

THE EXCITATION OF HCN AND HCO⁺ IN THE GALACTIC CENTER CIRCUMNUCLEAR DISK

E. A. C. MILLS^{1,2,4,5}, R. GÜSTEN³, M. A. REQUENA-TORRES³, AND M. R. MORRIS²

¹ National Radio Astronomy Observatory, P.O. Box O 1009, Lopezville Drive, Socorro, NM 87801, USA

² Department of Physics and Astronomy, University of California, Physics and Astronomy Building, 430 Portola Plaza, Box 951547 Los Angeles, CA 90095-1547, USA; millsb@astro.ucla.edu

³ Max Planck Institut für Radioastronomie, Auf Dem Hugel 69, D-53121 Bonn, Germany

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ABSTRACT

We present new observations of HCN and HCO⁺ in the circumnuclear disk (CND) of the Galaxy, which we obtained with the Atacama Pathfinder Experiment telescope. We mapped emission in rotational lines of HCN $J = 3-2$, $4-3$, and $8-7$, as well as of HCO⁺ $J = 3-2$, $4-3$, and $9-8$. We also present spectra of H¹³CN $J = 3-2$ and $4-3$ as well as H¹³CO⁺ $J = 3-2$ and $4-3$ toward four positions in the CND. Using the intensities of all of these lines, we present an excitation analysis for each molecule using the non-LTE radiative transfer code RADEX. The HCN line intensities toward the northern emission peak of the CND yield log densities (cm⁻³) of $5.6^{+0.6}_{-0.6}$, consistent with those measured with HCO⁺ as well as with densities recently reported for this region from an excitation analysis of highly excited lines of CO. These densities are too low for the gas to be tidally stable. The HCN line intensities toward the CND's southern emission peak yield log densities of $6.5^{+0.5}_{-0.7}$, higher than densities determined for this part of the CND with CO (although the densities measured with HCO⁺, $\log [n] = 5.6^{+0.2}_{-0.2}$, are more consistent with the CO-derived densities). We investigate whether the higher densities we infer from HCN are affected by midinfrared radiative excitation of this molecule through its 14 μ m rovibrational transitions. We find that radiative excitation is important for at least one clump in the CND, where we additionally detect the $J = 4-3$, $v_2 = 1$ vibrationally excited transition of HCN, which is excited by dust temperatures of $\gtrsim 125$ –150 K. If this hot dust is present elsewhere in the CND, it could lower our inferred densities, potentially bringing the HCN-derived densities for the southern part of the CND into agreement with those measured using HCO⁺ and CO. Additional sensitive, high-resolution submillimeter observations, as well as midinfrared observations, would be useful to assess the importance of the radiative excitation of HCN in this environment.

Key words: Galaxy: center – ISM: molecules – radiative transfer – techniques: imaging spectroscopy

Online-only material: color figures

1. INTRODUCTION

The circumnuclear disk (CND) is a ring of gas and dust around the central supermassive black hole (SMBH). It has an inner radius of ~ 1.5 pc and an inclination of 70° from the Galactic plane (Güsten et al. 1987; Jackson et al. 1993). The CND has been studied for decades in a range of molecular transitions; Amo-Baladrón et al. (2011) provide a comprehensive list of molecular lines studied in the CND to date. The molecular gas temperatures determined from observations of CO range from 50 to 400 K (Harris et al. 1985; Lugten et al. 1987; Bradford et al. 2005; Oka et al. 2011). Atomic gas temperatures measured at the inner edge of the CND are comparable, ranging from 200 to 350 K (Genzel et al. 1985; Jackson et al. 1993). Measured dust temperatures are much lower, ranging from 20 to 90 K (Becklin et al. 1982; Mezger et al. 1989; Etzaluze et al. 2011; Molinari et al. 2011; Lau et al. 2013). Kinematic studies of the CND (Jackson et al. 1993; Wright et al. 2001; Martín et al. 2012; Liu et al. 2012) show that the motion of the bulk of its gas is consistent with orbiting filaments in several planes.

The CND is the closest large molecular structure to the SMBH (mass $\sim 4.5 \times 10^6 M_\odot$; Ghez et al. 2008; Gillessen et al. 2009; Genzel et al. 2010) and thus should be subject to strong tidal shearing forces. If the CND is to be stable against tidal shearing, it must have an extremely high density: the fluid Roche approximation for gas at a radius of 2 pc from the SMBH

yields a limiting density of 8×10^7 cm⁻³. Observations of molecular clumps in the CND with lines of HCN and HCO⁺ have led to virial density estimates for individual clumps that range from 10^7 to 10^8 cm⁻³ (Shukla et al. 2004; Christopher et al. 2005; Montero-Castaño et al. 2009). However, the high densities derived in this way are in disagreement with lower densities recently inferred from the dust emission characteristics (Etzaluze et al. 2011) and from an excitation analysis using the CO molecule (Requena-Torres et al. 2012, hereafter RT12).

Both Christopher et al. and Montero-Castaño et al. also estimate a total mass for the CND ($\sim 10^6 M_\odot$) by assuming virialization, which greatly exceeds previous mass estimates of a few $\times 10^4 M_\odot$, based on CO excitation and dust emission (Harris et al. 1985; Genzel et al. 1985; Lugten et al. 1987; Mezger et al. 1989). More recent estimates of the mass from the FIR and submillimeter dust emission also favor a lower mass: Etzaluze et al. (2011) estimate a mass of $5 \times 10^4 M_\odot$, and RT12 estimate a mass of 10^3 – $10^4 M_\odot$. Lau et al. (2013) measure an even lower mass, $\sim 600 M_\odot$, but just for the relatively warm “circumnuclear ring” of material at the inner edge of the CND. Recent observations then suggest that the high values derived for the CND mass and density are due to an (invalid) assumption of virialization for the bulk of the gas. However, due to the nature of the tracers used in each analysis (HCN and HCO⁺, versus the lower density tracer CO and dust), it is not clear whether recent observations rule out the existence of any virialized clumps in the CND. Verifying whether there is any CND gas for which the assumption of virialization is valid is important for constraining the mass of the molecular gas reservoir in the central two parsecs of the galaxy and for determining whether the gas densities are

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Table 1
Properties of the Observed Transitions

Molecule	Transition $J-J-1, v_2$	Frequency (GHz)	Upper State Energy (K)	Critical Density ^a (cm ⁻³)	APEX Beam FWHM
HCN	3–2	265.88618	25.5	5.2×10^7	23''.6
	4–3	354.50548	42.5	1.1×10^8	17''.7
	4–3, 1 f	356.25561	1067.1	3.1×10^{11} ^b	17''.6
	8–7	708.87721	153.1	8.7×10^8	8''.9
HC ¹³ N	3–2	259.01182	24.9	4.8×10^7	24''.3
	4–3	345.33976	41.4	1.1×10^8	18''.2
HCO ⁺	3–2	267.55753	25.7	3.5×10^6	23''.5
	4–3	356.73413	42.8	8.2×10^6	17''.6
	9–8	802.45822	192.6	1.0×10^8	7''.8
H ¹³ CO ⁺	3–2	260.25534	25.0	3.1×10^6	24''.2
	4–3	346.99834	41.6	7.3×10^6	18''.1

Notes.

^a Assuming a kinetic temperature of 200 K.

^b This is actually the critical density required to populate the $J = 4, v_2 = 1$ level, using a collision rate estimated from CO₂ at ~ 200 K (Ziurys & Turner 1986).

consistent with recent suggestions of star formation in the CND (Yusef-Zadeh et al. 2008), given the strong tidal forces that are present in this region.

In order to investigate whether higher-density molecular tracers indicate the presence of virialized gas in the CND, we have conducted an excitation analysis using the $J = 3-2$, $4-3$, and $8-7$ transitions of HCN and the $J = 3-2$, $4-3$, and $9-8$ transitions of HCO⁺ from single-dish observations with the Atacama Pathfinder Experiment (APEX⁶) telescope. These lines should be particularly sensitive to the presence of dense gas, having critical densities of 10^6 – 10^9 cm⁻³ and spanning a range of energies from 25 K to 190 K above the ground state. Single-dish observations also have the advantage that they are not subject to the filtering out of spatially extended flux, which may have affected previous interferometric studies. This is the first excitation analysis of the CND using these dense gas tracers, and is the first detection of the highly excited HCN $J = 8-7$ and HCO⁺ $J = 9-8$ lines in the CND. In Section 2, we describe the APEX observations. In Section 3, we present velocity-integrated maps and spectra of all of the observed transitions. In Sections 4 and 5 we discuss the excitation analysis and our derived constraints on the temperature and density of the CND. Finally, we conclude in Section 7 with a discussion of the excitation mechanisms for HCN in the CND and an assessment of the validity of the assumption that all CND gas clumps are virialized. We also comment on whether the chemistry in the CND is likely to be affected by X-rays or cosmic rays.

2. OBSERVATIONS AND CALIBRATION

All of the data used for the analysis in this article were obtained with the APEX telescope (Güsten et al. 2006), a single 12 meter modified ALMA prototype antenna located at an elevation of 5106 m on the Chajnantor plain in Chile. Data were obtained over a multiple-day run in 2010 July. Conditions for the run were excellent, with a precipitable water vapor overburden of less than 0.5 mm. Additional observations of H¹³CN $J = 4-3$ and H¹³CO⁺ $J = 4-3$ were obtained in 2010 November

toward the northern emission peak of the CND. Observations of H¹³CN $J = 3-2$, HC¹⁵N $J = 3-2$, H¹³CN $J = 4-3$, and HC¹⁵N $J = 4-3$ were obtained in 2012 April toward the southern emission peak of the CND and an additional pointing toward the southwest component of this peak. Properties of all of the observed transitions are listed in Table 1.

2.1. 260 GHz Observations

Using the APEX1 facility receivers, we simultaneously observed the $J = 3-2$ transition of HCN and the $J = 3-2$ transition of HCO⁺ over a rectangular field covering the CND. Our maps were centered on the position of Sgr A*, at R.A. = 17^h45^m39^s.92, decl. = $-29^\circ 00' 28''.1$ (J2000). In addition, we made pointed observations toward three positions in the CND in the $J = 3-2$ transitions of the isotopologues H¹³CN and H¹³CO⁺. The GILDAS⁷ software CLASS90 was used to reduce the calibrated data. We fit and removed a first-order baseline from all of the spectra and boxcar-smoothed the spectra to a resolution of 5.2 km s⁻¹. A correction for a main-beam efficiency of 0.71 for the 2010 data and 0.75 for the 2012 data was also applied. The data were then gridded onto rectangular maps of $\sim 5.8 \times 2.3$ extent (13×7 parsecs at the assumed 8.4 kpc distance of the Galactic center; Ghez et al. 2008; Gillessen et al. 2009), with a pixel size of 11''.8. The spatial resolution of the maps varies slightly for each line, but at these frequencies is $\sim 24''$. The estimated calibration uncertainty of these data is 10%.

2.2. 350 GHz Observations

Using the FLASH receiver (Heyminck et al. 2006), we also simultaneously mapped the $J = 4-3$ lines of HCN and HCO⁺ over a field centered on Sgr A*. We additionally made pointed observations toward three positions in the CND in the $J = 4-3$ transitions of the isotopologues H¹³CN and H¹³CO⁺. All of these data were processed in the same manner as the 260 GHz observations, with the main-beam efficiency at the frequency of this line being 0.67 for the 2010 data and 0.73 for the 2012 data. The data were then gridded onto rectangular maps of $\sim 4.2 \times 2.3$, with a pixel size of 8''.9. The angular resolution of the maps at these frequencies is $\sim 18''$. The estimated calibration uncertainty of these data is 10%.

⁶ This publication is based on data acquired with the Atacama Pathfinder EXperiment. APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

