), including correcting the dependence of the gain curve on elevation for the antennas and atmospheric opacity and by using the clean component models of 3C 286 in self-calibrations. The bootstrap accuracy should be 1%–2% at 20, 6, and 3.6 cm, and perhaps 3%–5% at 2, 1.3, and 0.7 cm (Perley & Taylor 2003). For flux scaling factors, we assumed uncertainties of 2% and 5% at 1.7–8.4 GHz and 15–43 GHz, respectively. All target images were synthesized with natural weighting and deconvolved with the AIPS IMAGR task.

2.3. JCMT Data

We retrieved archival data for the 1998 March 18 observations of NGC 4258 that were acquired by the JCMT at 347 GHz (λλ0.85 μm) in jiggle-map mode with the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999). The data were processed with the SCUBA User Reduction Facility package. We applied standard reduction procedures including flat fielding, flagging of transient spikes, correcting the extinction, pointing correction, sky removal, and flux density scaling. A Uranus scan gave us a flux scaling factor, with an uncertainty assumed to be ∼15% and an effective beam size of 15′. On the blank sky, the measured rms of the image noise was 10.5 mJy beam⁻¹.

12 One of the data sets (AN8500) has already been published by Nagar et al. (2001).
Table 2
Flux Densities of Radio Continuum Emission at the Nucleus of NGC 4258

| Date      | $S_{1.7}$ (mJy) | $S_{5}$ (mJy) | $S_{44}$ (mJy) | $S_{15}$ (mJy) | $S_{12}$ (mJy) | $S_{84}$ (mJy) | $S_{100}$ (mJy) | $S_{437}$ (mJy) | $\alpha^{22}$ |
|-----------|-----------------|---------------|----------------|---------------|---------------|----------------|----------------|----------------|--------------|
| 1996 Dec 7 | 1.8 ± 0.1       | 1.9 ± 0.1     | 2.2 ± 0.2      | 2.4 ± 0.3     |               |                |                |                | 0.21 ± 0.04  |
| 1996 Dec 22| 2.0 ± 0.1       | 2.2 ± 0.1     | 2.2 ± 0.2      | 2.2 ± 0.2     |               |                |                |                | 0.06 ± 0.06  |
| 1996 Dec 29| 1.9 ± 0.1       | 2.3 ± 0.1     | 2.7 ± 0.2      | 2.5 ± 0.3     |               |                |                |                | 0.21 ± 0.07  |
| 1996 Dec 31| 1.9 ± 0.2       | 2.3 ± 0.1     | 2.7 ± 0.3      | 3.1 ± 0.4     |               |                |                |                | 0.32 ± 0.01  |
| 1997 Jan 4 | 1.8 ± 0.2       | 2.0 ± 0.1     | 3.5 ± 0.2      |               |               |                |                |                | 0.64 ± 0.23  |
| 1997 Jan 5 | 2.3 ± 0.1       | 2.3 ± 0.1     | 2.6 ± 0.3      | 3.6 ± 0.4     |               |                |                |                | 0.19 ± 0.12  |
| 1997 Jan 7 | 2.0 ± 0.1$^b$   |               |                |               | 3.7 ± 0.4     |                |                |                |              |
| 1997 Mar 6 | 3.1 ± 0.3       | 2.7 ± 0.2     |      5.4 ± 0.3 |              |               |                |                |                | 0.62 ± 0.19  |
| 1997 Mar 19| 2.7 ± 0.3       | 2.8 ± 0.3     | 3.2 ± 0.4      |              |               |                |                |                | 0.10 ± 0.01  |
| 1998 Feb 28|               | 4.4 ± 0.6     | 7.1 ± 0.9      | 93.7 ± 20.8$^d$|              |                |                |                | 0.26 ± 0.21  |
| 1998 Sep 5 | 2.5 ± 0.3       | 2.2 ± 0.1     | 3.6 ± 0.4      | 3.0 ± 0.4     |               |                |                |                | 0.19 ± 0.24  |
| 1999 Sep 5$^a$ | 2.1 ± 0.2    | 1.8 ± 0.1     | 2.5 ± 0.3      | 6.8 ± 1.0     | 10.0 ± 1.3    | 7.4 ± 1.6     | 5.2 ± 1.1     | 8.0 ± 3.2     |              |
| 2000 Dec 21| 2.6 ± 0.2       |               |                |               |               |                |                |                |              |
| 2001 Dec 21|               |               |                |               |               |                |                |                |              |
| 2002 Mar 21|               |               |                |               |               |                |                |                |              |
| 2003 Dec 22|               |               |                |               |               |                |                |                |              |
| 2004 Jan 14|               |               |                |               |               |                |                |                |              |
| 2004 Mar 31|               |               |                |               |               |                |                |                |              |
| 2004 Apr 1 |               |               |                |               |               |                |                |                |              |
| 2005 Apr 5 |               |               |                |               |               |                |                |                |              |
| 2005 Apr 8 |               |               |                |               |               |                |                |                |              |
| 2005 May 13|               |               |                |               |               |                |                |                |              |
| 2005 May 14|               |               |                |               |               |                |                |                |              |
| 2005 May 15|               |               |                |               |               |                |                |                |              |
| 2006 Mar 25|               |               |                |               |               |                |                |                |              |
| 2006 Mar 29|               |               |                |               |               |                |                |                |              |
| 2006 Mar 31|               |               |                |               |               |                |                |                |              |
| 2006 Apr 1 |               |               |                |               |               |                |                |                |              |
| (Average)  | 2.0 ± 0.1       | 2.2 ± 0.1     | 2.7 ± 0.2      | 2.9 ± 0.4     | 6.9 ± 0.2     | 6.9 ± 0.6$^c$ | 0.21 ± 0.04  |              |              |
| ($\chi^2$/dof) | 3.80           | 4.92          | 3.22           | 11.69         | 0.05          | 1.06$^c$      | 25.81         |              |              |
| (Probability) | <10$^{-4}$   | <10$^{-4}$    | 0.002          | <10$^{-4}$    | 0.817         | 0.386$^c$     |              |              |              |

