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CO EMISSION FROM THE NUCLEUS OF INFRARED GALAXY NGC 4418: AN EARLY AGN PHASE?

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ABSTRACT

The ^{12}CO ($J = 1$–0) emission has been detected in an extremely extinguished galaxy NGC 4418. The inferred mass of molecular gas is $4 \times 10^8\ M_\odot$ in the central 15″ region of the galaxy. Combining the narrow CO line width (85 km s^{-1}) with the extinction value derived from the 10 μm silicate absorption, it is suggested that the molecular gas clouds are highly concentrated toward the center or dynamically decoupled from the underlying stellar system, rotating more slowly than the stars and falling to the center. We hypothesize that NGC 4418 is at the very early phase of its AGN activity, and that the radiation from the nucleus is efficiently absorbed by dense ambient gas and reemitted in the far-infrared, taking the following peculiar properties into account: (1) the 1.5 GHz map recently reported by Condon *et al.* that measured 38.5 mJy in a 0″.5 × 0″.3 core (brightness temperature of 150,000 K), (2) no emission lines in the optical and near-infrared, (3) the ratio of the 1.5 GHz flux relative to the *IRAS* flux which is 10 times smaller than those of other *IRAS* galaxies, and (4) the ratio (=170) of the IR luminosity to the molecular gas mass which is 10 times greater than those of other galaxies with the comparable IR luminosity ($L = 7 \times 10^{10}\ L_\odot$) and comparable to that of an ultraluminous *IRAS* galaxy Mrk 231 (Seyfert 1/QSO with $L = 2 \times 10^{12}\ L_\odot$).

Subject headings: galaxies: interstellar matter — galaxies: nuclei — galaxies: Seyfert — radio sources: galaxies

I. INTRODUCTION

NGC 4418, a normal-looking Sa or S0 galaxy, has been drawing much attention since *IRAS* sky survey (Neugebauer *et al.* 1984) detected an excess emission in the far-infrared. Its far-infrared luminosity amounts to $7 \times 10^{10}\ L_\odot$ at a distance of 26 Mpc for its optical galactocentric velocity 1911 km s^{-1} (Karachentsev 1980) assuming a pure Hubble flow with a Hubble constant of 75 km s^{-1} Mpc^{-1}.

Its far-infrared spectrum peaking at the 60 μm *IRAS* band (*Cataloged Galaxies and Quasars Observed in the IRAS Survey, Version 2*, 1989) classifies NGC 4418 as an *IRAS* warm galaxy. In contrast to other warm galaxies that are known to have a starburst and/or an active galactic nucleus (AGN) (see Osterbrock and De Robertis 1985; Sanders *et al.* 1988), NGC 4418 shows no direct evidence for having a starburst or AGN activity (Roche *et al.* 1986). The optical spectral features of the nucleus are characterized by stellar absorption lines with faint Hα, [N II], and [S II] emission lines (Roche *et al.* 1986). The extremely deep silicate absorption indicates the extinction $55 < A_v < 120$ mag toward the galactic nucleus (Roche *et al.* 1986). Roche *et al.* (1986) thus called NGC 4418 an extinguished galaxy, underscoring NGC 4418 as a unique *IRAS* warm galaxy. Recently, Martin *et al.* (1988) discovered an OH megamaser source in NGC 4418, being direct evidence for nuclear activity powered by starburst or AGN activity since such strong OH emission requires a strong background continuum energy source (cf. Baan 1985).

These unusual observational properties suggest that the nuclear engine of NGC 4418 is completely hidden by exceptionally dense molecular/dust clouds. To study these clouds which are inhibiting any observable emission lines from the nucleus, we have made ^{12}CO ($J = 1$–0) spectroscopy of this galaxy. In this *Letter*, we report the first detection of the CO emission in NGC 4418 and discuss its implications on the nature of this unusual galaxy.