⁷ <http://www.iram.fr/IRAMFR/GILDAS>

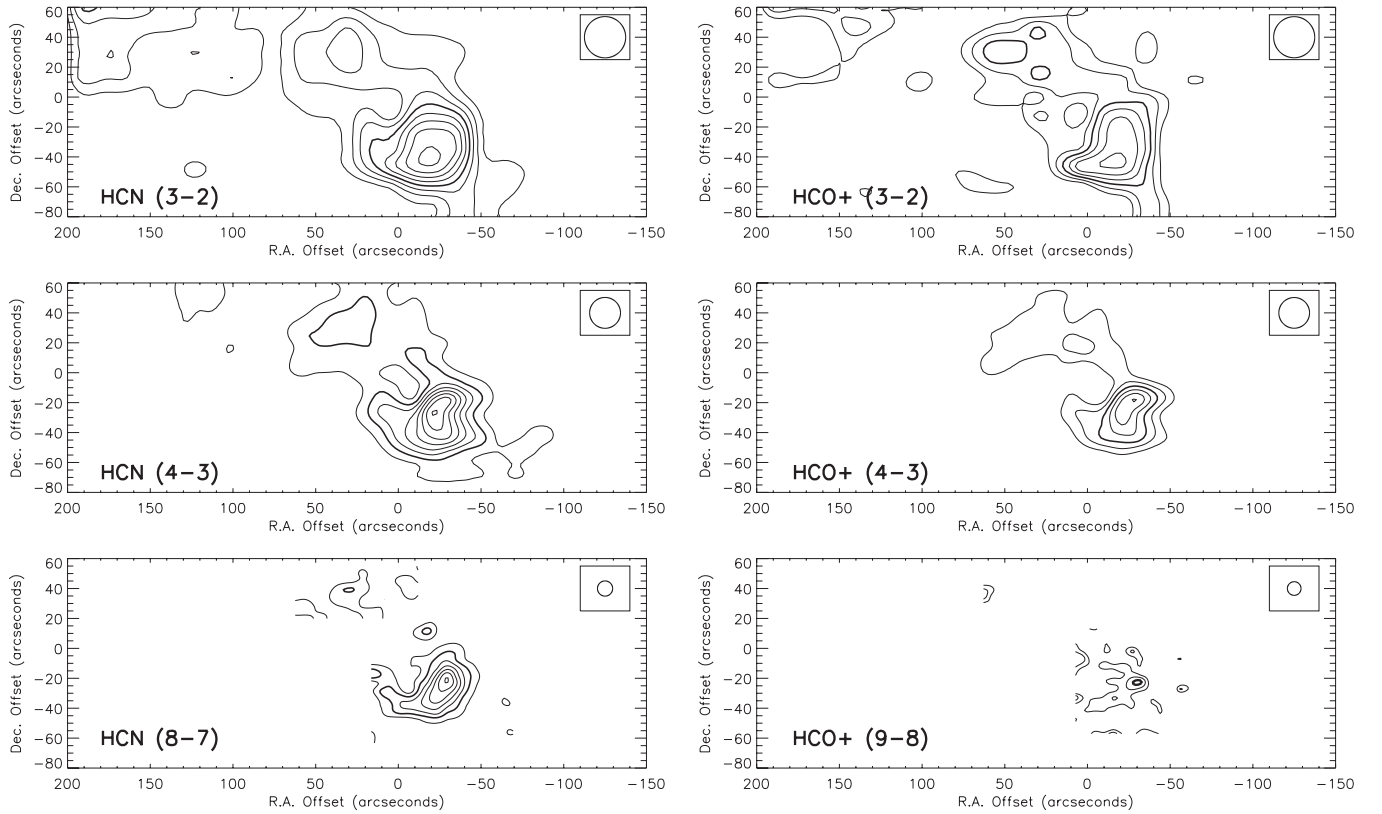


Figure 1. Contour maps of spatially unconvolved main beam brightness temperature integrated from -200 to 200 km s^{-1} for the observed lines of HCN and HCO^+ . Contours are linearly spaced. Top left: HCN 3–2, contours from 750 to 2650 K km s^{-1} , spaced by 268 K km s^{-1} . Top right: HCO^+ 3–2, contours from 575 to 1400 K km s^{-1} , spaced by 166 K km s^{-1} . Middle right: HCN 4–3, contours from 600 to 2620 K km s^{-1} , spaced by 288 K km s^{-1} . Middle left: HCO^+ 4–3, contours from 575 to 1400 K km s^{-1} , spaced by 169 K km s^{-1} . Bottom left: HCN 8–7, contours from 150 to 810 K km s^{-1} , spaced by 110 K km s^{-1} . Bottom right: HCO^+ 9–8, contours from 110 to 250 K km s^{-1} , spaced by 67 K km s^{-1} . The beam sizes are given in Table 1.

Table 2
Clumps

Name	Offset (R.A., decl.)	Velocity	Alternate ID ^{1a}	Alternate ID ^{2b}
N	(+25", +40")	90 to 110 km s^{-1}	D	A
S1	(−20", −30")	−115 to −95 km s^{-1}	O	Q
S2	(−20", −30")	−25 to −5 km s^{-1}	...	...
SW	(−30", −20")	−25 to −5 km s^{-1}	P	N
W	(−20", +0")	35 to 55 km s^{-1}	T	K

Notes.

^a Christopher et al. (2005).

^b Montero-Castaño et al. (2009).

2.3. 700–800 GHz Observations with CHAMP⁺

Using the CHAMP⁺ heterodyne array receiver (Güsten et al. 2008; Kasemann et al. 2006), we simultaneously observed the HCN $J = 8-7$ transition and the HCO^+ $J = 9-8$ (the HCO^+ $J = 8-7$ transition at 713 GHz is not observable from the ground, due to low atmospheric transmission at that frequency). Emission from both of these lines was mapped around two positions in the CND, toward the northern and southern emission peaks. These data were processed in the same manner as the 260 and 350 GHz observations. The HCN 8–7 data were then gridded onto rectangular maps of $\sim 1.5 \times 1.5$ covering the southern emission peak of the CND and rectangular maps of $\sim 1.3 \times 0.7$ covering the northern emission peak, with pixel sizes of $5''$. The angular resolution for HCN 8–7 is $9''$. The HCO^+ 9–8 data were also gridded onto rectangular maps of $\sim 1.2 \times 1.2$ (for the

southern emission peak) and rectangular maps of $\sim 1.0 \times 0.5$ (for the northern emission peak), with pixel sizes of $5''$. A correction for a main-beam efficiency of 0.40 was applied, with the estimated calibration uncertainty for both lines being 20%.

3. RESULTS

Contour maps of HCN and HCO^+ integrated intensity are shown in Figure 1. For all the mapped lines, the strongest emission is seen toward the southern emission peak of the CND, consistent with the HCN 4–3 and CS 7–6 maps of Montero-Castaño et al. (2009). Emission from M-0.02-0.07, the 50 km s^{-1} cloud, can be seen in the northeast corner of the HCN and HCO^+ 3–2 and 4–3 maps. The HCN and HCO^+ maps exhibit largely the same morphology, though the HCO^+ intensity in a given transition is weaker than HCN in the same transition by a factor of $\sim 1.5-2$.

3.1. Pointed Isotopologue Observations

Pointed observations of the ^{13}C isotopologues of HCN were made toward four positions: the southern emission peak (R.A., decl. offset⁸ = $-20''$, $-30''$), the southwest portion of the southern emission peak ($-30''$, $-20''$), the northern emission peak ($+25''$, $+40''$), and the western edge of the CND ($-20''$, $+0''$). Observations of H^{13}CO^+ were made toward three of these positions (north, south, and west). The locations of all four pointings are shown in Figure 2.

⁸ All offset positions are given in arcseconds with respect to the position of Sgr A*.

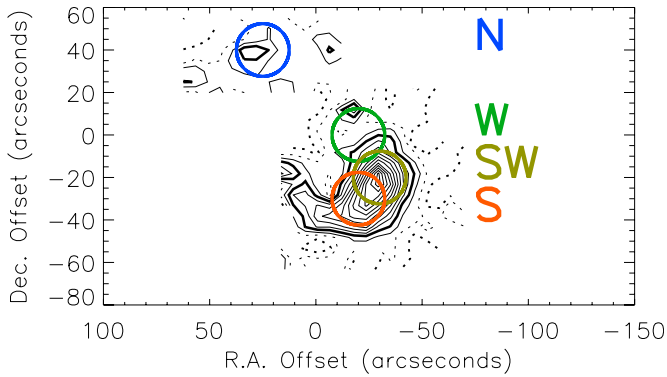


Figure 2. Contour map of unconvolved HCN 8–7 emission in the CND integrated over a velocity range from -200 km s^{-1} to 200 km s^{-1} . Contours are linearly spaced, from 0 to 810 K km s^{-1} . The circles are the size of the H^{13}CN 3–2 beam and show positions where spectra of the ^{13}C isotopologues were obtained.

(A color version of this figure is available in the online journal.)

These pointings cover four (or possibly five) distinct features in position and velocity space (listed in Table 2), the properties of which will be the focus of this article. We identify these features in our HCN 8–7 cubes, as they have the highest spatial resolution. Channel maps of these cubes toward the northern and southern emission peaks of the CND are shown in Figure 3. The locations of the HCN 8–7 peak emission deviate slightly from the positions of the pointed isotopologue observations, but all features fall in the beam of the corresponding isotopologue pointings. Compared to H^{13}CN , the H^{13}CO^+ intensities for the same J -transition are typically a factor of 2.5–5 times weaker. The relative intensities of HCN and HCO^+ are discussed further in Section 7.4.

Feature SW ($v = -25$ to -5 km s^{-1} , offset = $-30''$, $-20''$) is the source of the strongest HCN 8–7 emission. It also is the location of the strongest H^{13}CN 4–3 emission. Emission at the velocities of this feature is seen in both the southwest and south pointings; we refer to emission at these velocities detected in the south pointing as feature S2 ($v = -25$ to -5 km s^{-1} , offset = $-20''$, $-30''$), though it is possible that S2 and SW are parts of the same extended source. The S1 feature ($v = -90$ to -120 km s^{-1} , offset = $-20''$, $-30''$) is slightly fainter than SW or S2 in HCN 8–7, but is the location of the peak HCN 4–3 emission. Feature

N ($v = 90$ to 115 km s^{-1} , offset = $+25''$, $+40''$) is the faintest of these four (or five) features. Feature W ($v = 35$ to 55 km s^{-1} , offset = $-20''$, $+0''$) is the location of very strong HCN 3–2 emission. The velocity range for each of the features is shown shaded in gray in Figures 4 and 5.

Although we observed at the frequencies of both the HC^{15}N 3–2 and 4–3 lines toward the southern pointing (corresponding to features S1 and S2), we do not detect either line. In both cases, the observations are somewhat confused by overlap with a nearby strong line. However, we report upper limits for the peak brightness temperatures of these lines of 0.05 K for HC^{15}N 3–2 and 0.03 K for HC^{15}N 4–3.

3.2. Comparison to Other Studies

Interferometric maps of the CND with resolutions of a few arcseconds in lines of HCN 1–0 and 4–3 (Christopher et al. 2005 and Montero-Castaño et al. 2009, respectively) resolve the CND into numerous clumps. Our spectra (Figures 4 and 5) allow us to associate the features that we can resolve in velocity space using our single-dish data with spatially resolved, interferometrically detected counterparts. The isotopologue spectra are most useful for this purpose, as they trace the highest column-density gas. This gas generally corresponds well to that detected by the interferometric data, which are less sensitive to faint and extended structure.

Our feature N corresponds to clump A from Montero-Castaño et al. (see their Figure 4). Gas from this clump peaks at a central velocity of $+100 \text{ km s}^{-1}$. Our feature S corresponds to their clump Q, which peaks at a central velocity of -110 km s^{-1} and is one of the brightest sources of HCN 4–3 emission detected by Montero-Castaño et al. The observed profiles of HCN 8–7 and the isotopologues (Figure 4) toward our feature W are most similar to the spectrum of clump K from Montero-Castaño et al. Clump H of Montero-Castaño et al. also lies on the edge of the west pointing and can be seen in the HCN 8–7 maps (Figures 1 and 2); however, the line profile of clump H in Montero-Castaño et al. (which is very narrow and peaks at 60 km s^{-1}) does not match our observed isotopologue profiles. This is likely because clump H lies at the very edge of the beam of the west isotopologue pointing, and emission from this source is not well sampled.

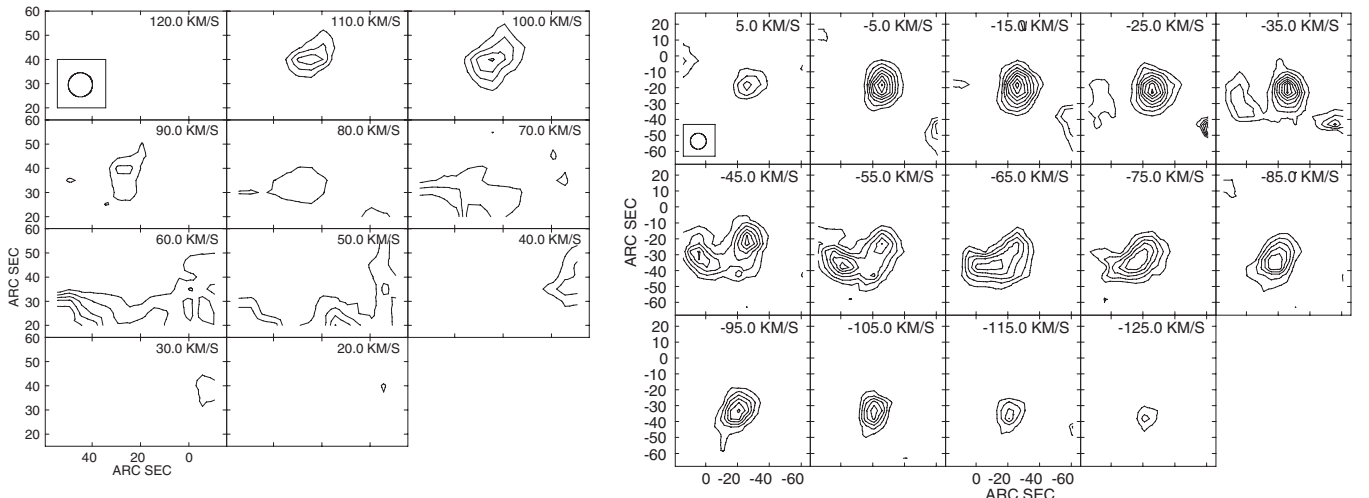


Figure 3. Channel maps of unconvolved HCN 8–7 emission toward the northern (left) and southern (right) emission peaks of the CND. Contours are linearly spaced by 0.21 K , from 0.43 to 2.13 K . Data are binned into 5 km s^{-1} channels, with every other channel pictured here.