Notes. Column 1: observation date; Columns 2–9: flux densities at 1.7, 5, 8.4, 15, 22, 43, 100, and 347 GHz, respectively; Column 10: spectral index, derived by the least-squares fit of $S_\nu \propto \nu^{\alpha}$ at 5–22 GHz. The last three lines: weighted average of flux densities at each frequency, reduced chi-square, and probability as statistics for the hypothesis of a constant value.

$^a$ Already published by Nagar et al. (2001).

$^b$ Aperture size of 3.8′ (see Section 3.3).

$^c$ Derived from only nine detected data sets.

$^d$ Aperture size of 15′.1.

3. RESULTS

The results of the flux measurements are presented in Table 2; Figure 1 shows the cm to submm spectrum of the NGC 4258 nucleus.

3.1. Upper Limit of Dust Contamination

The 347 GHz (λ850 μm) JCMT image of the nuclear region with a field of view of ~2′ shows a structure elongated along the major axis of the host galaxy with no apparent nuclear prominence (Figure 2). Such a structure is very similar to that of carbon monoxide (CO) line emission (Regan et al. 2001). These results suggest that most of the submillimeter emission does not originate in the AGN continuum but in interstellar dust associated with the host galaxy. We measured the flux density from the region corresponding to the JCMT beam of 15′.1 (~530 pc) centered at the nucleus. The continuum emission may be contaminated by the CO(3–2) emission of only ~1 mJy in the SCUBA bandwidth of ~40 GHz, according to 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 general, the dust spectrum of external galaxies can be well represented via one- or two-temperature dust spectral models by using the modified blackbody emission $S_\nu \propto \nu^\beta B(T_D)$, where $B(T_D)$ is the blackbody spectrum at temperature $T_D$, with $\beta \sim 1.6$–2 and two temperatures of $T_D \sim 20$ and ~43 K; the lower-temperature component dominates at <1000 GHz in total flux (Temi et al. 2004, and references therein). We adopt $\beta = 1$ as an extreme case for conservative constraint at frequencies lower than 347 GHz of the JCMT data. As shown by a dashed line in Figure 1, the dust contribution is expected to be <2.4 mJy at 100 GHz within a 15′.1 region, which means a strong upper limit for dust contamination toward the active nucleus of NGC 4258 in the flux measurements with smaller beam sizes of NMA (<10′) and VLA (<3′.8) at the lower frequencies (cf. Doi et al. 2005b, 2011).