II. OBSERVATION AND RESULTS

The ^{12}CO ($J = 1$–0) observation was made with the 45 m telescope of the Nobeyama Radio Observatory (NRAO) in 1990 January during an observation run of CO survey for Seyfert galaxies (Taniguchi *et al.* 1990). The measured HPBW and the main-beam efficiency at 115 GHz were 15″ and 0.36, respectively. The pointing was checked using an SiO maser source, RT Vir, resulting in the accuracy of ±3″ or better (peak value). The position-switching mode was used, and the total integration time on source was 25 minutes in total. The receiver frontend was a cooled Shottky barrier diode mixer receiver with a system noise temperature T_{sys}(SSB) = 700 K including the atmospheric effect and the antenna ohmic loss. The backend was the 2048 channel wide-band acousto optical spectrometer operated with the bandwidth 250 MHz, covering a velocity range of 650 km s^{-1}. The frequency resolution was 250 kHz, correponding to a velocity resolution of 0.65 km s^{-1}. The final data were boxcar-averaged by 64 channels to improve the signal-to-noise ratio, resulting in a final velocity resolution of 20 km s^{-1}.

Figure 1 (Plate L1) shows the spectrum and the results are summarized in Table 1. Other observational properties are given in Table 2. The mean CO velocity of 2150 km s^{-1} is in agreement with the H 21 cm velocity of 2179 km s^{-1} (Richter and Huchtmeier 1987). The integrated CO intensity (I_{CO}) was estimated by

$$I_{CO} = \int T_A^* \, dv/\eta_B \ \mathrm{K\ km\ s^{-1}} ,$$

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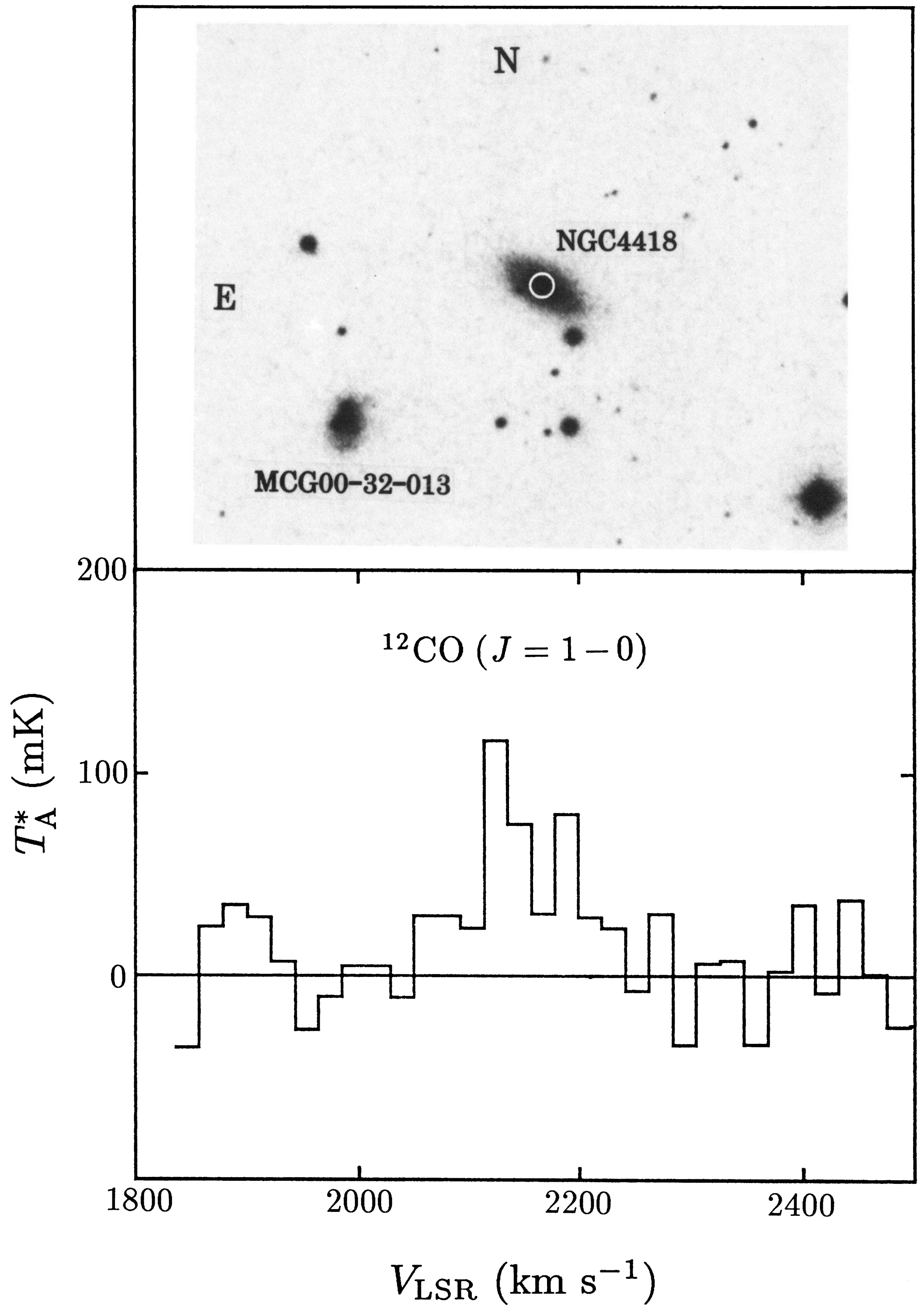