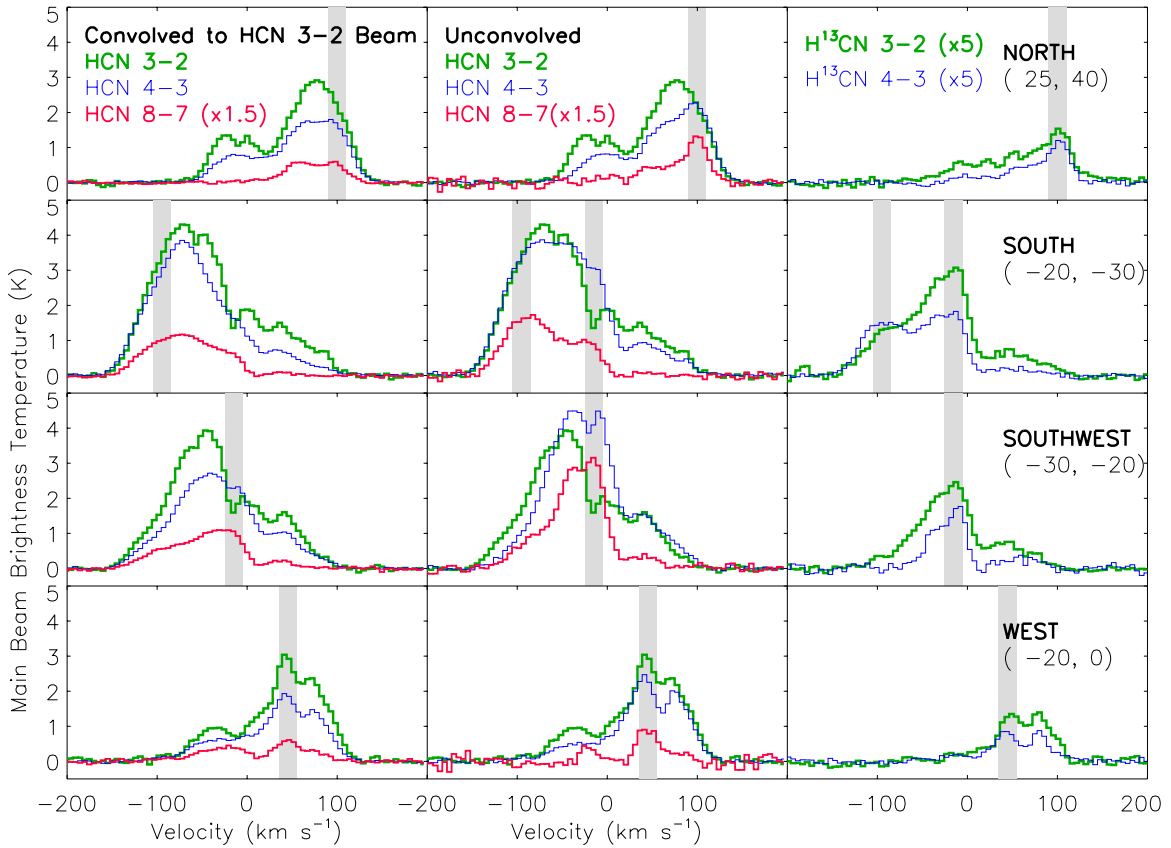


Figure 4. Line profiles of HCN (left, middle) and H^{13}CN (right) toward four positions in the CND, from the top: north, south, southwest, and west. Spectra have been extracted from maps convolved to the beam size of the 3–2 observations ($23''.6$). The gray-shaded regions represent the narrow velocity ranges corresponding just to the peaks of individual features listed in Table 2.

(A color version of this figure is available in the online journal.)

Our feature SW corresponds to clump N from Montero-Castaño et al. Their line profile for clump N is double-peaked, with a dip at a velocity of -20 km s^{-1} that Montero-Castaño et al. ascribe to missing short baselines. We see the same dip in our HCN and HCO^+ 3–2 and 4–3 line profiles (Figures 4 and 5, third row) and, significantly, the line profiles of H^{13}CN and H^{13}CO^+ peak at the central velocity of the dip, indicating the main lines suffer from self-absorption. As the line profile of HCN 8–7 peaks at the same velocity, this self-absorption is likely related to the dense CND gas and not to foreground gas along the line of sight. Absorption at this velocity can also be seen in the CS 7–6 spectrum of Montero-Castaño et al. for this clump, as well as in spectra of CO 6–5 and 7–6 from RT12. Absorption at the same velocity is also seen in our spectra of HCN and HCO^+ in the south pointing, toward feature S2. The position of clump N from Montero-Castaño et al. puts it $\sim 14''$ from the center of the south pointing, placing this clump at the very edge of the beam of our south pointing, consistent with feature S2 and feature SW being the same source, with their emission sampled at slightly different positions.

3.3. Line Intensities

Before measuring the line intensities, we correct the maps for the varying beam sizes by spatially convolving all maps to the resolution of the HCN $J = 3-2$ observations and interpolating so that the pixelization of the maps is identical. All of the data are also convolved in velocity to a common resolution of 5 km s^{-1} . We report line intensities that are integrated over the majority of the line profile, avoiding emission from other contaminating

features such as the nearby “ 50 km s^{-1} ” cloud (M-0.02-0.07) and the southern streamer, an extension of the “ 20 km s^{-1} ” cloud (M-0.13-0.08) identified by Coil & Ho (1999) that may be interacting with the CND. The chosen velocity ranges for each line profile and the resulting integrated intensities are also given in Table 3.

For each of the four pointings, the line intensities are also integrated over velocity ranges (width $\sim 20 \text{ km s}^{-1}$) corresponding to interferometrically detected clumps from Christopher et al. (2005) and Montero-Castaño et al. (2009), given in Table 2. The velocity range of each feature is chosen to correspond to velocities where the clump is isolated and there is minimal confusion from nearby clumps at similar velocities. The resulting integrated intensities toward all of the features we identify are also reported in Table 3.

Figures 4 and 5 show the spectra extracted from the spatially convolved maps (left-hand column) and unconvolved maps (central column) at each position in the CND. The velocity range corresponding to individual features is shaded in gray. The noise in each spectrum is much higher for the west position than for other positions in the HCN 8–7 and HCO^+ 9–8 lines, as this pointing lies near the edge of the map. All of the HCO^+ 9–8 spectra also suffer from increased noise.

3.4. The Detection of the Vibrationally Excited $v_2 = 1f$, $J = 4-3$ Transition of HCN

In addition to the transitions already mentioned, we also detect the $J = 4-3$, $v_2 = 1f$ line of HCN ($\nu = 356.256 \text{ GHz}$) toward the southern emission peak of the CND (in our southwest

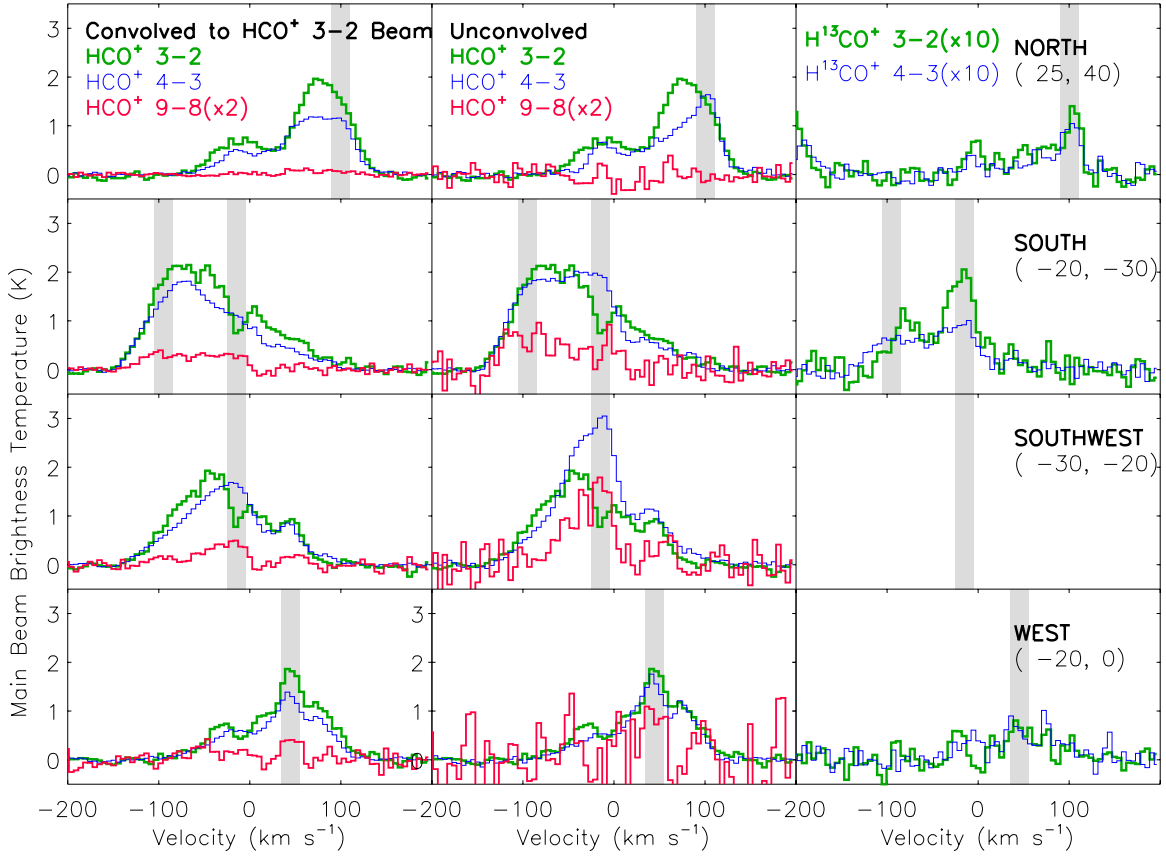


Figure 5. Line profiles of HCO^+ (left, middle) and H^{13}CO^+ (right) toward four positions in CND, from the top: north, south, southwest, and west. Spectra have been extracted from maps convolved to the beam size of the 3–2 observations.

(A color version of this figure is available in the online journal.)

Table 3
Integrated Brightness Temperatures

$\int T_{\text{MB}} dv \text{ (K km s}^{-1}\text{)}$										
HCN			H^{13}CN		HCO^+		H^{13}CO^+			
3–2	4–3	8–7	3–2	4–3	3–2	4–3	9–8	3–2	4–3	
Integrated over the majority of the line profile										
North $v = 20$ to 120 km s^{-1}										
198 ± 20	137 ± 14	27.3 ± 5.5	17.9 ± 1.8	10.8 ± 1.1	127 ± 13	93.2 ± 9.3	2.8 ± 0.6	5.6 ± 0.6	4.1 ± 0.4	
South $v = -120$ to -20 km s^{-1}										
340 ± 34	285 ± 29	62 ± 12	33.3 ± 3.3	28.1 ± 2.8	173 ± 17	140.4 ± 14	14.2 ± 2.9	7.4 ± 0.7	6.1 ± 0.6	
South $v = -50$ to 5 km s^{-1}										
152 ± 15	117 ± 12	25.3 ± 5.1	29.1 ± 2.9	17.1 ± 1.7	81.7 ± 8.2	67.8 ± 6.8	7.7 ± 1.6	7.5 ± 0.8	4.4 ± 0.4	
Southwest $v = -50$ to 5 km s^{-1}										
159 ± 16	137 ± 14	36.0 ± 7.2	22.5 ± 2.3	13.2 ± 1.3	82.1 ± 8.2	86.0 ± 8.6	10.1 ± 2.0	7.5 ± 0.8	4.4 ± 0.4	
West, $v = 0$ to 100 km s^{-1}										
194 ± 19	124 ± 12	20.4 ± 4.1	17.1 ± 1.7	9.8 ± 1.0	111 ± 11	83.7 ± 8.4	5.8 ± 1.2	3.2 ± 0.3	4.4 ± 0.4	
Integrated over the velocity ranges of individual features (reported in Table 2)										
N	49.0 ± 4.9	35.0 ± 3.5	7.5 ± 1.5	5.6 ± 0.6	4.3 ± 0.4	33.8 ± 3.4	23.5 ± 2.4	0.7 ± 0.1	1.7 ± 0.2	1.7 ± 0.2
S1	57.2 ± 5.7	49.9 ± 5.0	11.9 ± 2.4	4.4 ± 0.4	5.8 ± 0.6	29.5 ± 3.0	24.3 ± 2.4	3.4 ± 0.7	0.6 ± 0.1	1.2 ± 0.1
S2	38.0 ± 3.8	35.8 ± 3.6	8.7 ± 1.7	12.2 ± 1.2	7.1 ± 0.7	21.6 ± 2.2	23.4 ± 2.3	3.0 ± 0.6	3.8 ± 0.4	1.9 ± 0.2
SW	62.6 ± 6.3	68.8 ± 6.9	18.3 ± 3.7	13.1 ± 1.3	8.2 ± 0.8					
W	57.9 ± 5.8	37.0 ± 3.7	7.6 ± 1.5	5.2 ± 0.5	3.1 ± 0.3	35.9 ± 3.6	26.1 ± 2.6	4.0 ± 0.9	1.3 ± 0.1	1.3 ± 0.1

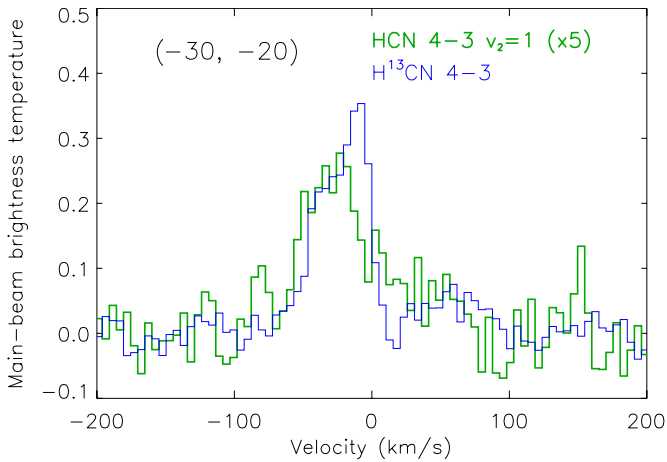


Figure 6. $J = 4-3$, $v_2 = 1$ line of HCN detected toward the southwest emission peak of the CNd. The spectrum of the H^{13}CN $J = 4-3$, $v_2 = 0$ line toward the same position is superposed for comparison.

(A color version of this figure is available in the online journal.)

pointing). This is the first detection of vibrationally excited HCN in the CNd. The $v_2 = 1$ transition corresponds to the bending mode of HCN and is the lowest-energy of the vibrational modes of this molecule. This line is a doublet; however, the $v_2 = 1e$ line at 354.460 GHz is strongly blended with emission from the main HCN 4–3 line and is not detected. The upper level energy of the $v_2 = 1f$ $J = 4-3$ transition of HCN is 1067.1 K. The line spectrum is shown in Figure 6. The peak intensity of the line is ~ 50 mK, and it has an integrated brightness temperature of $2.28 \pm 0.23 \text{ km s}^{-1}$. The peak of this line lies at a velocity of -20 km s^{-1} , associating it with the S2/SW clump.