3.2. Nuclear Millimeter Emission

NMA images at 100 GHz (λ3 mm) with a field of view of ~1′ revealed only a point-like single emission component at the nucleus. We detected the emission for 9 out of 15 epochs.
The flux densities were measured in the image domain by elliptical Gaussian profile fitting with the AIPS JMFIT task. We determined the total errors in the flux measurements from the root sum square of errors of the Gaussian fitting and flux scaling (15%: see Section 2.1). For detected epochs, the millimeter continuum emission is significantly stronger than the centimeter emission.

The upper limit of dust contamination is <2.4 mJy at 100 GHz in an ~15″ region at the nucleus (Section 3.1). Moreover, an upper limit at 115 GHz was obtained on 1998 April 20 with a smaller beam size of 6′1 × 5′4 (Helfer et al. 2003); an upper limit at 225 GHz was obtained on 2004 May 4 with an even smaller beam size of 3′0 × 2′0 (Sawada-Satoh et al. 2007; see Figure 1), indicating <0.8 mJy at 100 GHz (assuming β ∼ 1) as a conceivable compact dust component. On the other hand, the contamination from the 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 of the anomalous arms (Hyman et al. 2001). Consequently, the contamination from both dust and anomalous arms can be practically neglected in our NMA measurements. The detected millimeter emission is presumably dominated by the active nucleus.

In a statistical sense, millimeter flux variability is unclear (cf. last line in Table 2), which may be due to large uncertainty in flux scaling (see Section 2.1).
The spectral index is not stable in a statistical sense (a probability $p < 10^{-4}$ for the hypothesis of a constant value; see Table 2); however, it remains inverted (i.e., $\alpha > 0$) throughout all epochs. Two-point spectra including 43 GHz ($\alpha = 0.71 \pm 0.45$ between 22 and 43 GHz on 1998 February 28 and $\alpha = 0.59 \pm 0.39$ between 8.4 and 43 GHz on 2000 December 21) produce evidence of this trend continuing up to millimeter wavelengths. The spectral features and their time evolutions were apparently complicated. Inverted spectra and, at the same time, flat and marginally steep spectra were locally observed in the frequency domain (Figure 4). The first six epochs show spectral features changing in only a month; the light curves for each frequency are shown in Figure 5. The flux variations of the two higher frequencies, 15 and 22 GHz, a gradual increase, appeared in the latter half of the six epochs. On the other hand, flux variations of the lower two frequencies, 5 and 8.4 GHz, also correlated with each other but in a different way from those at the higher frequencies; a modest peak-out is apparent around the second or third epoch, and subsequently a (possible) sudden enhancement appears at the sixth epoch at both frequencies. We estimate the size of the emitting region from $L < c \left| d \ln S_\nu / dt \right|^{-1}$, where $L$ is the size, $c$ is the speed of light $S_\nu$ is the flux density, and $t$ is the observation time, assuming an exponential light curve (Burbidge et al. 1974; Valtaoja et al. 1999). The synchronized increments by ~65% in light curves at 15 and 22 GHz during the last two weeks result in $L < 0.02 \, \text{pc}$ ($<4000 \, \text{AU}$ or $<5300 \, \text{Rs}$). A flux decrease at 22 GHz over 13 days from 1997 March 6 to March 19 (beyond the time range of Figure 5) results again in $L < 0.02 \, \text{pc}$. The flux density ranges and the timescales of variability are consistent with previous observations at 22 GHz (see the Appendix).

4. DISCUSSION

We found (1) a complexly variable radio spectrum and (2) the trend of a slightly inverted spectrum continuing throughout from centimeter (5 GHz, $\lambda$ cm) at least up to millimeter (100 GHz, $\lambda$ mm) regimes for the NGC 4258 nuclear radio continuum component.