FIG. 1.—The ^{12}CO (J = 1–0) spectrum of NGC 4418. The ordinate is T_A^*, uncorrected for the beam efficiency. The beam size (15″) is shown by an open circle in the direct photograph reproduced from a blue print of the Palomar Observatory Sky Survey (*upper panel*).

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TABLE 1

Observational Results

Quantity	Symbol	Value
Integrated CO intensity	I_{CO}	21.4 ± 3.3 K km s^{-1}
Line width	FWHM	85 km s^{-1}
LSR velocity	V_{LSR}	2150 km s^{-1}
Molecular gas mass	M_{H_2}	$4.2 \times 10^8 M_\odot$

where η_B is the main beam efficiency of the telescope; $\eta_B = 0.36$. The mass of molecular gas (M_{H_2}) is estimated by the relation (Scoville *et al.* 1987), $M_{H_2} = 5.8 \times 10^6 I_{CO} A$ ($M_\odot$), where A is the projected area of a 15″ FWHM beam (in kpc^2), 15″ corresponding to 1.9 kpc in a physical dimension at a distance of 26 Mpc. We obtain a molecular gas mass of $4 \times 10^8 M_\odot$ in the central 15″ region of NGC 4418. This relation is commonly used in many literatures (e.g., Verter 1987) and is convenient to compare the presented results with others; however, it should be noted that this relationship is based on the properties of cool galactic molecular clouds ($T \approx 10$ K). This then results in the large uncertainty: the mass will be overestimated by a factor of 6 for warm clouds in NGC 4418 whose dust temperature is $T \approx 60$ K and will be underestimated for dense molecular clouds which are seriously overlapped along the line of sight, which is probable in the case of NGC 4418.

III. DISCUSSION

a) Distribution and Motion of Molecular Clouds

The column density within a 15″ beam is 1.5×10^{22} atoms cm^{-2} if the filling factor is unity. Assuming the galactic dust-to-gas ratio, this value yields $A_v = 6.9$ mag, much smaller than the extinction value of 55–120 mag derived from the silicate absorption feature (Roche *et al.* 1986). This difference could arise if dust is about 10 times more abundant in NGC 4418 than in the Milky Way. A more possible explanation is that either the filling factor is much less than unity or that the distribution of molecular gas is clumpy. To be consistent with the silicate extinction value 55–120 mag or (12–26) $\times 10^{23}$ atoms cm^{-2} with the galactic dust-to-gas ratio, the CO emission should be dominated by a central 4″–6″ (500–750 pc) diameter region. This surface density of molecular gas is higher by one or two orders of magnitude than those of typical starburst or Seyfert galaxies (Heckman *et al.* 1989; Taniguchi, Kameya, and Nakai 1990). We note that the 8–13 and 17–23 μm fluxes taken with a 3″.8 beam (470 pc) centered on the optical nucleus (Roche *et al.* 1986) agree well with the *IRAS* 12 and 25 μm fluxes, indicating the size of the IR region at the *IRAS* 12 and 25 μm fluxes is a 3″.8 diameter or less.