3.4.1. Properties of the Vibrationally Excited Emission

By comparing the upper level column densities of the HCN $J = 4-3$ $v_2 = 0$ and $v_2 = 1$ lines, we can derive the vibrational excitation temperature for feature S2/SW (technically, just for the SW component of this clump, as we do not have a good observation of the vibrationally excited line from the south pointing).

We assume that the HCN $J = 4-3$ $v_2 = 1$ line is optically thin. As the HCN $J = 4-3$ $v_2 = 0$ line is not optically thin, we determine the integrated intensity of this line by scaling the H^{13}CN 4–3 line intensity (assumed to be optically thin) by the $^{12}\text{C}/^{13}\text{C}$ ratio of 25. The column densities are then determined using

$$N_{\text{HCN}} = \frac{8\pi k\nu^2}{A_{ul}hc^3} \int T_{\text{MB}} dv, \quad (1)$$

where k is Boltzmann’s constant ($1.380658 \times 10^{-16} \text{ erg K}^{-1}$); h is Planck’s constant ($6.626076 \times 10^{-27} \text{ erg s}$); $A_{(4,3,0)} = 2.054 \times 10^{-3} \text{ s}^{-1}$ is the Einstein A -coefficient for the $J = 4-3$; $v_2 = 0$ transition (Dumouchel et al. 2010), taken from the Leiden Atomic and Molecular Database (LAMDA; Schöier et al. 2005); $A_{(4,3,1)} = 1.876 \times 10^{-3} \text{ s}^{-1}$ for the $J = 4-3$; $v_2 = 1$ transition (Harris et al. 2006); ν_0 is the frequency at line center; and $\int T_{\text{MB}} dv$ is the velocity-integrated main beam brightness temperature.

Solving for the vibrational excitation temperature, we find $T_{\text{ex}} = T_{\text{vib}} = 205 \pm 10 \text{ K}$ for feature S2/SW. If, however, the H^{13}CN 4–3 line is not optically thin, the value we derive would be an overestimate of the true T_{vib} .

3.4.2. Collisional versus Radiative Excitation of the $v_2 = 1$ Line

We consider two possibilities for the excitation of this line: either collisional excitation, due to extremely high volume densities or radiative excitation through the rovibrational transitions of HCN at $14 \mu\text{m}$. For collisional excitation to excite this transition requires the density to be at least comparable to the critical density of the $v_2 = 1$ transition, which is $\sim 5 \times 10^{11} \text{ cm}^{-3}$ (Ziurys & Turner 1986). As we will show in Section 5, such a density is more than four orders of magnitude above the highest densities that we constrain in the CNd, making purely collisional excitation an unlikely source of excitation. More likely is that HCN is radiatively excited, either externally (via a sufficiently strong $14 \mu\text{m}$ background radiation field), or internally, via sufficiently hot dust mixed with the gas.

Radiative excitation of HCN will not just populate the $v_2 = 1$ states, but will also affect the populations of the rotationally excited levels in the ground vibrational state. In the presence of a strong $14 \mu\text{m}$ radiation field, molecules in a given rotational state have a statistical likelihood to be vibrationally excited and subsequently decay into a higher rotational level of the ground vibrational state (Morris 1975; Carroll & Goldsmith 1981). This pumping shifts the populations of the rotationally excited levels to the higher J levels, mimicking the effect of a higher gas density. This phenomenon was first observed for HCN in the ISM by Ziurys & Turner (1986) and more recently was suggested to be an important source of excitation for HCN in NGC 4418 (Sakamoto et al. 2010), based on the detection of the $J = 4-3$, $v_2 = 1$ line, as well as on absorption in the $14 \mu\text{m}$ band. The $J = 4-3$, $v_2 = 1$ line of HCN has also been detected in the $z = 0.043$ AGN-hosting galaxy IRAS 205514250 (Imanishi & Nakanishi 2013). However, it is unclear to what extent radiative pumping may be affecting the populations of the $v_2 = 0$ states in this source. Radiative pumping has also been suggested to be important for other molecules, such as CS in hot protostellar cores (Hauschildt et al. 1993, 1995), HNC in luminous infrared galaxies (Aalto et al. 2007), and, most recently, HF, HCl, SiO, and CO in the presence of a sufficiently strong near-IR, optical, or UV radiation field (Godard & Cernicharo 2013).

Given the vibrational temperature we infer from our HCN observations, we can determine which levels of the ground vibrational state would be affected by radiative pumping. The criterion for effective radiative pumping is given by Equation (2) of Sakamoto et al. (2010), reproduced here:

$$e^{-T_0/T_{\text{vib}}} A_{\text{vib}} \geq A_{\text{rot},J}, \quad (2)$$

where T_0 is the level energy of the $J = 4$, $v_2 = 1$ state, T_{vib} is our computed vibrational excitation temperature, A_{vib} is the Einstein A for the rovibrational transition that links the $J = 4$ $v_2 = 0$ and $v_2 = 1$ states, equal to $\sim 2.3 \text{ s}^{-1}$ (Harris et al. 2006), and $A_{\text{rot},J}$ is the Einstein A -coefficient for $J = 4-3$, $v_2 = 0$.

Given our observed T_{vib} , Equation (2) shows that pumping of the $v_2 = 0$ rotational transitions of HCN via the rovibrational transitions should be efficient up to $J \sim 12$ for feature S2/SW, indicating the level populations of all observed lines in this feature (both $v_2 = 0$ and 1) are likely affected by radiative pumping.

4. EXCITATION ANALYSIS

For the remainder of this article we focus on excitation analyses of the lines of HCN and HCO^+ in the CNd, both for the majority of the line profile as well as for selected velocity intervals corresponding to previously identified clumps

in the CND, listed in Table 2. Again, we separately report both emission from feature S2 observed at $(-20'', -30'')$ and feature SW observed at $(-30'', -20'')$, although these are likely part of the same structure. The resulting velocity-integrated main beam brightness temperatures for five transitions of both HCN and HCO^+ for each feature (Table 3) are sufficient to constrain a fit to single gas component characterized by four parameters: the temperature, H_2 density, molecular column density, and beam filling factor, with a fifth parameter, $[\text{C}^{12}]/[\text{C}^{13}]$, set to a fixed value of 25 (Wilson & Rood 1994; Wilson 1999; Riquelme et al. 2010).

To fully model the line radiative transfer of HCN and HCO^+ , we also consider contributions to the radiation field due to the local and global radiation background. In addition to the cosmic microwave background, emission from warm dust in the CND gives rise to a continuum background at the frequencies of the rotational lines of HCN and HCO^+ . Both HCN and HCO^+ also have rovibrational transitions in the near and mid-infrared (the lowest energy modes for both are the bending modes, occurring at 14 and 12 μm , respectively). Our initial analysis reveals that radiative excitation through these rovibrational transitions is the most likely source of excitation of the detected $v_2 = 1 f J = 4-3$ line of HCN (see Section 3.4), making it important to include an accurate description of the radiation field in the CND.

We first use the statistical equilibrium radiative transfer code RADEX (van der Tak et al. 2007), a zero-dimensional non-LTE code that employs the escape probability formalism to model the observed line intensities as a function of the physical conditions in the source. The escape probability method simplifies the radiative transfer calculation by assuming that photons either completely escape the source (the likelihood of this is dependent on the local opacity, which is itself determined by the source geometry) or are immediately absorbed at the same location where they were emitted. A further simplification employed in the above method is the assumption of uniform physical conditions throughout the source.

In addition, in Section 6 we also compare the RADEX results for HCN to those from a more sophisticated radiative transfer code (RATRAM; Hogerheijde & van der Tak 2000) that takes into account the internal radiation field due to embedded dust.

4.1. RADEX

4.1.1. Input Parameters

The radiative and collisional coefficients were obtained from LAMDA for the rotational lines of both HCN and HCO^+ (Dumouchel et al. 2010; Flower 1999). We also used the radiative excitation rates of the vibrationally excited lines of HCN from Thorwirth et al. (2003) to model the observed $v_2 = 1$ line. As the collisional coefficients of the vibrationally excited transitions are unknown, we do not take into account any collisional excitation of the vibrationally excited states, consistent with our previous conclusion that collisions do not contribute to the excitation of this line. We assume in our analysis of the collisional excitation of the rotationally excited levels that H_2 is the main collisional partner for HCN and HCO^+ .

For fits to the intensities of individual features, we assume a velocity FWHM of 20 km s^{-1} for the determination of the escape probability, consistent with values of 15–50 km s^{-1} measured by interferometric studies for the corresponding clumps (Christopher et al. 2005; Montero-Castaño et al. 2009). For fits to the majority of the profile, we use a larger FWHM

of 50–100 km s^{-1} . The assumed geometry for determining the escape probability is that of an expanding sphere (equivalent to the large velocity gradient or LVG approximation). Changing the assumed geometry to that of a uniform sphere, slab, or turbulent medium does not significantly alter the results presented here.

For the radiation field at the wavelength of the rovibrational transitions of HCN and HCO^+ , we adopt the midinfrared spectrum as measured by *Infrared Space Observatory* (ISO). Only the observations centered on the nucleus Sgr A* have been published (Lutz et al. 1996). However, an additional spectrum of the southern emission peak of the CND is available from the NASA-IRAC Infrared Science Archive⁹ toward an offset of $(-1''.3, -37''.6)$ from the position of Sgr A*, which we use for this analysis. The calibrated spectrum is not corrected for the variable extinction in the region and additionally represents the total flux of radiation from a fairly large aperture ($14'' \times 20''$). The local intensity of the ambient radiation field might then differ by a factor of two or more from the measured value.

4.1.2. Grids

We use RADEX to construct grids of predicted line intensities over the given range of input temperature, density, and column density. For each set of temperature, density, and column density values, RADEX calculates main line intensities and opacities, from which the isotopologue intensities can also be derived using our assumed $[\text{C}^{12}]/[\text{C}^{13}]$ ratio. We fit separately for each molecule (HCN and HCO^+). The line intensities generated by RADEX for all five lines of each species can then be compared to the measured line intensities by introducing an additional parameter: a beam filling factor for the emitting region. Given the measured uncertainties on the line intensities, one can then determine the (reduced) χ^2 parameter for the fit of the measured to the modeled line intensities for the entire range of temperature, density, and column density considered.

4.1.3. Fitting Constraints

We impose several constraints on our model to eliminate unphysical solutions. First, as ammonia temperature measurements indicate that gas temperatures in the CND are at least as hot as 50 K (McGary et al. 2001), we exclude lower temperatures from our input parameter grid. We also find that where column densities are in excess of 10^{16} cm^{-2} and densities are between 10^5 and 10^6 cm^{-3} the HCN 1–0 line undergoes strong maser action. HCN 1–0 masering is not observed (Christopher et al. 2005) and so this region of parameter space is also excluded.

4.1.4. Models

We fit the line intensities integrated over the majority of the line profile at each position (north, south, southwest, and west) with a single temperature and density model. We consider temperatures in the range 50 to 600 K, densities in the range of 10^4 to 10^8 cm^{-3} , and column densities in the range of $10^{14.5}$ to $10^{16.5} \text{ cm}^{-2}$ for HCN and 10^{13} to 10^{15} cm^{-2} for HCO^+ . In addition, we perform fits over the same range of physical parameters to line intensities from each of the identified features (N, S2, S2/SW, and W) integrated over the velocity ranges given in Table 3.

⁹ <http://irsa.ipac.caltech.edu/>

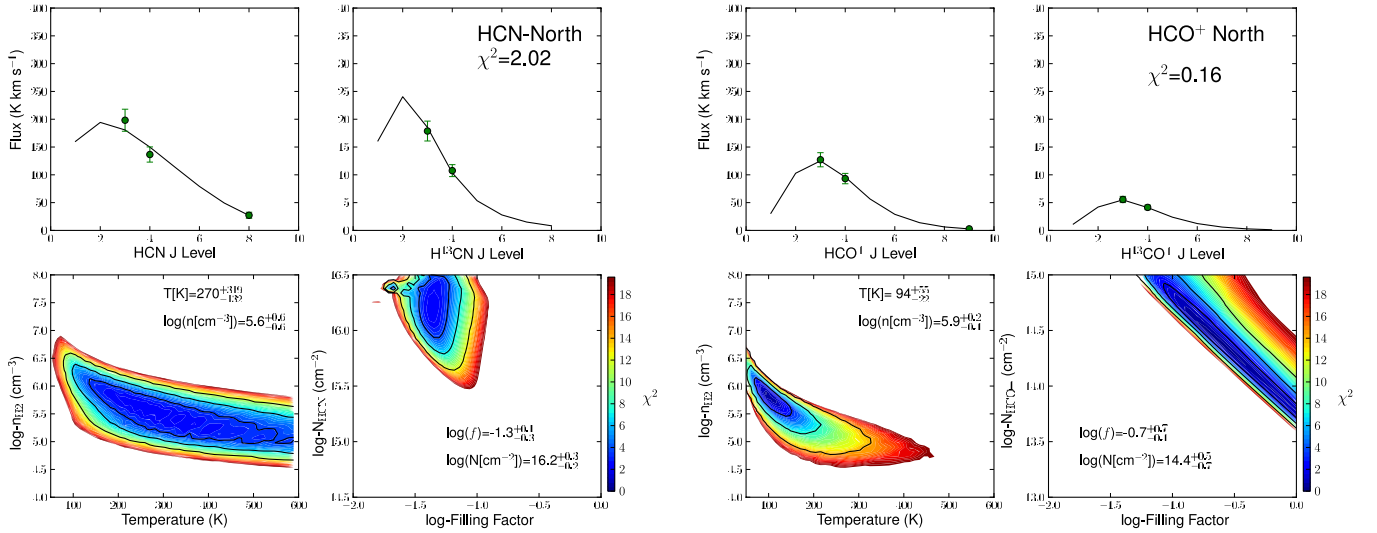


Figure 7. χ^2 fits to a one-component model of HCN and HCO^+ excitation for line intensities toward the north position in the CNB (integrated over the majority of the line profile). Top row: Boltzmann plots for (left to right) HCN, H^{13}CN , HCO^+ , and H^{13}CO^+ , showing the best-fit solution. Bottom row: two-dimensional likelihood distributions, with contours of the 1σ , 2σ , and 3σ deviations from the most likely value over the full grid of temperatures and densities considered, as well as filling factor and column density.

