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HCN AND CO IN THE NUCLEUS OF NGC 1068

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ABSTRACT

Recent interferometric observations of HCN and CO 1–0 molecular emission from the Seyfert galaxy NGC 1068 have revealed an unusually large HCN/CO emission-line ratio at the galactic nucleus. We argue that the large HCN/CO intensity ratio is due, in part, to a selective depletion of gas-phase oxygen in the dense molecular clouds within the narrow-line region. The reduced oxygen abundance inferred from the HCN and CO millimeter wave observations is consistent with a similar oxygen depletion inferred from optical, ultraviolet, and X-ray spectral observations of the ionized gas component in the nucleus of NGC 1068.

Our multiwavelength analysis provides the first quantitative link between the chemical properties of the molecular and ionized gas clouds in the immediate vicinity of an active galactic nucleus.

Subject headings: galaxies: individual (NGC 1068) — galaxies: ISM — galaxies: Seyfert — molecular processes

1. INTRODUCTION

NGC 1068 is one of the best-studied galaxies [Sb(rs)II spiral: Sandage & Tammann 1981] containing an active galactic nucleus (AGN). It is nearby ($d = 14$ Mpc, $1'' = 68$ pc for $H_0 = 75$ km s^{-1} Mpc^{-1}), and it has been observed extensively from radio to X-ray wavelengths. The central luminosity is dominated by a compact dusty 10 μm source (Braatz et al. 1993; Cameron et al. 1993) which emits 1.5×10^{11} $L_\odot$. The galaxy contains a prominent star formation ring with a 15″ radius and contains an optical "narrow-line region" (NLR) $\sim 4''$ in diameter (Balick & Heckman 1985; Evans et al. 1991; Lynds et al. 1991). NGC 1068 is a Seyfert 2 galaxy, but optical and X-ray emission from an obscured "broad-line region" (BLR) is visible in scattered light (Antonucci & Miller 1985; Miller, Goodrich, & Mathews 1991).

Recent near-infrared array imaging of the 2.12 μm 1–0 $S(1)$ H_2 vibrational emission line (Blietz et al. 1994; Tacconi et al. 1994) and aperture synthesis mapping of the 88.6 and 115 GHz HCN and CO 1–0 rotational emission lines (Owens Valley: Planesas, Scoville, & Myers 1991; Nobeyama: Jackson et al. 1993; IRAM: Tacconi et al. 1994; BIMA: Helfer & Blitz 1994) have revealed the presence of dense molecular clouds inside the narrow-line region of NGC 1068. The total molecular hydrogen gas mass likely exceeds 3×10^7 $M_\odot$ within the central 4″ (Blietz et al. 1994; Tacconi et al. 1994). Individual molecular clouds along the line of sight to the AGN, in an extended molecular cloud layer or "torus," may provide most of the obscuration to the BLR (Cameron et al. 1993; Pier & Krolik 1993).

In this *Letter* we focus attention on the unusually large nuclear HCN/CO 1–0 intensity ratio revealed by the recent interferometric observations. These observations show that the HCN/CO 1–0 line brightness temperature ratio exceeds unity across the NLR, and is larger than seen anywhere in our Galaxy, except in much smaller ($\lesssim 0.02$ pc) dense optically thick cores in star-forming clouds. The interferometric HCN/CO line ratio in NGC 1068 is much larger than is observed (using single-dish telescopes) in other galaxies including the most luminous *IRAS* galaxies (Nguyen-Q-Rieu et al. 1992; Solomon, Downes, & Radford 1992; Helfer & Blitz 1993). In the star-forming ring the HCN/CO intensity ratio is much smaller, and does not exceed $\sim 1/30$.

As pointed out by Jackson et al. (1993) and Tacconi et al. (1994) the large nuclear HCN/CO intensity ratio implies that the molecular clouds in the NLR are probably very dense, with hydrogen particle densities close to 10^5 cm^{-3}. In this *Letter* we show that the large HCN/CO intensity ratio also suggests that the HCN/CO *abundance* ratio is unusually large in the NLR. We argue that the large HCN/CO abundance ratio may be due to a selective depletion of gas-phase oxygen which results in enhanced HCN and reduced CO densities in the nuclear molecular clouds. The oxygen depletion we derive from the millimeter wave observations is consistent with a similar oxygen depletion inferred from ultraviolet and X-ray spectral observations of the ionized component (Marshall et al. 1993).

Our multiwavelength analysis provides the first quantitative link between the chemical properties of the molecular and ionized gas clouds in the immediate vicinity of an active galactic nucleus.

