Dense Molecular Gas and Star Formation in Nearby Seyfert Galaxies

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Abstract. An imaging survey of CO(1−0), HCN(1−0), and HCO+(1−0) lines in the centers of nearby Seyfert galaxies has been conducted using the Nobeyama Millimeter Array and the RAINBOW interferometer. Preliminary results reveal that 3 Seyferts out of 7 show abnormally high HCN/CO and HCN/HCO+ ratios, which cannot occur even in nuclear starburst galaxies. We suggest that the enhanced HCN emission originated from X-ray irradiated dense obscuring tori, and that these molecular line ratios can be a new diagnostic tool to search for “pure” AGNs. According to our HCN diagram, we suggest that NGC 1068, NGC 1097, and NGC 5194 host “pure” AGNs, whereas Seyfert nuclei of NGC 3079, NGC 6764, and NGC 7469 may be “composite” in nature.

1. Introduction

Dense molecular matter is considered to play various roles in the vicinity of active galactic nuclei (AGNs). The presence of dense and dusty interstellar matter (ISM), which obscures the broad line regions in AGNs, is inevitable at a few pc - a few 10 pc scale according to the unified model of Seyfert galaxies. This circumnuclear dense ISM could be a reservoir of fuel for nuclear activity, and also be a site of massive star formation.

In order to investigate dense molecular matter in the centers of Seyfert galaxies, we have conducted an imaging survey of CO(1−0), HCN(1−0), and
HCO⁺(1−0) lines in nearby Seyfert galaxies using the Nobeyama Millimeter Array (NMA). High resolution HCN observations of Seyfert galaxies are of interest because unusually strong HCN emission has been reported in the type-2 Seyfert galaxies NGC 1068 (Jackson et al. 1993; Tacconi et al. 1994; Helfer & Blitz 1995) and NGC 5194 (Kohno et al. 1996). The HCN/CO integrated intensity ratios in brightness temperature scale, $R_{\text{HCN/CO}}$, hereafter, within the central $r \sim$ a few 10 pc region exceed 0.4, which is never observed in non-Seyfert galaxies including nuclear starburst galaxies ($R_{\text{HCN/CO}} < 0.3$; see Kohno et al. 1999 and references therein).

2. **CO, HCN, and HCO⁺ Images of Seyferts**

Figure 1 shows a part of the CO images of Seyfert galaxies obtained with the NMA so far. Some Seyfert galaxies have also been observed using the RAINBOW interferometer, which is a 7 elements combined array consisting of six 10 m dishes (NMA) and NRO 45 m telescope; see Sofue et al. (2001) for NGC 3079, and see Okiura et al. (2001, this volume) for NGC 7469.

These CO images show a wide variety of gas morphologies in the central kpc regions of Seyferts, just as in the case of normal spirals (Sakamoto et al. 1999). Single dish CO surveys aiming to determine the global amount of molecular gas in Seyferts have revealed that there is no significant difference between the total amounts of molecular gas in Seyfert and quiescent spirals (e.g., Vila-Vilaró et al. 1998). Our higher angular resolution CO images may already suggest that the accumulation of molecular gas in the central kpc region is still insufficient for Seyfert activity.