(A color version of this figure is available in the online journal.)

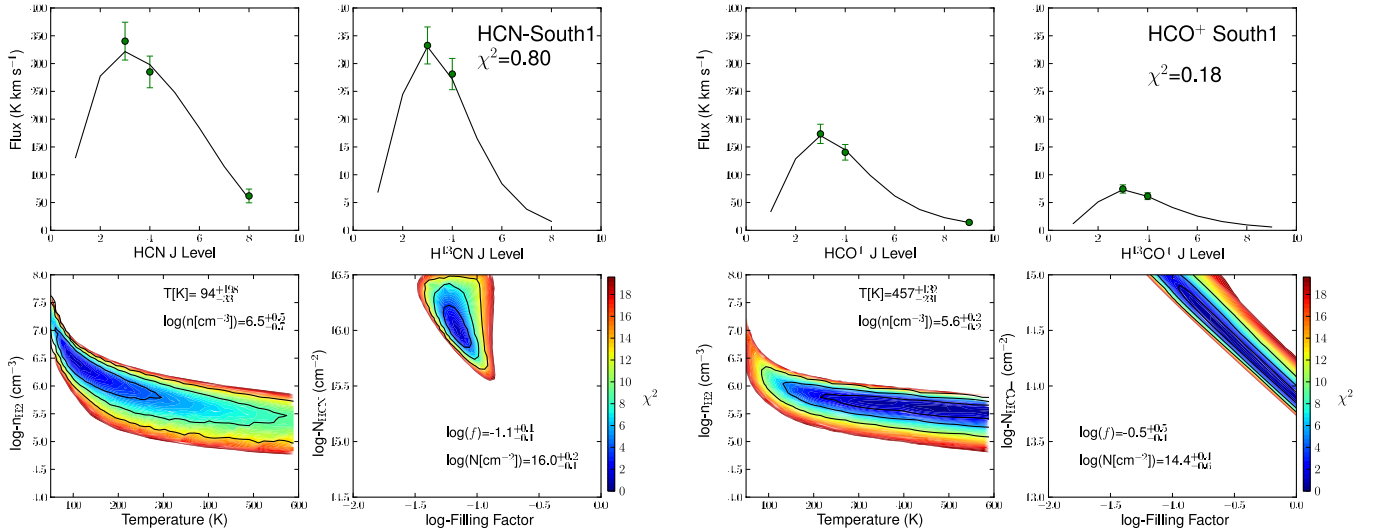


Figure 8. χ^2 fits to a one-component model of HCN and HCO^+ excitation for line intensities toward the south-1 position in the CNB (integrated over the majority of the line profile). Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

5. RESULTS OF THE RADEX EXCITATION ANALYSES

5.1. Fits to the Majority of the Line Profile

For the observed CNB positions, we find acceptable fits ($\chi^2 < 5$, where the χ^2 values presented here are equivalent to the reduced χ^2 values, as our fits have a single degree of freedom) to line intensities integrated over the majority of the line profiles for all positions except HCO^+ intensities toward the south-2, southwest and west positions. We show plots of the χ^2 distribution for the fits to HCN and HCO^+ emission over the majority of the line profile at all positions in Figures 7, 8, 9, and 10. The resulting best-fit density, temperature, column density, and filling factor for each position as well as 1σ errors are reported in Table 4. The volume density for typical dense gas in the CNB is relatively well constrained by these fits to be between 10^5 and 10^7 cm^{-3} . In contrast, the temperature is more poorly constrained and varies from 60 K to 600 K, which

is the upper limit of the range of temperatures probed by our models. For several cases, including HCN fits to the north and west pointings and HCO^+ fits to the south-1 pointing, the upper bound on the temperature is unconstrained by these fits.

The volume densities derived from our HCO^+ and HCN observations are comparable for the north position, but the densities derived for the south position are not consistent within the uncertainties; the best-fit density derived for this position from HCN is an order of magnitude higher than that derived using HCO^+ . In contrast, the derived temperatures are consistent for the south position, but the temperature derived from HCO^+ is significantly cooler for the north position than that derived using HCN.

The derived filling factors for both positions also differ significantly: the best-fit filling factors for HCN emission toward all positions are less than 0.08, while they are substantially greater for HCO^+ (Table 4). This suggests either that the

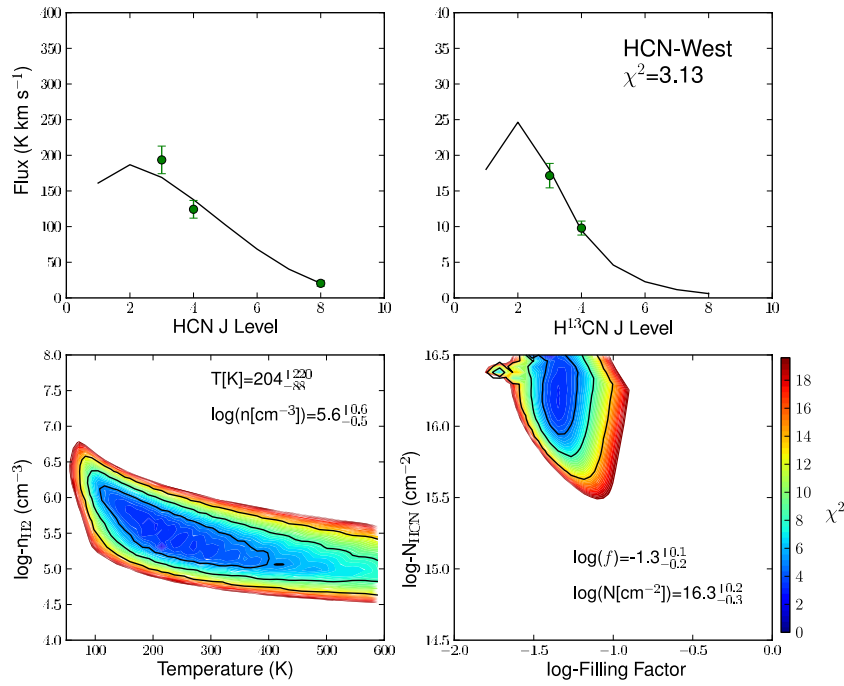


Figure 9. χ^2 fits to a one-component model of HCN excitation for line intensities toward the west position in the CND (integrated over the majority of the line profile). Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

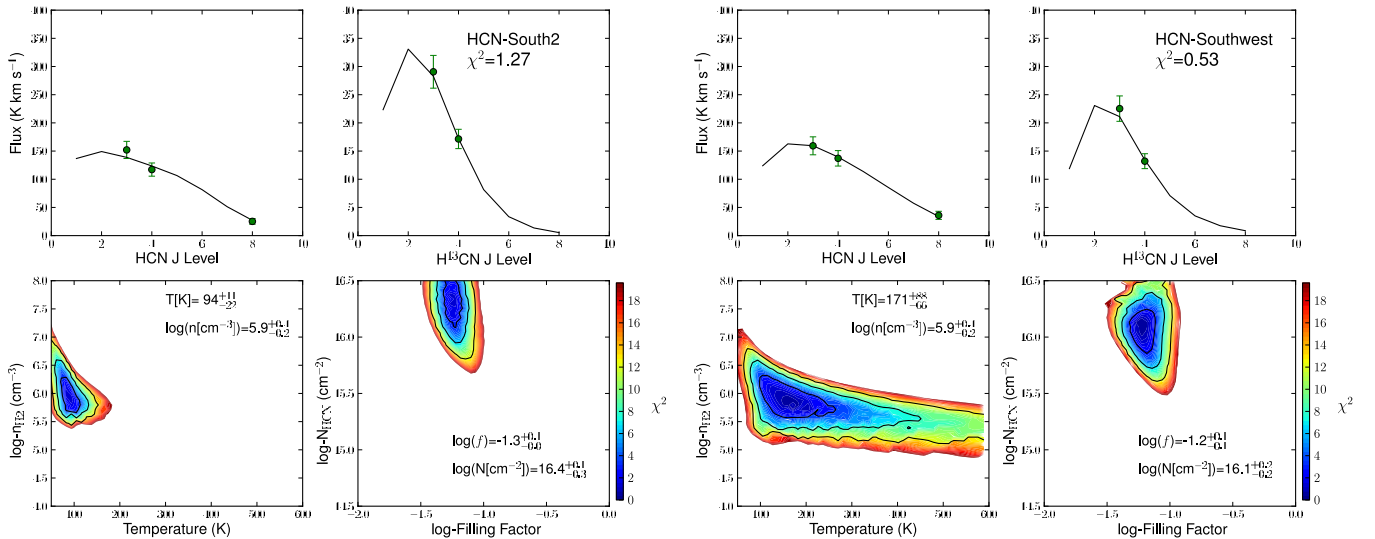


Figure 10. χ^2 fits to a one-component model of HCN excitation for line intensities toward the south-2 and southwest positions in the CND (integrated over the majority of the line profile). Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

HCN emission in the CND is significantly more clumpy than HCO^+ emission or (as interferometric maps show that the two species exhibit similar small-scale structure; Christopher et al. 2005) that more of the HCO^+ emission detected in single-dish observations originates in an extended gas component. If the extended component has different excitation conditions than the gas that is predominantly traced by HCN, this could also explain the fact that we are unable to fit the HCO^+ intensities well with a single excitation component for three positions in the CND (south-2, southwest, and west).

The best-fit HCN column densities are somewhat higher than mean HCN column densities of $\sim 10^{15} \text{ cm}^{-2}$ derived by Christopher et al. (2005) from observations of HCN 1–0 in individual clumps in the CND. This could either be the result of

missing flux in the interferometric observations of Christopher et al., or it could indicate that column densities derived from the HCN 1–0 line are underestimated if, for example, the line is more optically thick than assumed. However, our best-fit models predict that the HCN 1–0 line should be generally be optically thin and/or weakly inverted ($\tau < 1$), consistent with that recently found by Smith & Wardle (2013). This is the case for all features except possibly S2 (for which our best-fit model predicts $\tau \sim 4$), making it more likely that the difference in column densities is due to extended emission that is missed by previous interferometric observations.

The HCO^+ 3–2 and 4–3 emission toward the north and south pointings is also found to be optically thin ($\tau < 1$), while the HCN 3–2 and 4–3 emission is quite optically thick ($\tau > 2$)