2. NUCLEAR HCN/CO ABUNDANCE RATIO

To set limits on the nuclear HCN/CO abundance ratio we used the interferometric CO and HCN 1–0 data presented by Planesas et al. (1991) and Tacconi et al. (1994) in combination with the single-dish observations (also presented by Tacconi et al.) of HCN 3–2, 4–3, $H^{13}CN$ 3–2, CO 3–2, 4–3, and ^{13}CO 3–2 line emission toward the center of NGC 1068. The observational results are summarized in Tables 1 and 2.

The interferometric measurements reveal a nuclear source with an equivalent Gaussian diameter $\theta_S = 2''$. In Tables 1 and 2 we list the line-center source brightness temperatures $T_S \equiv T_B \times (\theta_B^2 + \theta_S^2)/\theta_S^2$ for each of the observed CO and HCN lines, where T_B are the measured brightness temperatures within regions with diameters θ_B. For the interferometrically observed

TABLE 1

INTERFEROMETRIC DATA

Species	Transition	ν (GHz)	T_S[a] (K)
CO	1–0	115.271	5.9
HCN	1–0	88.632	12

[a] T_S are the line-center brightness temperatures within the central 4″ for a nuclear source with a Gaussian diameter $\theta_B = 2''$ (see text).

TABLE 2

SINGLE-DISH DATA

Species	Transition	ν (GHz)	θ_B[a]	T_S[b] (K)
CO	3–2	345.796	14″	44
CO	4–3	461.040	11	25
^{13}CO	3–2	330.588	15	0.03
HCN	3–2	265.886	19	6.5
HCN	4–3	354.506	14	3.1
H^{13}CN......	3–2	259.012	19	1.1

[a] θ_B are the effective sizes of the single-dish beams (Tacconi et al. 1994).

[b] The inferred source brightness temperatures for a nuclear source size $\theta_S = 2''$ (see text).

lines $\theta_B = 4''$ is the total size of the nuclear emission source. For the single-dish measurements θ_B are the main beam sizes. The source brightness temperatures in the CO and HCN 1–0 emission lines are equal to 6 and 12 K, respectively. Similar values for the nuclear HCN and CO line have been found by Helfer & Blitz (1994). The single-dish measurements may include some emission from the star-forming ring, and the values of T_S listed in Table 2 are upper limits.

We have analyzed the observations using single-component large velocity gradient (LVG) calculations of the molecular emission-line intensities for a range of cloud densities, temperatures, and molecular column densities (Genzel 1992). As pointed out by Tacconi et al., the large CO 4–3/1–0 line ratio of $\sim$4 (see Tables 1 and 2) suggests that the nuclear molecular clouds are dense and warm with gas temperatures $\gtrsim$50 K, and in Figure 1 we display the results of our LVG calculations for 50 K clouds. In our calculations we adopted an isotopic abundance ratio $^{12}C/^{13}C = 40$ (Wannier 1980).

Figure 1*a* shows that a 6 K CO 1–0 line is produced in 50 K clouds provided $N_{CO}/\Delta v \gtrsim 10^{16}$ cm^{-2} km^{-1} s, where N_{CO} is the CO column density and Δv is the line width. From the CO 4–3/1–0 line ratio it follows that for cloud temperatures near 50 K the cloud densities must be large with $n \sim 10^5$ cm^{-3}. The nuclear CO emission beam-filling factor is likely large because the isotopic CO/^{13}CO 3–2 line ratio of 21 is large. Thus, $N_{CO}/\Delta v$ is probably not much greater than 10^{16} cm^{-2} km^{-1} s, and the CO 1–0 line is likely optically thin. However, these conclusions are based on single-dish 3–2 CO line measurements. Interferometric ^{13}CO 1–0 emission-line observations are crucial to constrain the total CO column density in the nucleus of NGC 1068 more accurately.

Figure 1*b* shows that a 12 K HCN 1–0 line is produced in 50 K clouds if $N_{HCN}/\Delta v \gtrsim 10^{14}$ cm^{-2} km^{-1} s. The HCN 4–3/1–0 line ratio of $\sim$0.25 and the HCN/H^{13}CN 3–2 ratio of $\gtrsim$6.5 both imply that the nuclear HCN emission filling factor is also large. The measured HCN 4–3/1–0 ratio implies further that the gas density in the HCN-emitting gas is no greater than a few 10^5 cm^{-3}. Thus, the available millimeter wave evidence yields a *lower* limit of $N_{HCN}/N_{CO} \gtrsim 0.01$ for the CO/HCN abundance ratio in the narrow-line region of NGC 1068. Our LVG calculations show that this limit is insensitive to the gas temperature in warm clouds. The nuclear HCN/CO abundance ratio is probably close to 1% since it is unlikely that the HCN-emitting gas is less dense than the CO-emitting gas.