TABLE 2

Basic Data of NGC 4418

Quantity	Symbol	Value	Reference
Right ascension	α(1950)	12^{h}24^{m}20^s.3	1
Declination	δ(1950)	−0°36′9″	1
Morphology		Sa	2
Inclination angle	i	57°	3
Optical heliocentric velocity	$v_\odot$(opt)	2045 ± 69 km s^{-1}	4
H I heliocentric velocity	$v_\odot$(H I)	2179 ± 8 km s^{-1}	3
Photographic magnitude	m_{pg}	14.2 mag	2
K magnitude (10″.3 × 21″)	m_K	11.1 mag	5
Distance	D	25.48 Mpc	6
H I mass	M_{HI}	$4.3 \times 10^8 M_\odot$	3
FIR flux	$S_{12\,\mu m}$	0.94 Jy	7
	$S_{25\,\mu m}$	9.57 Jy	7
	$S_{60\,\mu m}$	43.86 Jy	7
	$S_{100\,\mu m}$	33.78 Jy	7
Radio continuum flux	$S_{1.49\,GHz}$	38.3 (1.5″ ϕ) mJy	8
	$S_{1.49\,GHz}$	40.2 (5″ ϕ) mJy	8
	$S_{1.49\,GHz}$	39.5 (18″ ϕ) mJy	8

References.—(1) Dressel and Condon 1976; (2) Nilson 1973; (3) Richter and Huchtmeier 1987; (4) Karachentsev 1980; (5) Kawara, Nishida, and Gregory 1987; (6) this *Letter*; (7) Fullmer and Lonsdale 1989; (8) Condon *et al.* 1990.

Figure 1 shows a narrow CO line width. It should be noted that the characteristics of the line profile such as single-peaked or double-horned are not clear in this figure due to the high noise level. The full width of the CO line is 85 km s^{-1} at the 50% level of the peak intensity, and 120 km s^{-1} at the 20% level. After correction for a galaxy inclination of 57° (Richter and Huchtmeier 1987), we obtain 100 km s^{-1} at the 50% level and 140 km s^{-1} at the 20% level. The CO line width can be compared with those rotational velocities of the underlying stellar system which are derived from the K magnitude. In the case of NGC 4418, the K magnitude probably provides the lower limit on the mass of the underlying stellar system by assuming the mass-to-luminosity ratio of unity in the K passband and the virial equilibrium, since the nucleus is heavily obscured even in the midinfrared and any contamination to the 2 μm K band from dust emission, young stars and a nonthermal source can be ignored. Kawara, Nishida, and Gregory (1987) obtained a K magnitude of 11.1 in a 10″.3 × 21″ slit whose equivalent circular diameter is 16″ (Kawara, Nishida, and Gregory 1987). Using the typical K growth curve for E and S0 galaxies (Frogel *et al.* 1978) implies $K = 12.7$ in a 3″.8 aperture diameter. We derive $6 \times 10^9 M_\odot$ for the stellar mass and 180 km s^{-1} for the rotation velocity of the underlying stellar system in a 16″ aperture diameter, and $1.5 \times 10^9 M_\odot$ and 200 km s^{-1} in a 3″.8 diameter. The narrow CO line width could then be due to the high concentration of molecular clouds in the central region, the molecular cloud disk system viewed in the polar direction whose inclination angle is different from that of the galaxy disk (57° for an inclination of the stellar system), or due to the self-gravitating cloud system where the cloud system is decoupled from the stellar gravity, the clouds being rotating slower than the stellar system and falling toward the center.

As noted by Roche *et al.* (1986), NGC 4418 has a companion galaxy MCG +00-32-013 (see Fig. 1). This galaxy may be interacting with NGC 4418, because its morphology shows a disturbed appearance, and its recession velocity is similar to that of NGC 4418 (the velocity difference is only 188 km s^{-1}: Karachentsev 1980). This feature would be a typical case of the numerical simulation made by Noguchi (1988) on the gas-dynamics in interacting disk galaxies: during a close encounter, a stellar bar is formed in the disk by the tidal force of the perturber, which induces the infall of gas to the nuclear region if the gas dissipates its energy through cloud-cloud collisions.