Table 4
Results of RADEX Excitation Analysis

	$\min. \chi^2$	T_{kin} (K)	$\log [n_{\text{H}_2}]$ (cm^{-3})	$\log [N_{\text{Mol}}]$ (cm^{-2})	f	Radius (pc)	Mass ($M_{\odot}$)	τ_{3-2}	τ_{4-3}
HCN fits (majority of the line profile)									
North ($v = 20, 120$)	2.0	270^{+319}_{-132}	$5.6^{+0.6}_{-0.6}$	$16.2^{+0.3}_{-0.2}$	$0.04^{+0.01}_{-0.02}$			$5.0^{+5.7}_{-2.3}$	$7.1^{+7.4}_{-3.2}$
South-1 ($v = -120, -20$)	0.8	94^{+198}_{-33}	$6.5^{+0.5}_{-0.7}$	$16.0^{+0.2}_{-0.1}$	$0.07^{+0.01}_{-0.02}$			$2.1^{+1.9}_{-0.4}$	$3.1^{+2.8}_{-0.6}$
South-2 ($v = -50, 5$)	1.3	94^{+11}_{-22}	$5.9^{+0.4}_{-0.2}$	$16.4^{+0.1}_{-0.3}$	$0.05^{+0.01}_{-0.01}$			$10.3^{+5.2}_{-5.0}$	$15.0^{+6.3}_{-7.3}$
Southwest ($v = -50, 5$)	0.5	171^{+88}_{-66}	$5.9^{+0.4}_{-0.2}$	$16.1^{+0.2}_{-0.2}$	$0.06^{+0.01}_{-0.01}$			$4.6^{+4.0}_{-1.7}$	$7.0^{+5.7}_{-2.4}$
West ($v = 0, 100$)	3.1	204^{+220}_{-88}	$5.6^{+0.6}_{-0.5}$	$16.3^{+0.2}_{-0.3}$	$0.04^{+0.01}_{-0.01}$			$9.8^{+1.7}_{-7.2}$	$13.8^{+1.5}_{-10.0}$
HCN fits (narrow features)									
N ($v = 90, 110$)	3.0	94^{+77}_{-22}	$6.3^{+0.4}_{-0.8}$	$15.5^{+0.9}_{-0.2}$	$0.04^{+0.01}_{-0.02}$	$0.10^{+0.01}_{-0.03}$	480^{+1100}_{-450}	$3.8^{+3.3}_{-1.4}$	$5.6^{+17.3}_{-2.0}$
S1 ($v = -115, -95$)	1.7	61^{+77}_{-11}	$7.2^{+0.4}_{-0.7}$	$15.1^{+0.1}_{-0.1}$	$0.09^{+0.02}_{-0.02}$	$0.15^{+0.01}_{-0.02}$	13000^{+34000}_{-11000}	$1.5^{+0.3}_{-0.3}$	$2.1^{+0.7}_{-0.2}$
S2 ($v = -25, -5$)	0.8	72^{+11}_{-11}	$5.7^{+0.6}_{-0.2}$	$16.4^{+0.1}_{-0.4}$	$0.04^{+0.01}_{-0.01}$	$0.10^{+0.01}_{-0.02}$	120^{+420}_{-40}	$26.4^{+11.1}_{-17.2}$	$37.1^{+14.2}_{-23.8}$
SW ($v = -25, -5$)	3.1	116^{+11}_{-33}	$6.0^{+0.4}_{-0.5}$	$15.9^{+0.5}_{-0.2}$	$0.04^{+0.01}_{-0.01}$	$0.10^{+0.01}_{-0.02}$	240^{+560}_{-160}	$6.8^{+25.4}_{-2.6}$	$10.4^{+21.2}_{-4.0}$
W ($v = 35, 55$)	3.7	237^{+286}_{-110}	$5.6^{+0.5}_{-0.6}$	$15.5^{+0.3}_{-0.2}$	$0.06^{+0.02}_{-0.02}$	$0.12^{+0.02}_{-0.02}$	170^{+660}_{-110}	$4.8^{+5.9}_{-2.0}$	$6.9^{+10.9}_{-2.7}$
HCO ⁺ fits (majority of the line profile)									
North ($v = 20, 120$)	0.2	94^{+55}_{-22}	$5.9^{+0.2}_{-0.4}$	$14.4^{+0.5}_{-0.7}$	$0.22^{+0.78}_{-0.14}$			$0.3^{+0.7}_{-0.2}$	$0.4^{+0.7}_{-0.3}$
South-1 ($v = -120, -20$)	0.2	457^{+132}_{-231} ^a	$5.6^{+0.2}_{-0.2}$	$14.4^{+0.4}_{-0.6}$	$0.29^{+0.71}_{-0.18}$			$0.2^{+0.4}_{-0.2}$	$0.3^{+0.4}_{-0.2}$
South-2 ($v = -50, 5$)	9.7								
Southwest ($v = -50, 5$)	7.3								
West ($v = 0, 100$)	7.4								
HCO ⁺ fits (narrow features)									
N ($v = 90, 110$)	4.5	61^{+22}_{-11}	$6.2^{+0.2}_{-0.3}$	$14.5^{+0.2}_{-0.3}$	$0.07^{+0.06}_{-0.02}$	$0.13^{+0.06}_{-0.02}$	840^{+3300}_{-590}	$0.9^{+0.3}_{-0.2}$	$1.3^{+0.3}_{-0.3}$
S1 ($v = -115, -95$)	3.5	336^{+253}_{-165} ^a	$5.9^{+0.2}_{-0.2}$	$13.1^{+0.7}_{-0.0}$	$1.00^{+0.00}_{-0.80}$			$0.0^{+0.0}_{-0.0}$	$0.1^{+0.0}_{-0.0}$
S2 ($v = -25, -5$)	19.8								
SW ($v = -25, -5$)	23.5								
W ($v = 35, 55$)	4.0	589^{+0}_{-352}	$5.6^{+0.2}_{-0.1}$	$13.3^{+0.9}_{-0.2}$	$0.69^{+0.31}_{-0.59}$			$0.1^{+0.3}_{-0.0}$	$0.1^{+0.4}_{-0.0}$

Note. ^a Upper bound on the temperature is unconstrained.

everywhere, with HCN 8–7 predicted to be optically thick as well ($\tau > 1$), although we do not observe this transition in H¹³CN. The distributions of opacities are shown in Figures 11 and 12. Opacities are not determined for HCO⁺ toward the south-2, southwest, and west pointings, as acceptable model fits were not found for the line intensities toward those positions. However, the HCO⁺ emission is likely optically thick toward the south-2 and southwest positions, as the ratios of H¹²CO⁺ lines to their ¹³C isotopologues are between 10 and 20, significantly less than the assumed [¹²C]/[¹³C] isotope ratio of 25. It is not possible, however, to accurately determine the opacity just from the ratio of these line intensities and the intrinsic [¹²C]/[¹³C] isotope ratio, as this also requires knowledge of the excitation temperature for each level. The excitation temperatures for the ¹²C and ¹³C isotopologues cannot be assumed to be the same; models show that the excitation temperature for the ¹³C isotopologue for typical CND conditions can be up to a factor of two lower than for the main line.

5.2. Fits to Individual Features

In addition to fitting for the brightness temperatures integrated over the entire line profile, we also fit to the brightness temperatures integrated over limited ($\Delta v = 20 \text{ km s}^{-1}$) velocity ranges corresponding to individual clumps identified in interferometric studies of the CND. For the five features we analyze, we find reasonable fits to observations of all features except for the HCO⁺ observations of the S2/SW clump. Plots of the χ^2 distribution

for all features are shown in Figures 13, 14, 15, and 16, and the fit parameters are reported in Table 4. Within our uncertainties, the volume densities of individual features range from $n = 10^{5.0}$ to $10^{7.6} \text{ cm}^{-3}$ (for feature S1). The densities and temperatures derived from fits to HCN and HCO⁺ are consistent except in the case of feature S1, where the HCN-derived density is higher by an order of magnitude. In this case, the HCN fits favor a cooler temperature ($\sim 100 \text{ K}$) than fits to HCO⁺, which favor a temperature $> 170 \text{ K}$. For HCO⁺ fits to S1, and fits for both molecules to feature W, the constraints from the observed lines are insufficient to constrain the temperatures, and acceptable fits are found for temperatures up to 600 K, the largest value considered in our grids of parameter values. In general, however, fits to the limited velocity ranges of individual features yield lower temperatures and higher densities than fits to the entire profile.

Similar to the results from fits to the majority of the line profile, the HCO⁺ filling factors from fits to individual features are uniformly larger than the HCN filling factors. Possibly related to this, but more likely a factor of the lower relative HCO⁺ abundance in the CND, the emission from HCO⁺ features is generally optically thin, with only emission from feature N being optically thick. In contrast HCN emission is extremely optically thick, with opacities ranging from 1.5 to potentially higher than 30 (for feature S2, if $T < 100 \text{ K}$ and $n < 10^6 \text{ cm}^{-3}$). The distribution of opacities derived from our fits to individual features are shown in Figures 17 and 12. For features N, S1, and W, the HCN optical depths are lower than those derived from fits to the majority of the line profile.

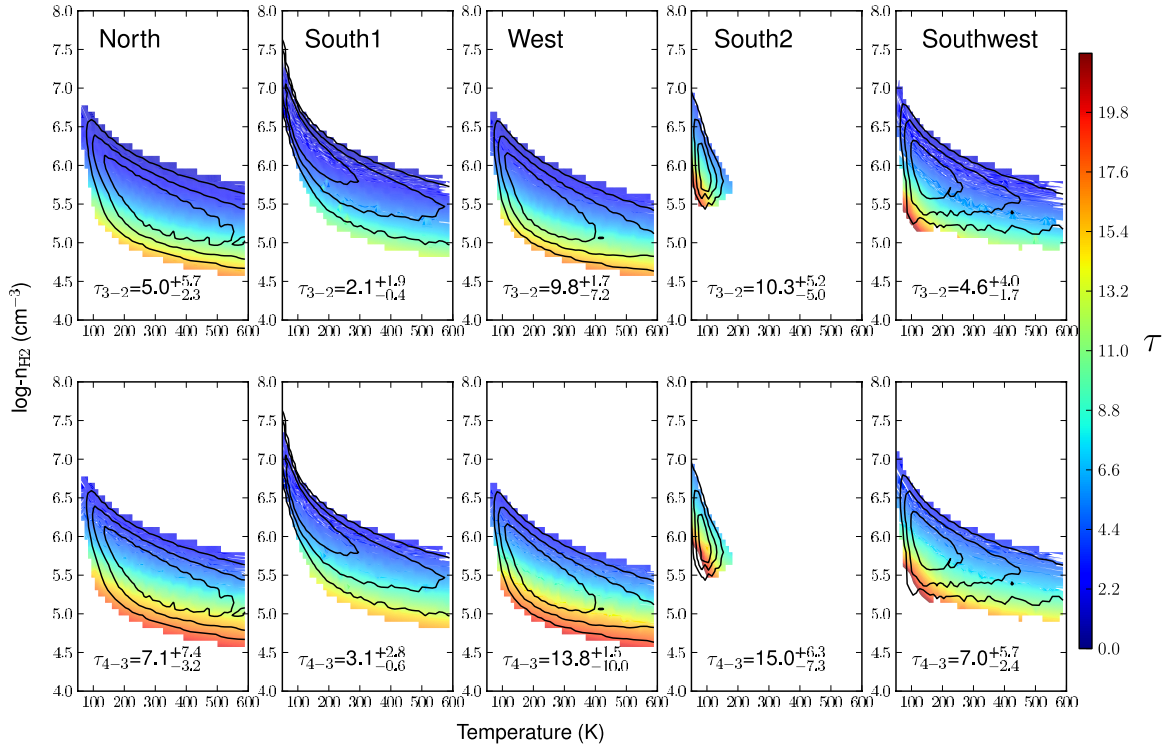


Figure 11. HCN line opacities for the 3–2 (top) and 4–3 (bottom) transitions, derived from fits to line intensities integrated over the majority of the line profile. Contours show the 1σ , 2σ , and 3σ deviations from the most likely temperature and density over the full grid of physical conditions that were considered.

(A color version of this figure is available in the online journal.)

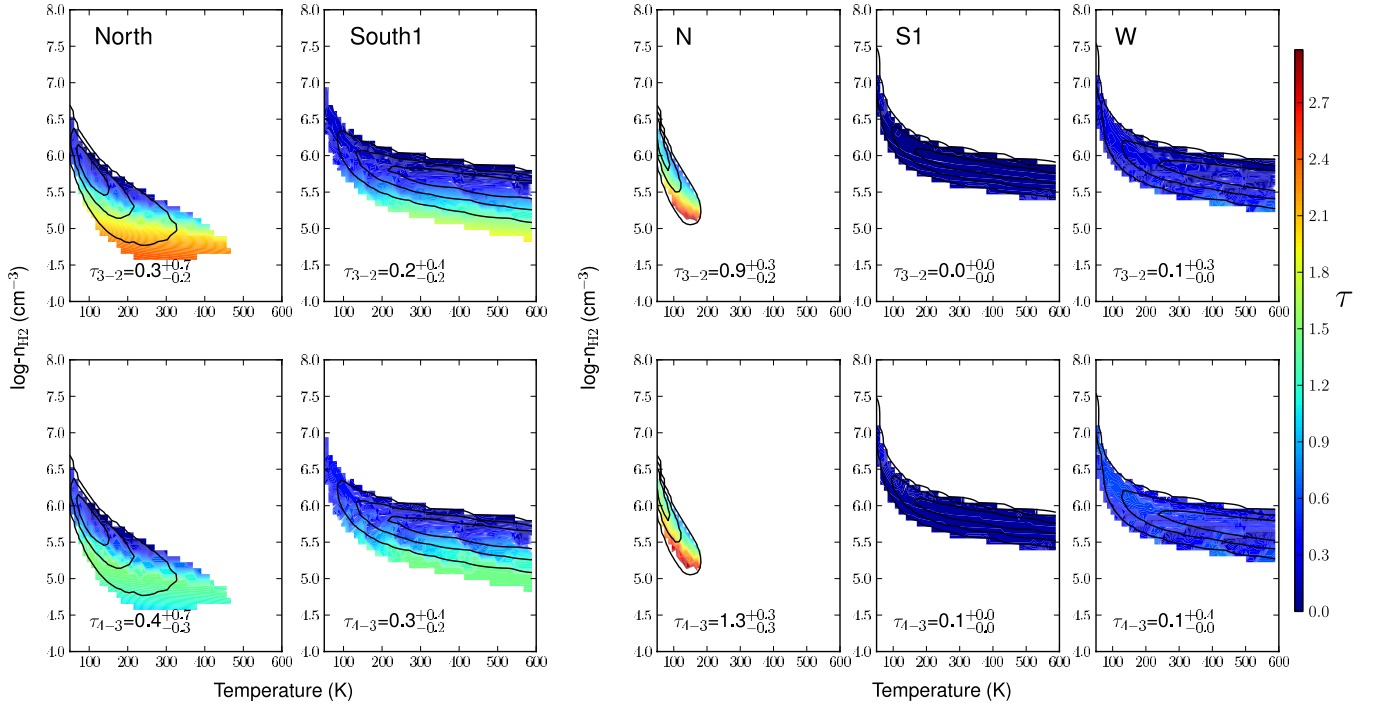


Figure 12. HCO⁺ line opacities for the 3–2 (top) and 4–3 (bottom) transitions, derived from fits to line intensities integrated over the majority of the line profile (left) and fits to individual features (right). Contours show the 1σ , 2σ , and 3σ deviations from the most likely temperature and density over the full grid of physical conditions that were considered.

(A color version of this figure is available in the online journal.)