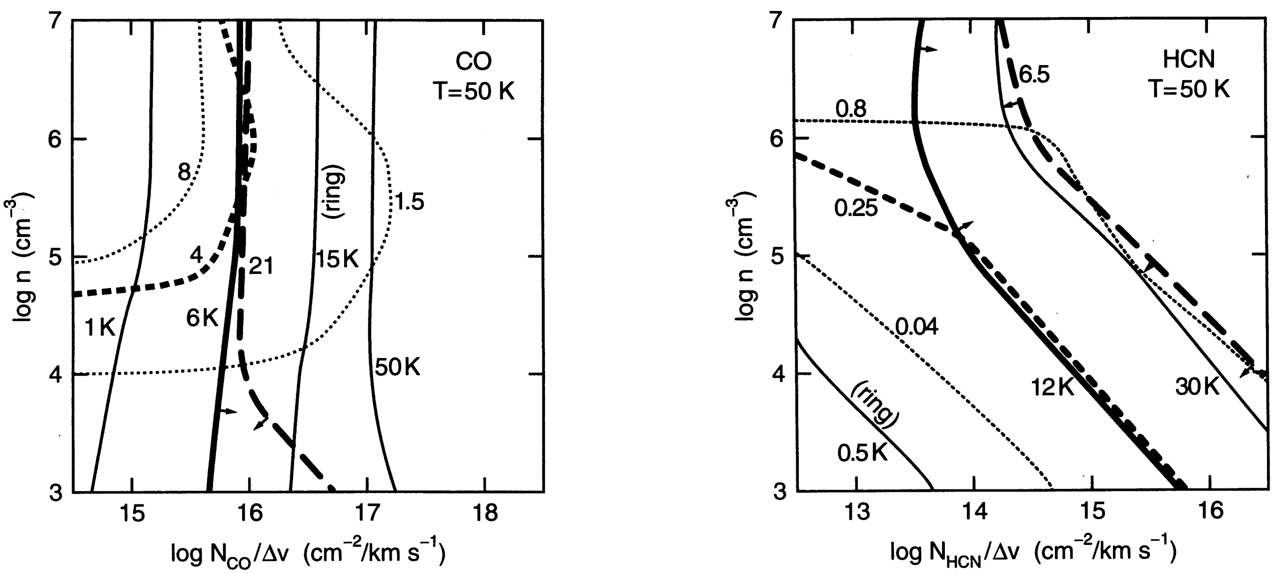

FIG. 1*a* FIG. 1*b*

FIG. 1.—(*a*) CO emission-line properties for 50 K clouds in the LVG approximation. Solid curves are contours of constant 1–0 line-center brightness temperature. Short dashed curves are contours of constant 4–3/1–0 line ratios. Long dashed curve is a contour of constant CO/^{13}CO 3–2 line ratio. Observed values are indicated by the thicker curves. The parameter n is the hydrogen gas density (cm^{-3}), N_{CO} is the CO column density (cm^{-2}), and Δv is the line width (km s^{-1}). (*b*) CO emission-line properties for 50 K clouds. Curves are identified as in (*a*).

We conclude that the unusually large HCN/CO 1–0 line ratio in NGC 1068 is due both to the presence of high-density $\sim 10^5$ cm^{-3} molecular clouds (Jackson et al. 1993; Tacconi et al. 1994) *and* to an unusually large HCN/CO *abundance* ratio in the narrow-line region. For comparison we note that in Milky Way molecular clouds the HCN/CO abundance ratio typically ranges from $\sim 10^{-4}$ in quiescent clouds to $\sim 10^{-3}$ in hot cores in star-forming regions (Blake et al. 1987).

3. CHEMISTRY

The large HCN/CO abundance ratio in NGC 1068 may be due to a selective depletion of gas-phase oxygen in the narrow-line region.