Figure 3. VLA image with A-array configuration of the nuclear region of NGC 4258 at 1.7 GHz ($\lambda$ cm) in natural weighting. Contour levels in black curves are separated by factors of $\sqrt{2}$ beginning at $3\sigma$ of the rms noise $1\sigma = 42 \, \mu\text{Jy beam}^{-1}$. The gray curves represent $2\sigma$ contours. The beam size of $1''.2 \times 1'.4$ at P.A. = $82'.6$ is shown in the lower-left corner of the image.

Figure 4. Radio spectra for the NGC 4258 nucleus at 5–43 GHz obtained with the VLA A- and B-array configurations. The dashed line represents the fit to a linear spectrum $S_\nu = 1.2 \, \text{mJy} \, \nu^{-0.02}$ throughout all data from 5 to 22 GHz.
4.1. Radio Emitting Site

We discuss the physical origin of observed radio emissions in our data. VLA beam sizes of ~0.05–3′, corresponding to 1.8–130 pc, decrease with increasing frequency; the observed inverted spectra are in opposite sense to the resolution effect. It means the radio emission should be dominated by a compact component significantly smaller than the beam sizes. VLA and VLBI flux densities are almost the same (e.g., ~3 mJy at 22 GHz; Herrnstein et al. 1998), indicating that the observed VLA flux densities originate in a sub-pc scale region. On the basis of VLBI images, the radio continuum flux comes from the northern side of the two-sided nuclear jet ~5–10 mas away at 1.5 GHz (Cecil et al. 2000) and ~0.4 mas (0.015 pc or 4000 Rs) away at 22 GHz (Herrnstein et al. 1997) with respect to the dynamical center of the nearly edge-on viewed Keplerian disk of rotating water masers. Thus, most of the detected flux at 5–22 GHz in the present study is presumably of nuclear jet origin (rather than accretion flow), particularly from the northern side of jet, at locations ~4000 Rs away from the black hole.

Then, we consider the locations of 22–100 GHz radio emitting sites. Our finding of a slightly inverted spectrum is consistent with the picture of a relativistic plasma flow with an opacity gradient (Blandford & Königl 1979). The frequency dependence of the position of the “core,” which is identified by an intensity peak at the root of the jet (i.e., the “core-shift effect”; Lobanov 1998), is frequently observed for radio-loud AGNs (Kovalev et al. 2008; O’Sullivan & Gabuzda 2009; Hada et al. 2011; Sokolovsky et al. 2011) and also for the LLAGN M81 (Bietenholz et al. 2004; Martí-Vidal et al. 2011). At a given frequency ν, the separation of the core from a central engine satisfies r = Ωνk with k ~ −1 in most cases. The northern offset of ~0.4 mas at 22 GHz in the NGC 4258 nuclear jet implies Ω ~ 9 mas GHz (~0.3 pc GHz or ~8 × 104 Rs GHz) with the assumption k = −1. According to this dependence, an expected position offset of ~6 mas at 1.5 GHz is actually consistent with the observed offset of ~5–10 mas at 1.5 GHz. Our finding of a continuous trend as an inverted spectrum at least up to 100 GHz suggests that the radial profile of jet structure maintains over the range of radio emitting sites of 1.5–100 GHz or higher because both the frequency dependence of core shift and spectral index are relevant to the radial profile of jet structure (Blandford & Königl 1979). The emitting site at 100 GHz is, therefore, expected to be ~800 Rs away, which is ~4.5 times as close as the 22 GHz emitting site to the central engine; it is still far from an effective radius of <100 Rs for an optically thick radio emitting photosphere of the ADAF (Mahadevan 1997; Herrnstein et al. 1998).