5.2.1. Feature Properties

If the source being observed is smaller than the telescope beam, its brightness temperature will be diluted. Assuming the features we observe are circularly symmetric Gaussian clumps at the center of the circular beam, the filling factor that describes

this dilution is given by the expression:

$$f = \frac{\theta_{\text{clump}}^2}{\theta_{\text{MB}}^2 + \theta_{\text{clump}}^2}, \quad (3)$$

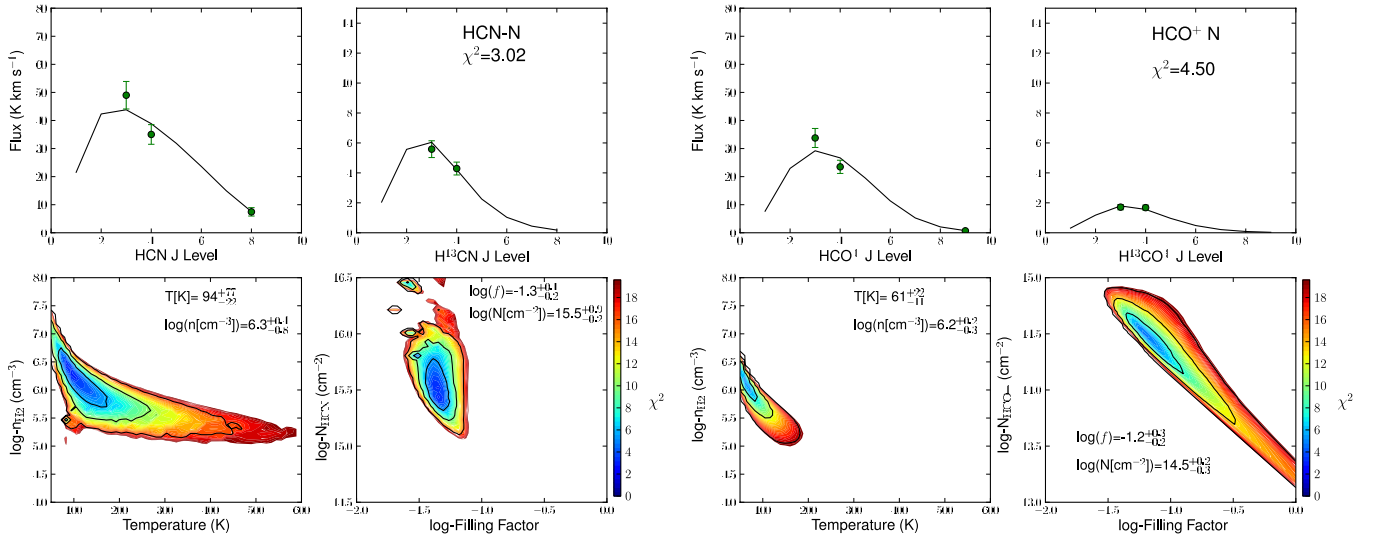


Figure 13. χ^2 fits to a one-component model of HCN and HCO⁺ excitation for feature N in the CND. Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

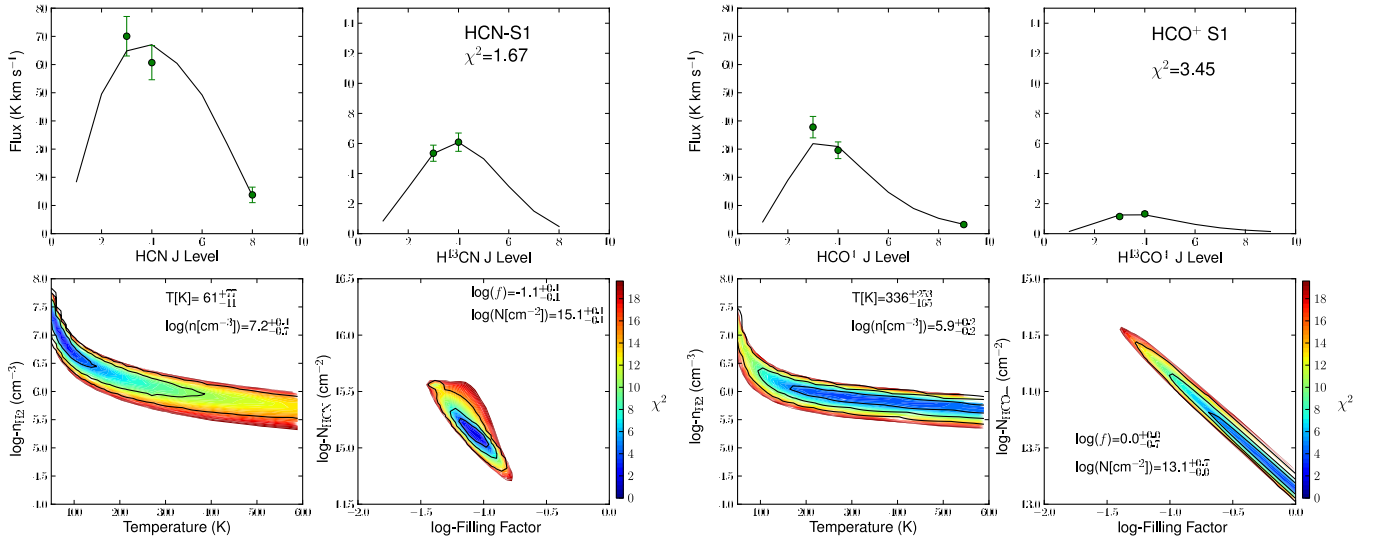


Figure 14. χ^2 fits to a one-component model of HCN and HCO⁺ excitation toward feature S1 in the CND. Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

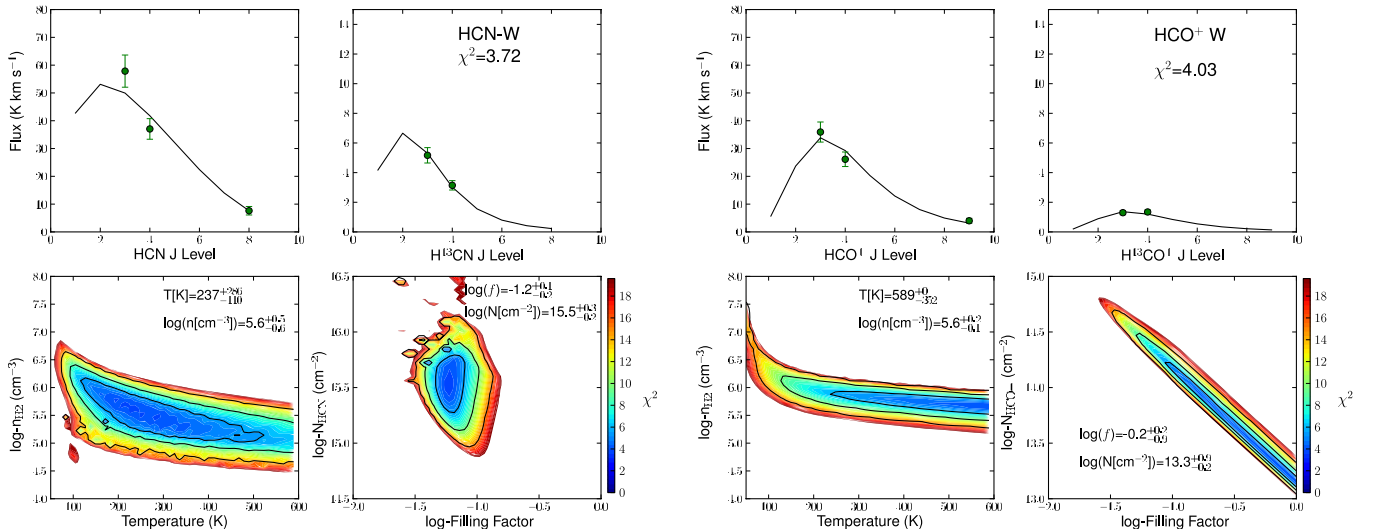


Figure 15. χ^2 fits to a one-component model of HCN and HCO⁺ excitation toward feature W in the CND. Rows are the same as for Figure 7.

(A color version of this figure is available in the online journal.)

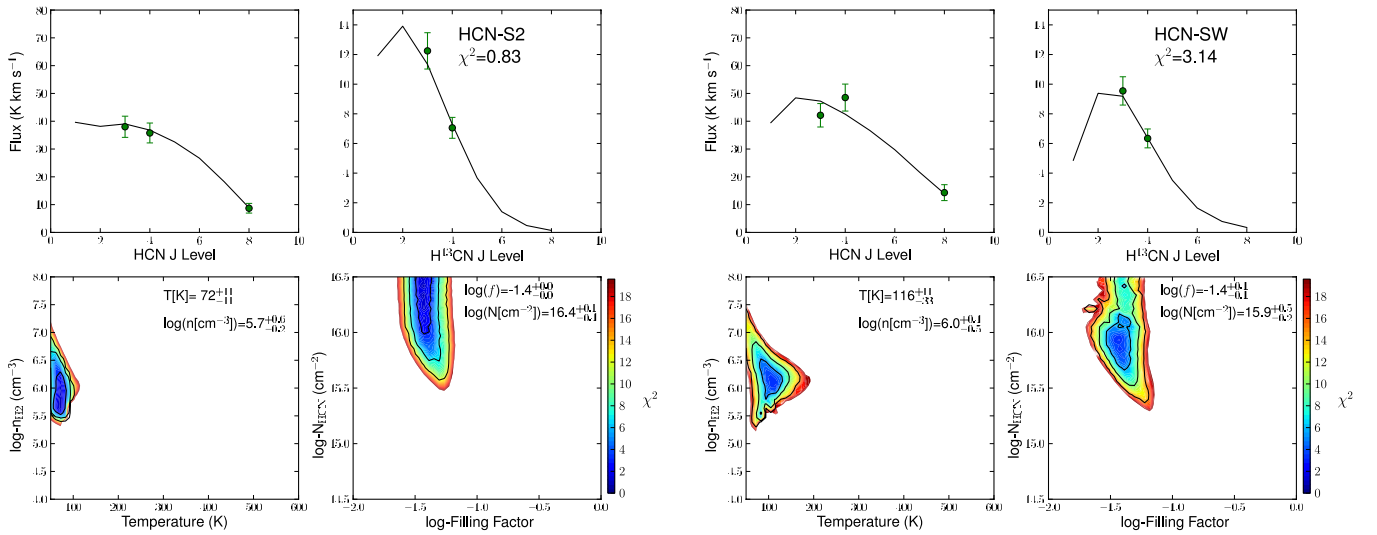


Figure 16. χ^2 fits to a one-component model of HCN excitation toward feature S2/SW in the CND. Rows are the same as for Figure 7. (A color version of this figure is available in the online journal.)

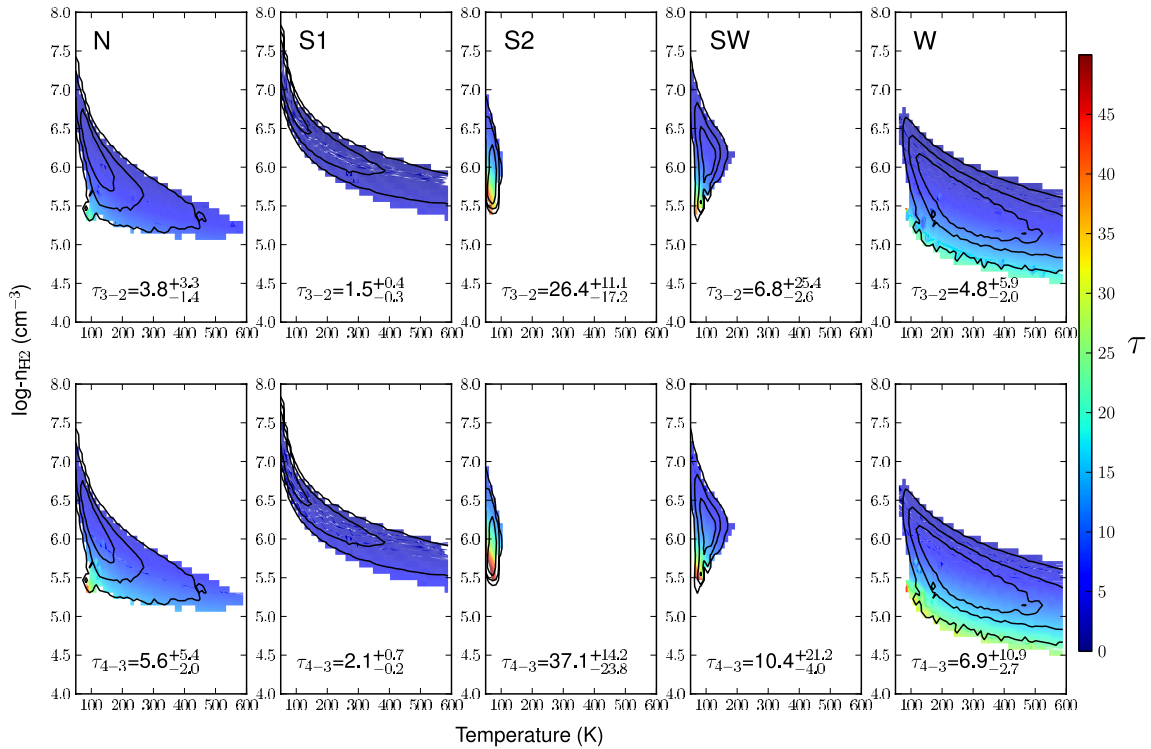


Figure 17. HCN line opacities for the 3–2 (top) and 4–3 (bottom) transitions, derived from fits to individual features. Contours show the 1σ , 2σ , and 3σ deviations from the most likely temperature and density over the full grid of physical conditions that were considered.

(A color version of this figure is available in the online journal.)

where θ_{MB} is the FWHM of the telescope beam and θ_{clump} is the FWHM of the clump. Taking the clump to be a sphere with a radius equal to half of the FWHM, we use the best-fit filling factors to determine equivalent radii for the observed features. These radii range from 0.1 to 0.15 pc and are reported in Table 4. In all cases, the radii we derive are slightly smaller than those derived from interferometric observations of the individual clumps (Montero-Castaño et al. 2009).

Using the clump radii we derive, we can also estimate masses for individual clumps, assuming a uniform clump density equal to the best-fit value. The resulting masses are reported in Table 4. The typical clump mass is a few hundred solar masses, except for clump S1, for which we estimate a mass of a few $10^4 M_{\odot}$

from our HCN observations. All of the masses derived using HCN are at least an order of magnitude lower than the virial masses determined for these clumps by Montero-Castaño et al. (2009) using HCN 4–3. For HCO^+ we only have model fits for three features, and two of these features have large filling factors inconsistent with emission from a clump. For the remaining feature (N), the mass we derive using HCO^+ ($\sim 840 M_{\odot}$) is similar to that derived for this clump using HCN and consistent within the uncertainties with the mass derived for this feature by Montero-Castaño et al. (2009).