In standard interstellar gas-phase schemes (van Dishoeck 1988; Sternberg & Dalgarno 1995) HCN molecules are produced by the neutral reactions

$$N + CH_2 \rightarrow HCN + H \quad (1)$$

and

$$N + CH_3 \rightarrow HCN + H_2 , \quad (2)$$

where the CH_2 and CH_3 radicals are products of a sequence of hydrogen abstractions and dissociative recombinations initiated by the proton transfer reaction

$$C + H_3^+ \rightarrow CH^+ + H_2 . \quad (3)$$

The HCN density is therefore sensitive to the abundance of free atomic carbon which is, in turn, sensitive to the oxygen abundance. In particular, the HCN density may become very large in environments where oxygen is less abundant than carbon because of the excess atomic carbon that remains in the gas after the CO molecules form. The CO density becomes small when the oxygen is severly depleted, so that the HCN/CO abundance ratio will, in general, rise with decreasing oxygen abundance.

Figure 2 shows the results of explicit chemical computations which display this effect. This figure shows the steady state HCN/CO abundance ratio as a function of the oxygen depletion factor $\delta_O \equiv [O]/[O]_\odot$ (where $[O]_\odot$ is the solar oxygen abundance) for 50 K clouds with hydrogen gas densities n ranging from 10^3 to 10^6 cm^{-3}. The results are insensitive to the cloud temperature. In our calculations we assumed that the chemistry is driven by impact ionization of hydrogen which proceeds at a rate equal to 5×10^{-17} s^{-1}. The HCN/CO abundance ratio is insensitive to the ionization rate. We adopted approximate solar oxygen, carbon, and nitrogen abundances: $[O]_\odot = 6 \times 10^{-4}$, $[C]_\odot = 3 \times 10^{-4}$, and $[N]_\odot = 1 \times 10^{-4}$ (Morton 1991). In solving for the molecular concentrations, we used the molecular data listed by Gredel et al. (1989) and Millar et al. (1991).

Figure 2 shows that the HCN/CO density ratio depends sensitively on δ_O, and that when $[O] < [C]$ (i.e., when $\delta_O < 0.5$) the HCN/CO ratio becomes large. Figure 2 also shows that when $[O] > [C]$ the HCN/CO density ratio is sensitive to the hydrogen gas density and decreases with increasing n. This behavior is due to the increase in free atomic carbon with decreasing cloud density (cf. Pineau des Forêts, Roueff, & Flower 1992).

Figure 2 shows that for $n \approx 10^5$ cm^{-3} the HCN/CO abundance ratio is $\gtrsim 1\%$ when $\delta_O \lesssim 0.25$. Thus, the HCN and CO line strengths observed in NGC 1068 appear to be consistent with a selective depletion of gas-phase oxygen in the molecular clouds in the NLR.

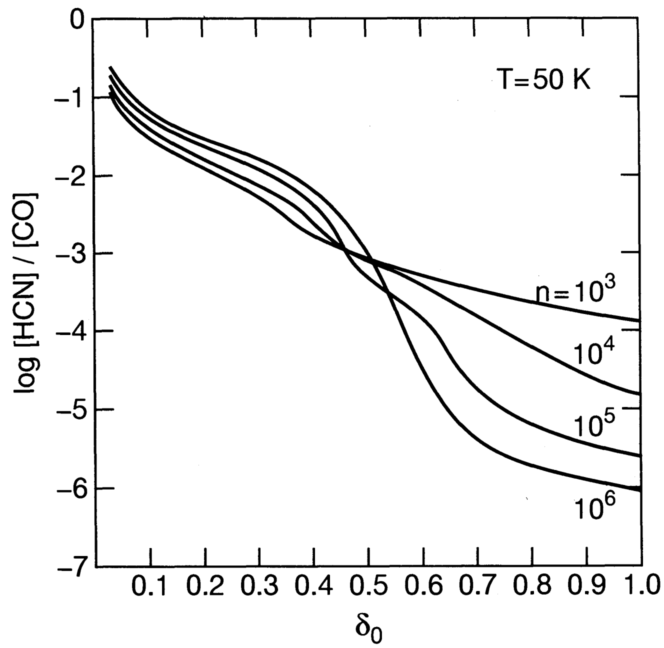

FIG. 2.—HCN/CO abundance ratio as functions of the oxygen depletion factor δ_O for 50 K clouds with hydrogen densities ranging from 10^3 to 10^6 cm^{-3}.

4. DISCUSSION

The oxygen depletion we have derived from the millimeter-wave HCN and CO observations of the molecular clouds is consistent with a similar oxygen depletion inferred from recent ultraviolet and X-ray observations of the hot ionized gas in the narrow-line region of NGC 1068.