Finally, we discuss emitting sites at even higher frequencies. We cannot determine a spectral profile at >100 GHz because the JCMT image at 347 GHz indicates heavy contamination by dust emission toward the nucleus (Section 3.1). On the other hand, infrared flux measurements by isolating the nucleus with high angular resolutions (Chary et al. 2000) are very suggestive. A flux density of 435 mJy at 17.9 μm (16,800 GHz) is much higher than an extrapolation from the radio spectrum of α ~ 0.3. It invokes a different origin, although the infrared–optical spectrum of α = −1.4 ± 0.1 indicates a nonthermal origin (Chary et al. 2000) as well. Yuan et al. (2002b) proposed a jet-dominated SED model for the observed broadband SED that peaks in the infrared regime for NGC 4258. The SED model ascribes the infrared peak and variable X-ray spectrum to synchrotron and self-Comptonized emissions, respectively, from the jet base with a shock diameter of 5 Rs, which is a preacceleration region in the jet connected with the innermost accretion flow. Radio emissions cannot be attributed to the jet base because of strong synchrotron self-absorption in a very compact region. An outer jet component as a postacceleration region in the jet on a scale of >100 Rs (Yuan et al. 2002b) is required to explain the radio emissions. Using our finding, the VLBI results, and the SED model, two predictions can be made for future observations: (1) the radio spectral variation will not be so promptly correlated with those in the infrared or X-ray regimes (cf. Miller et al. 2010, for M81) because of significantly different linear scales of emitting sites and (2) the outer jet component will provide a contribution comparable with that of the jet base at submillimeter wavelengths, which implies a spectral upswing from α ~ 0.3 at lower frequencies to α < 2.5 at higher frequencies rather than a spectral turnover.

4.2. Mechanism of Radio Spectral Variation

The complexly variable inverted spectrum we found should reflect the nature of the northern side of the nuclear jet, where a large fraction of radio emission arises (Section 4.1). The time variation of bright systemic masers is strongly correlated with the northern jet emission; it is naturally explained by intrinsic variability in the background continuum of the southern jet and only mildly saturated masers (Herrnstein et al. 1997). It means that the observed radio properties in the northern jet mainly originate in intrinsic ones, rather than in the external effect such as free–free absorption. On the geometry of a warped disk model (see Figure 10 in Herrnstein et al. 2005), the northern jet is behind the disk at radii of >0.29 pc in line of sight, where intervening medium is not ascribable to an effective free–free absorber in terms of the opacity (Neufeld & Maloney 1995) or timescale (an inhomogeneity of ~1015 cm in size and a rotating velocity of <750 km s−1; Fruscione et al. 2005).

In this framework, the frequency dependence of the core shift in the northern jet (Section 4.1) is ascribable to synchrotron
self-absorption; the emitting site at 22 GHz would be almost opaque at 5 GHz. The light curves at the lower two frequencies were very similar; those at the higher two frequencies formed in synchronization. However, the former pair showed a different trend from the latter pair (see Figure 5 in Section 3.3). This behavior is consistent with a picture of different emitting regions at different frequencies. The observed complexly variable inverted spectrum in the NGC 4258 nucleus can be interpreted as the superposition of emission spectra originating at different locations in the nuclear jet with frequency-dependent opacity. Even if a phenomenon propagates from upstream to downstream at the speed of light, a variation at 15 and 22 GHz would appear as a corresponding variation at 5 and 8.4 GHz a few months later. Such behavior was not detectable in our data for the first month (Figure 5); a series of the later epochs (1997 March onward) were too sparse.

4.3. Comparisons with M81

Our findings of the radio spectral properties for the NGC 4258 nucleus allow us to understand that the underlying mechanism in the jet component (Sections 4.1 and 4.2) is basically identical to that of M81. This is because the two LLAGNs share all the following observational aspects in radio regimes: (1) a variable and complex spectral profile, (2) a slightly inverted spectrum with $\alpha \approx 0.3$ on average, and (3) core shift on a nuclear jet (see Section 1 for M81). Presumably, the underlying mechanism must be compatible with other more distant LLAGNs (spatially unresolved so far) too, whose nuclear components are rapidly varying radio emissions (Anderson & Ulvestad 2005) showing flat/slightly inverted spectra (Nagar et al. 2001; Doi et al. 2005b).