b) Origin of the Far-Infrared Luminosity

NGC 4418 is quite different from any other starburst or AGN galaxies. Most importantly, there are no significant emission lines in the optical, while strong optical emission lines are common characteristics of other *IRAS* galaxies. No emission lines such as Brα and H_2 $v = 1$–0 $S(1)$ in the near-infrared have been detected, either (Kawara, Nishida, and Gregory 1987: Kawara, Nishida, and Phillips 1989). The lack of emission lines indicates that the nucleus is completely enshrouded by dense molecular clouds so that there are no holes in the molecular cloud system through which photons in the optical and the near-infrared can leak. NGC 4418 also shows no dust emission features at 8.65 and 11.25 μm in the 8–13 μm spectrum (Roche *et al.* 1986) which are usually associated with the starburst activity. The presence of the OH megamaser source (Martin *et al.* 1988) indicates only that the strong far-infrared continuum is present in the galaxy.

The ratio of the far-infrared luminosity ($L_{\rm fir}$) to molecular gas mass ($M_{\rm H_2}$) is also unique in NGC 4418, because this ratio of NGC 4418 (=170) is the highest among *IRAS* galaxies. It is known that the ratio is a function of the far-infrared luminosity: the greater the luminosity, the higher the $L_{\rm fir}/M_{\rm H_2}$ ratio (Sanders *et al.* 1988). Close to the far-infrared luminosity of NGC 4418 ($7 \times 10^{10}\ L_\odot$), the ratio of NGC 4418 is 10 times greater than those of other *IRAS* galaxies and is comparable to or even greater than that of an ultraluminous *IRAS* galaxy Mrk 231 (Seyfert 1/QSO with $L_{\rm fir} = 2 \times 10^{12}\ L_\odot$) which is the highest in the sample of Sanders *et al.*). For further comparison the $L_{\rm fir}/M_{\rm H_2}$ ratio is 14 for NGC 5506 (Seyfert 2 with $L_{\rm fir} = 10^{10}\ L_\odot$) and 24 for NGC 7469 (Seyfert 1 with $L_{\rm fir} = 2 \times 10^{11}\ L_\odot$). We note that NGC 6240, one of the exceptional merging galaxies, has only 20 for this ratio. This significantly high $L_{\rm fir}/M_{\rm H_2}$ ratio suggests that the energy conversion per unit mass in NGC 4418 is much larger than those in other *IRAS* galaxies, which would imply that NGC 4418 is in a special evolutionary phase during its nuclear activity.

Recently, Condon *et al.* (1990) reported 1.49 GHz maps of this galaxy, where the radio-emitting region was highly concentrated toward the center, 38.5 mJy (95% of the total flux), coming from a 0″.5 × 0″.3 region. The brightness temperature of this concentrated region is about 150,000 K, indicating that an AGN resides in the galaxy. Hence, it is probable that the AGN is the orgin for the far-infrared emission, an explanation which is consistent with the absence of the dust emission feature. NGC 4418 demonstrated its uniqueness again when the 1.49 GHz flux was mapped, because there is a close correlation between the thermal far-infrared and the nonthermal 1.4 GHz fluxes in *IRAS* galaxies (Helou, Soifer, and Rowan-Robinson 1985; Sanders and Mirabel 1985) after subtracting the bright point AGN source from the total radio flux. This correlation is considered as evidence that star-forming activity is responsible for the far-infrared emission, since the radio continuum is dominated by supernova remnants. Relative to the *IRAS* far-infrared flux, NGC 4418 has the 1.49 GHz flux which is 10 times smaller than those of starburst galaxies. Since AGN galaxies have larger 1.49 GHz fluxes than starburst galaxies do, this suggests that NGC 4418 is still probably at an early stage in its AGN activity, where the 1.49 GHz flux is significantly attenuated by the large optical depth due to the thick ionized gas density around the nucleus. If the interstellar matter is funnelled into the massive black hole (e.g., Shlosman, Begelman, and Frank 1990), there would be a stage where the molecular gas completely enshrouds the black hole and completely blocks out the center from our view. After that, the intense radiation or the jet from the AGN destroys the ambient molecular gas and makes holes in the molecular cloud system from which optical and near-infrared photons can leak, resulting in the AGN's being partially visible as in the case of other *IRAS* galaxies. This picture is considered to be consistent with the high $L_{\rm fir}/M_{\rm H_2}$ ratio, since most of the energy from the AGN would be processed in molecular clouds and reemitted by dust in the far-infrared at this stage.

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