Marshall et al. (1993) carried out 0.1–10 keV X-ray spectral observations of NGC 1068 and detected several Fe K- and L-shell emission lines superposed on a Compton-scattered X-ray AGN continuum. The emission lines are produced by Fe ions present in a broad range of ionization states in hot photoionized plasma with temperatures between 2×10^5 and 4×10^6 K. However, no recombination emission lines from highly ionized oxygen species (e.g., O VIII 19 Å Lyα) nor any K-shell absorption lines of oxygen ions in low ionization states were detected in the X-ray spectrum. Marshall et al. concluded that oxygen is underabundant in the NLR. They noted that this conclusion is consistent with ultraviolet spectra of NGC 1068 (Snijders, Netzer, & Boksenberg 1986; Kriss et al. 1992) which show strong N III] λ1750, C III] λ1909, and C IV λ1549 lines but reveal a conspicuous absence of O III] $\lambda\lambda$1661, 1667 lines which are usually prominent in photoionized gas.

Marshall et al. presented models of the photoionized gas in NGC 1068, and found that gas-phase iron is probably overabundant in the NLR, and that oxygen must be selectively depleted by a factor of at least 5, relative to solar values, to account for the missing X-ray and ultraviolet oxygen emission and absorption features. In their model, strong [O III] $\lambda\lambda$4959, 5007 cooling lines are produced despite the large oxygen depletion, with intensities close to the observed values (Evans et al. 1991). The large gas-phase iron abundance of $\sim 10^{-4}$ inferred from the X-ray data is consistent with the large intensity ratio of the near-infrared 1.64 μm [Fe II] and 2.17 μm H I Brγ lines in the central 1″ of NGC 1068 (Blietz et al. 1994).

An important characteristic of the photoionization models presented by Marshall et al. is that oxygen is required to be less abundant than carbon by factors of 2–3, precisely the condition required to generate large HCN/CO abundance ratios in the molecular component. Thus, an oxygen depletion factor of $\delta_O \lesssim 0.2$ in both the ionized and molecular gas in the NLR can simultaneously explain the weak ultraviolet and X-ray oxygen spectral lines and the large HCN/CO intensity ratio observed in NGC 1068. This link between the chemical properties of the molecular and ionized gas is plausible if the ionized gas is produced at the irradiated faces of dusty and optically thick molecular clouds in the NLR (Cameron et al. 1993; Genzel, Cameron, & Krabbe 1993).

A selective underabundance of gas-phase oxygen relative to carbon is peculiar and is a puzzle. It is difficult to understand within the framework of standard stellar nucleosynthesis, particularly since the possible presence of massive stars in the nucleus (Terlevich et al. 1992) would lead to efficient synthesis of oxygen atoms (Wheeler, Sneden, & Truran 1989). However, unusual elemental abundances and low oxygen abundances in the vicinity of other active galactic nuclei have been reported (Storchi-Bergmann & Pastoriza 1989; Winge et al. 1992). A significant underabundance of oxygen in the molecular clouds in the NLR suggests that they have formed in situ, and have not streamed in from the star-forming ring where the elemental abundances may be normal. Alternatively, rapid depletion of oxygen onto dust grains may occur in the dense gas flowing into the nucleus.

The total CO 1–0 line flux of 200 K km s^{-1} within the central 4″ (Planesas et al. 1991) implies a total H_2 column density of 4×10^{22} cm^{-2} if the Galactic CO to H_2 conversion factor is used (Bloemen 1989). However, if oxygen is very underabundant and the CO 1–0 line is optically thin, as implied by the observations, the inferred H_2 column densities of the nuclear molecular clouds may actually be close to the $\gtrsim 10^{24}$ cm^{-2} required to obscure a central X-ray source from direct view (Mushotzky, Done, & Pounds 1993; Pier & Krolik 1993).

If oxygen is underabundant then CS emission may be unusually strong and HCO^+ emission relatively weak in the NLR since the CS density depends on the available atomic carbon, and HCO^+ is a derivative of CO (Sternberg & Dalgarno 1995). HCO^+ 1–0 and CS 2–1 emission lines have been detected in NGC 1068 using single-dish telescopes in which the star-forming ring and the NLR are not resolved (Nguyen-Q-Rieu et al. 1992; Helfer & Blitz 1993). The single-dish observations suggest that the ratio of CS 2–1 and CO 1–0 emission is unusually large in the nucleus. Interferometric measurements of the CS and HCO^+ emission-line intensities in the narrow-line region of NGC 1068 would be valuable.

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