Now, the two well-studied LLAGNs enable us to supply a physical understanding by means of quantitative comparisons. NGC 4258 exhibits aspects that differ from M81 in terms of (1) the apparent flux ratio of jet to counter jet $R_F$: two-sided morphology in NGC 4258 ($R_F \approx 6$; Herrnstein et al. 1998), whereas one-sided in M81 ($R_F > 170$); (2) radio loudness (radio-to-X-ray luminosity ratio) $R_X \equiv vP_{\text{radio}}/L_X$ (Terashima & Wilson 2003): a much radio-louder SED for M81 ($R_X \approx 2 \times 10^{-5}$) compared to NGC 4258 ($R_X \approx 4 \times 10^{-5}$); and (3) magnitude of core shift: $\Omega \approx 9$ mas GHz ($\sim 0.3$ pc GHz or $\sim 8 \times 10^2$ Rs GHz) for NGC 4258 (Herrnstein et al. 1997; Cecil et al. 2000) and then consider the ratio of $P_{\text{radio}}/L_X$ at a given frequency $\nu$. We assume that the intrinsic radio power ($P_{\text{int}}^{\nu}$) is relevant to a total radiated synchrotron luminosity ($L_{\text{syn}}$). Moreover, we adopt a tentative assumption of $L_{\text{syn}} \propto L_X \propto \delta$. Where, $L_{\text{jet}}$ and $L_X$ are the total jet luminosity and X-ray luminosity, respectively, as non-beamed ($\Gamma \sim 1$) component.

Under fixed inclinations $\theta$, Lorentz factors $\Gamma_{\text{M81}}$ and $\Gamma_{\text{NGC 4258}}$ in Doppler factors $\delta$ can constrain each other as represented by a solid curve in Figure 6, panel 2. We can find $\Gamma_{\text{NGC 4258}} \gtrsim 3$ based on Equation (2) together with the constraint from the observed one-sidedness in the M81 nuclear jet (the dot-dashed curve in Figure 6, panel 2 is in the forbidden region).

Third, we discuss the difference in magnitude of core shift $\Omega$. The value of $\Omega$ also depends on both inclination angle $\theta$ and Lorentz factor $\Gamma$. We employ Equation (11) in Lobanov (1998) and then consider the ratio of $\Omega$ for NGC 4258 and M81:

$$
\Omega \propto \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{2/3} \frac{L_{\text{syn}} \delta}{\Gamma \sqrt{1 - \delta^2}}.
$$

With this equation, $\theta = 82^\circ$ for NGC 4258 implies $R_F < 1.61$ at any value of $\Gamma$ (i.e., almost symmetric); the observed value of $R_F \approx 6$ must be affected by free–free absorption on the southern jet (Herrnstein et al. 1996). On the other hand, M81 with $R_F > 170$ requires $\Gamma > 2.8$ at $\theta = 14^\circ$, and then $\delta > 3.8$. Thus, we can understand the two-sidedness in NGC 4258 as an inevitable result and obtain a constraint of jet speed for M81.

Second, we verify the difference in radio loudness $R_X$. At these inclinations, the Doppler beaming effect makes the (approaching) jet emission boosted for M81 and deboosted for NGC 4258 at any bulk Lorentz factors ($\Theta$ and $\delta$) as shown in Figure 6, panel 2 is in the forbidden region).
where $D_L$ is the luminosity distance. We assume that $\phi$ and $\Theta$, the opening angle of jet and the range of emission region along jet ($\Theta \equiv \ln (r_{\text{max}}/r_{\text{min}})$; Blandford & Königl 1979), respectively, are the same between NGC 4258 and M81 and then eliminated in the ratio in Equation (3). We assume $L_{\text{syn}} \propto L_X$ again. Under fixed inclinations $\theta$, Lorentz factors $\Gamma_{(\text{M81})}$ and $\Gamma_{(\text{NGC 4258})}$ involved in Equation (3) can constrain each other as represented by a dashed line in Figure 6, panel 2. The dependence suggests that the jet speed is not so different but may be a slightly lower speed in NGC 4258.