Figure 2 shows the HCN and HCO⁺ images of Seyfert galaxies. Except for NGC 5194 and NGC 6951, HCN and HCO⁺ lines were observed simultaneously, thanks to the wide (1024 MHz) band width of a new spectro-correlator.
We have observed extremely strong HCN emission in 3 Seyferts out of 7. What is the nature of these “HCN-enhanced Seyferts”? Here we compare the observed line ratios in Seyferts with those in nuclear starburst galaxies, which were also measured with similar angular resolutions. In Figure 5, it is immediately evident that Seyferts without abnormal HCN enhancements, i.e. NGC 3079, NGC 6764, and NGC 7469, show $R_{\text{HCN}/\text{CO}}$ and $R_{\text{HCN}/\text{HCO}^+}$ values just comparable to those in nuclear starbursts; they have $R_{\text{HCN}/\text{CO}}$ less than 0.3, and $R_{\text{HCN}/\text{HCO}^+}$ ranging from 0.5 to 1.5. On the other hand, HCN-enhanced Seyferts, i.e. NGC 1068 and NGC 1097, also have very high $R_{\text{HCN}/\text{HCO}^+}$ values ($> 2$). Note that Nguyen-Q-Rieu et al. (1992) reported a very high $R_{\text{HCN}/\text{HCO}^+}$ in NGC 3079 and Maffei 2 ($> 3$), yet our new simultaneous measurements gave moderate ($\sim 1$) ratios.
Figure 3. The CO(1−0) and HCN(1−0) images of the type-1 Seyfert NGC 1097 taken with the NMA. The central cross in (a), (b), and (c) marks the position of the nucleus (6 cm continuum peak; Hummel et al. 1987). The circumnuclear starburst ring with a radius of $r \sim 10''$ or 700 pc, clearly traced with Hα and radio continuum (e.g. Hummel et al. 1987) and dust lanes along the bar (see (d)) are indicated. (a) CO(1−0) integrated intensity map. The synthesized beam is 7''7 × 3''9 (540 × 270 pc) with a P.A. of −16°. Contour levels are 1.5, 3, 4.5, 6, 7.5, 9, 12, 15, and 18 $\sigma$, where $1 \sigma = 3.39$ Jy beam$^{-1}$ km s$^{-1}$ or 10.4 K km s$^{-1}$ in $T_b$. This corresponds to a face-on gas surface density $\Sigma_{\text{gas}}$ of 34.7 $M_\odot$ pc$^{-2}$, calculated as $\Sigma_{\text{gas}} = 1.36 \times \Sigma_{\text{H}_2}$ and $\Sigma_{\text{H}_2} = 4.81 \times (I_{\text{CO}}/K \text{ km s}^{-1}) \cdot \cos(i) \cdot (X_{\text{CO}}/(3.0 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1})$, where $i = 46°$. The “CO twin peaks” is evident, as well as the nuclear CO source. (b) HCN(1−0) integrated intensity. The synthesized beam is 10''1 × 4''4 (710 × 310 pc) with a P.A. of −8°. Contour levels are 1.5, 3, 4.5, ⋯, and 16.5 $\sigma$, where $1 \sigma = 0.711$ Jy beam$^{-1}$ km s$^{-1}$ or 3.54 K km s$^{-1}$ in $T_b$. Most of the HCN emission is dominated by the central unresolved peak. (c) Intensity-weighted mean velocity map of CO(1−0). The contour interval is 30 km s$^{-1}$. Very strong non-circular motion along the bar is suggested by isovelocity contours parallel to the dust lanes. (d) V-band image of 400'' × 400'' (28 kpc × 28 kpc) region of NGC 1097 (Quillen et al. 1995).
We propose that these two groups in our “HCN diagram” (Figure 5) can be understood in terms of “AGN - nuclear starburst connection” (note that this should not be confused with “AGN - starburst cohabitation”, which often refers to the association of AGN with star formation on galactic scales in AGN hosts). In the Seyferts with line ratios comparable to those in nuclear starburst galaxies, it seems likely that nuclear starburst (presumably in the dense molecular torus) is associated with the Seyfert nucleus (i.e., “composite”). In the nuclear regions of composite Seyferts, HCO$^+$ fractional abundance is expected to increase due to frequent supernova (SN) explosions. In fact, in evolved starbursts such as M82, where large scale outflows have occurred due to numerous SN explosions, HCO$^+$ is often stronger than HCN (e.g. Nguyen-Q-Rieu et al. 1992). On the other hand, the HCN-enhanced Seyferts, which shows $R_{\text{HCN/CO}} > 0.3$ and $R_{\text{HCN/HCO}^+} > 2$, would host “pure” AGNs, where there is no associated nuclear starburst activity. In such a condition, the HCN line can be very strong because it has been predicted that fractional abundance of HCN is enhanced by strong X-ray radiation from AGN (Leep & Dalgarno 1996), resulting in abnormally high $R_{\text{HCN/CO}}$ and $R_{\text{HCN/HCO}^+}$ values. Our interpretation is supported by other wavelength data; for instance, NGC 1068 has been claimed as a pure Seyfert (Cid Fernandes et al. 2001 and references therein), whereas NGC 6764 (Schinnerer et al. 2000) and NGC 7469 (Genzel et al. 1995) have a composite nature. We need further analysis to validate the proposed interpretation, but if it is the case, this will serve as a new way to investigate the nature of AGNs; although this technique requires high angular resolution observations in order to avoid contaminations from extended circumnuclear star-forming regions, it has some advantages (e.g., not being affected by dust extinction).

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Figure 5. Molecular line ratios in Seyfert and non-Seyfert (nuclear starburst) galaxies.

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