Thus, the combination of these three ratios in terms of (1) $R_F$, (2) $R_X$, and (3) $\Omega$ constrains Lorentz factors: the intersection of the two equations (Equations (2) and (3)) is at $\Gamma_{(\text{NGC 4258})} \sim 2.8$ ($\beta \sim 0.932$ and $\delta \sim 0.42$) and $\Gamma_{(\text{M81})} \sim 3.7$ ($\beta \sim 0.963$ and $\delta \sim 4.1$), shown as a filled circle in Figure 6, panel 2 and corresponding values of $\delta^{2-\alpha}$ in Figure 6, panel 1. This $\Gamma_{(\text{M81})}$ value is consistent with $\Gamma > 2.8$ derived from the observed one-sidedness using Equation (1). Thus, jet speeds in both M81 and NGC 4258 are fairly relativistic, although these discussions are based on several assumptions. Roughly speaking, a lower ratio in Equation (2) leads to a larger $\Gamma_{(\text{M81})}$; a smaller ratio in Equation (3) leads to a larger $\Gamma_{(\text{NGC 4258})}$; $\Gamma_{(\text{M81})} > \Gamma_{(\text{NGC 4258})}$ is always seen in a reasonable range of $\Gamma \approx 1.5–30$ and a conceivable uncertainty of $\sim \pm 50\%$ in the ratios. If we adopt another assumption as $L_{\text{syn}} \propto L_{2–10 \text{ keV}}^{0.69} M_{\text{BH}}^{0.61}$ (the revised relation of the fundamental plane by Plotkin et al. 2012) instead of $L_{\text{syn}} \propto L_{2–10 \text{ keV}}$, $\Gamma_{(\text{NGC 4258})} \sim 3.2$ and $\Gamma_{(\text{M81})} \sim 6.8$ are obtained.

Consequently, the observed differences between NGC 4258 and M81 in (1)–(3) can be naturally interpreted by the Doppler beaming effect due to fairly relativistic jet speeds and quite different inclinations. In previous studies, $\Gamma \gtrsim 2–3$ was also

Figure 6. (1) Boosting factors of Doppler beaming in flux densities for continuous jets. Solid and dashed curves represent the cases of inclinations of 14° and 82°, respectively (Equation (1)). Filled circles represent possible solutions for M81 and NGC 4258 (Section 4.3). (2) Relationship between bulk Lorentz factors of M81 and NGC 4258. The solid curve represents Equation (2), a constraint from the ratio of radio loudness of M81 and NGC 4258. The dashed line represents Equation (3), a constraint from the ratio of observed core shifts of M81 and NGC 4258. The range ($\Gamma_{(\text{M81})} < 2.8$) illustrated by dot-dashed curves would not be allowed because of the observed one-sidedness.
predicted for NGC 4258 (Falcke & Biermann 1999; Yuan et al. 2002b) and M81 (Falcke 1996; Markoff et al. 2008) by the model of the outer jet freely expanding and weakly accelerated by internal pressure gradients, which can naturally explain the frequency-dependent size and spectral index of the compact radio core (Falcke & Biermann 1995). In fact, mildly or fairly relativistic jet speeds have been inferred from observations from other LLAGNs/nearby Seyfert galaxies, e.g., Arp 102B (0.45c; Fathi et al. 2011), NGC 4278 (~0.76c (Γ ≈ 1.5); Giroletti et al. 2005), and NGC 7674 (~0.92c in projection; Middelberg et al. 2004).

5. SUMMARY

We investigated the spectral properties of the second closest LLAGN radio nucleus in NGC 4258 and discussed the physical origin of these properties and comparisons with the closest LLAGN M81. The research is summarized by the following points:

1. Radio flux variability was detected at all bands in the centimeter regime (5–22 GHz). In a statistical sense, millimetric variability is unclear, which may be due to an insufficient number of epochs (43 GHz) and the large uncertainty in flux measurements (100 GHz). The VLA 1.7 GHz deep image and the JCMT 347 GHz observation provided the upper limits of extended synchrotron and dust contaminations, respectively.

2. Time-averaged flux densities showed a slightly inverted spectrum (α ~ 0.3) at 5–100 GHz. A spectral turnover at a higher frequency is unclear from the available data.

3. Quasi-simultaneous multi-frequency VLA observations at 5, 8, 15, and 22 GHz revealed a variable and complicated spectral profile, but always an inverted spectrum in all 10 epochs. The first six epochs contained intra-month variation. The light curves at the lower two frequencies were very similar; those at the higher two frequencies formed in synchronization. However, the former pair showed a different trend from the latter pair.

4. The observed radio spectral properties can be interpreted as the superposition of emission spectra originating at different locations with frequency-dependent opacity along the nuclear jet.

5. The NGC 4258 nucleus demonstrates the following characteristics similar to those of M81: (1) a complexly variable spectral feature, (2) a slightly inverted spectrum with α ≈ 0.3 on average, and (3) apparent core shift in the AU-scale jet.

6. We made quantitative comparisons between NGC 4258 and M81 in terms of jet/counter jet ratio, radio loudness, and magnitude of core shift. We found a solution of the combination of bulk Lorentz factors Γ_{NGC4258} ~ 2.8 and Γ_{M81} ~ 3.7 for inclinations of 82° and 14°, respectively. These discussions are based on several assumptions; however, these results are consistent with relativistic jet speeds inferred in a few other LLAGNs in the literature.

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APPENDIX

PREVIOUS RADIO CONTINUUM OBSERVATIONS

Spectrum (by quasi-simultaneous observations). Ho & Ulvestad (2001) reported a slightly resolved core of S_{1.4 GHz} = 2.73 and S_{5 GHz} = 2.18 (mJy), α = −0.18, in matched angular resolutions of ~1′, which were in agreement with previous observations at a similar resolution (Vila et al. 1990). Hyman et al. (2001) reported the time variation of spectral indices ranging from −0.18 to −0.41 between 1.4 and 5 GHz toward the nucleus using the VLA A-array configuration. On the other hand, the spectral index map shows a relatively uniform distribution of the steep spectrum of α ∼ −0.65 ± 0.10 throughout “the anomalous arms.” An inverted spectrum had been seen toward the nucleus at higher frequencies: S_{1.7 GHz} = 2.4 and S_{5 GHz} = 3.2 (mJy), α = +0.4, in matched resolutions of ~3″ (Turner & Ho 1994). 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) by the VLA A-array observations at matched resolutions of 0.7″.

Variability. Significant flux variability has been previously suggested at 22 GHz: the continuum component in VLBI images seems to vary by a factor of several times (S_{22 GHz} = 0.7–4.0 mJy) during 15 epochs in the period 1997.18–2001.61, 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 <2 to 6 mJy based on both VLA and VLBI in the period 1994.3–1996.3. The emission varied by up to 100% over the timescale of a few weeks.

REFERENCES

An, T., Goss, W. M., Zhao, J.-H., et al. 2005, ApJL, 634, L49
Anderson, J. M., & Ulvestad, J. S. 2005, ApJ, 627, 674
Anderson, J. M., Ulvestad, J. S., & Ho, L. C. 2004, ApJ, 603, 42
Argon, A. L., Greenhill, L. J., Reid, M. J., Moran, J. M., & Humphreys, E. M. L. 2007, ApJ, 659, 1040
Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2000, ApJ, 532, 895
Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2004, ApJ, 615, 173
Bietenholz, M. F., Bartel, N., Rupen, M. P., et al. 1996, ApJ, 457, 604
Blandford, R. D., & Königl, A. 1979, ApJ, 232, 34
Burbridge, G. R., Jones, T. W., & Odlill, S. L. 1974, ApJ, 193, 43
Cecil, G., Greenhill, L. J., DePree, C. G., et al. 2000, ApJ, 536, 675
Chary, R., Becklin, E. E., Evans, A. S., et al. 2000, ApJ, 531, 756
de Gasperin, F., Merloni, A., Sell, P., et al. 2011, MNRAS, 415, 2910
Devereux, N., Ford, H., Tsvetanov, Z., & Jacoby, G. 2003, A1, 125, 1226
Doi, A., Kamen, S., & Inoue, M. 2005a, MNRAS, 360, 119

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