Finally, given the clump radii we derive, we can also compare the observed line brightness temperatures from our convolved data to those in the unconvolved HCN 8–7 data, which has a

higher resolution (8''9). We find that, for the derived clump radii, the difference in beam dilution should lead the unconvolved HCN 8–7 brightness temperatures to be a factor of 3–4 times larger than the HCN 8–7 brightness temperatures from data convolved to the resolution of the HCN 3–2 beam (23''6). However, we find that it is only typically a factor of 2–3 times brighter for these features. This suggests that the sources are actually slightly more extended than our analysis suggests, and/or that other estimates made when deriving radii from the filling factors (that the sources are circular, Gaussian, and lie in the center of the beam) may not hold.

Overall, our results indicate that conditions in the individual clumps we examine are consistent with the average temperatures and densities in the bulk of the CN D gas, although some features, such as S1, may be slightly denser. However, the results presented here for individual features are based upon line intensities that still likely suffer from the superposition of line profiles from multiple clumps in the large beam of these observations. Higher spatial-resolution observations are necessary in order to fully isolate the contribution to the CN D emission from these individual clumps and to properly model their line profiles.

5.3. Radiative Excitation of HCN due to the 14 μm Background Field

Thus far in these analyses, we have been assuming that HCN (and HCO⁺) are purely collisionally excited. However, our detection of the $J = 4-3$ $v_2 = 1$ line of HCN suggests that the excitation of HCN in the CN D is not entirely collisional and that radiative excitation also plays a role. There are two possibilities for this radiative excitation: either the gas traced by HCN is irradiated externally by a midinfrared background field, or it is irradiated internally through embedded hot dust mixed with the gas. We use the midinfrared background spectra measured by Lutz et al. (1996) to run multiple RADEX models incorporating a midinfrared background radiation field and find that the results from these runs are indistinguishable from the case in which no midinfrared background radiation is included for the full range of temperatures and densities we consider. We thus conclude that background 14 μm radiation fields up to several times the highest value measured toward the central parsec (250 Jy nsr⁻¹, for an aperture centered on Sgr A*) are a negligible contribution to the excitation of HCN. This favors embedded hot dust as the most likely excitation mechanism for the observed $J = 4-3$ $v_2 = 1$ HCN line, which we explore further with excitation analyses using RATRAN.

6. RATRAN

6.1. Input Parameters

We model the radiative excitation of HCN in the CN D with RATRAN, using the same collisional and radiative excitation data as for the RADEX analysis. Like RADEX, RATRAN is a one-dimensional non-LTE code. However, RATRAN differs from RADEX in that it uses Monte Carlo techniques to more carefully sample the radiation field, combined with an accelerated lambda convergence method that allows the code to operate efficiently even for extremely high opacities. Unlike RADEX, RATRAN is not limited to the assumption of uniform source conditions, but can model gradients in the physical parameters, allowing for a more realistic modeling of the shape of the emergent line profiles, as opposed to the simple RADEX model of a rectangular line profile (having constant intensity and opacity).

For simplicity, we assume a spherically symmetric clump, with a uniform HCN abundance.

RATRAN modeling requires several more constraints on the gas properties. We assume the same turbulent line FWHM (20 km s⁻¹) as used in the RADEX fitting. However, we now also define a separate velocity gradient, dv/dr , for the CN D, which we assume to be 150 km s⁻¹ pc⁻¹, consistent with observations of the kinematics of CN D gas (Christopher et al. 2005; Martín et al. 2012). For the source radii, we adopt a value taken from interferometric observations (assuming spherical clumps): ~ 0.19 pc, consistent with our best-fit filling factors from the RADEX analysis. We also have to input the abundance of HCN compared to that of its primary collision partner (H₂). We assume the radiative excitation of HCN is predominantly due to emission from hot dust that is mixed with the gas and fix the intensity of the internal midinfrared radiation field by assuming isotropically distributed dust with temperatures between 100 and 150 K, a gas-to-dust ratio of 100, and assuming a dust emissivity model (grains with no ice mantle and $\sim 10^5$ yr of coagulation, Ossenkopf & Henning 1994). For typical CN D column densities, this results in emission that is optically thick at the wavelengths of the 14 μm rovibrational transitions. As there are now more free or uncertain parameters to our fit, including the dust temperature and the HCN abundance, we do not try, as with RADEX, to produce grids of conditions to constrain the most likely solution. Instead, we look for the existence of well-fitting solutions, acknowledging that they may not be unique.

6.2. Overlap of the 14 μm Rovibrational Lines

In addition to taking into account radiative excitation due to embedded hot dust, we also consider the effects of line overlap in the Q-branch transitions at 14 μm , which connect the $v_2 = 0$ and $v_2 = 1$ states.

If the opacity at the wavelength of the $v_2 = 1-0$ rovibrational transitions ($\lambda = 12.5-16.0 \mu\text{m}$) is sufficiently high, then the midinfrared photons at this wavelength are less likely to escape the vicinity of a given gas molecule and can instead be reabsorbed by the molecule. This trapping phenomenon reduces both the critical density for collisional excitation and the infrared background necessary for radiative excitation of the $v_2 = 1$ line.

Although both RATRAN (and RADEX) take into account the trapping of radiation for high opacities, neither code treats the effects of overlapping line emission on the excitation. The 14 μm rovibrational transitions of HCN occur in three bands: the R-branch ($\Delta J = +1$), Q-branch ($\Delta J = 0$), and P-branch ($\Delta J = -1$). The Q-branch transitions in particular are sufficiently closely spaced that for CN D line widths (20–100 km s⁻¹) transitions up to $J \sim 4$ will overlap. We calculate the expected overlap as a function of line width and make a correction for this overlap (as seen in Figure 18, lines overlap by a factor of 1.5–2.75 for J up to 5) by dividing the Einstein-A values of the Q-branch transitions by the overlap factor, which will increase the populations in the $v_2 = 1$ states. Here, the overlap factor for each line is defined as the contributions from Gaussian profiles of all the lines (where the peak intensity of the Gaussian is normalized to 1) summed at the frequency of each line.

We find that including the effects of Q-branch overlap for line widths as large as 100 km s⁻¹ has a substantial effect on the predicted intensity of the $v_2 = 1$ $J = 4-3$ line, while the effect of overlap on the predicted intensities of the $v_2 = 0$ rotational lines is much smaller. Accounting for this overlap alters the $v_2 = 1$ $J = 4-3$ line intensity by a factor of 2–4 for line widths of 50–100 km s⁻¹; however, the $v_2 = 0$ line intensities vary by

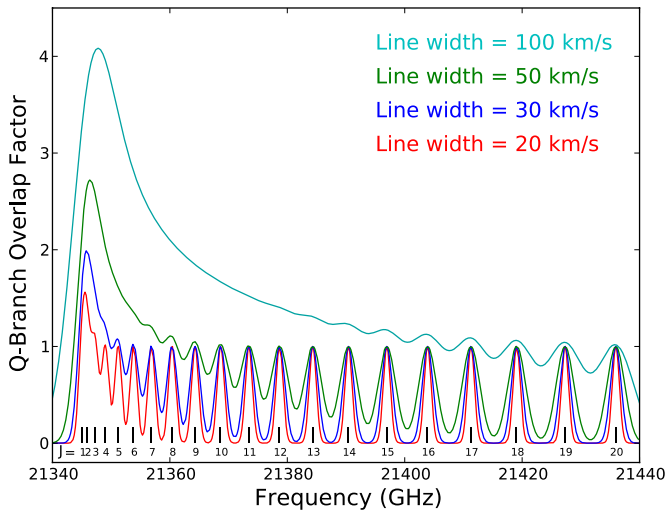


Figure 18. Degree of overlap in the Q -branch rovibrational lines of HCN for a range of line widths. An overlap factor of one signifies no overlap. (A color version of this figure is available in the online journal.)

$<10\%$. The smaller variation observed in the $v_2 = 0$ lines is likely because the Q -branch transitions are $\Delta J = 0$ transitions and so contribute less to altering the level populations of the $v_2 = 0$ rotational lines than the R -branch transitions. The effect of Q -branch overlap on the $v_2 = 1$ ladder is stronger because of the increase of the effective lifetime of the $v_2 = 1$ upper states, giving a greater probability for the rotational transition to occur before the vibrational decay. For the following analysis, we include the effects of overlap for the HCN 4–3 line widths from interferometric observations of individual clumps: 50 km s^{-1} for the south pointing and 100 km s^{-1} for the southwest pointing (Montero-Castaño et al. 2009).

6.3. Radiative Excitation of HCN by Embedded Dust

The $J = 4-3$ $v_2 = 1$ line is predominantly detected at velocities around -20 km s^{-1} , corresponding to the southwest pointing (or the S2/SW clump). For this source, we adopt an interferometrically determined radius of 0.25 pc from Montero-Castaño et al. (2009). We then run a coarse grid of RATRAN models covering the range of conditions indicated by our RADEX fitting to the observed line intensities toward southwest ($T = 100 \text{ K}$, $n = 10^{5.5}-10^{6.4} \text{ cm}^{-3}$, $[\text{HCN}/\text{H}_2] = 5 \times 10^{-9}$ to 1×10^{-8}), varying the dust temperatures between 100 and 175 K. We find that dust temperatures of $\sim 125-150 \text{ K}$ are required to generate the observed $J = 4-3$ $v_2 = 1$ line strength ($\int T_{\text{MB}} dv = 2.28 \text{ K km s}^{-1}$). The T_{vib} for these models are $\sim 150 \text{ K}$, smaller than the T_{vib} we calculate from the simplified analysis underlying Equation (2) ($\sim 200 \text{ K}$, although this value could be an overestimate if the H^{13}CN 4–3 line used to calculate this value is actually optically thick).

These dust temperatures are also sufficient to cause the derived density for south-1 to be up to a factor of five lower than predicted by RADEX. Thus, as we discuss further in Section 7.2, if this hot dust is widespread throughout the CND and not just localized in feature S2/SW, this could bring the densities derived using HCN for the southern emission peak into agreement with those derived by RT12 using CO. If our density estimates for other clumps are indeed overestimated due to the radiative excitation of HCN, $v_2 = 1$ emission should be seen in these clumps as well. It should be noted that these results assume a homogenous spherical source. If there are spatial variations

in temperature, density, or abundance, these would alter our assumption that all the line emission from the $v_2 = 0$ transitions is arising from the same gas as the $v_2 = 1$ transition and could change the inferred dust temperature and thus the degree to which radiative excitation could affect the derived densities.

7. DISCUSSION

7.1. Hot Dust in the CND

The detection of the $J = 4-3$ $v_2 = 1$ HCN line toward the southwest emission peak of the CND and subsequent RATRAN modeling of its intensity indicate that HCN emission from this region is radiatively excited and that a $125-150 \text{ K}$ dust component is necessary to explain the observed strength of this line.

However, existing observations have not detected this hot dust component in the CND. Etxaluze et al. (2011) fit the far-infrared and submillimeter emission spectrum of this region with photometric data from 21.3 to $180 \mu\text{m}$, indicating the presence of at least three temperature components in the dust: 23 , 44.5 , and 90 K . More recently, Lau et al. (2013) used the FORCAST instrument on the Stratospheric Observatory For Infrared Astronomy to map emission from the CND and central parsec at 19.7 , 31.5 , and $37.1 \mu\text{m}$ and to construct a map of the dust color temperature, showing clearly that the hottest dust, with temperatures up to 150 K , originates in the central cavity, while in the CND the dust color temperature ranges from 60 to 90 K , which is consistent with lower-resolution observations at similar wavelengths by Telesco et al. (1996).

We consider several potential mechanisms for heating CND dust to temperatures of $125-150 \text{ K}$. Lau et al. (2013) find that, given the radiation field from the central cluster and assuming a distance of 1.4 pc and dust grain sizes of $0.1 \mu\text{m}$, the equilibrium CND dust temperature should be $\sim 90 \text{ K}$. Assuming a smaller distance (1 pc , the projected distance of feature SW from the central star cluster) will only increase the assumed dust temperature by 10% . However, if there are smaller dust grains present in the CND (for example, with an order-of-magnitude smaller size of $0.01 \mu\text{m}$), then approximating the dust temperature to depend on particle size a as $a^{1/6}$ (Kruegel 2003), the equilibrium temperature of those grains could exceed 125 K . However, this is approaching the regime of small grains, where this approximation breaks down.

In sufficiently dense regions, the dust could also be heated via collisions with the gas. Gas-dust thermal coupling should be effective at typical densities of $\sim 10^5 \text{ cm}^{-3}$ (Goldsmith 2001; Juvela & Ysard 2011), although the density required is increased if the cosmic ray background is higher than typical interstellar values (Clark et al. 2013). As noted in the introductory section of this article, gas temperatures in the CND have been found to range from 50 to 400 K and exceed 200 K in the atomic gas on the inner edge. Thus given that we constrain the typical CND densities to be between 10^5 and a few 10^6 cm^{-3} , it is not unreasonable to expect the dust and gas should be coupled, with some fraction of both having temperatures $>125-150 \text{ K}$. We thus find that either a population of small dust grains or heating via coupling with the gas are potentially viable explanations for the hot dust component we infer from these observations and should be investigated further. We additionally discuss potential heating sources for the gas in Section 7.4.

There are several possible reasons why such a hot dust component in the CND could have been missed by previous observations. First, the wavelengths observed by Etxaluze et al.

(2011) and Lau et al. (2013) are slightly longer than the wavelengths of the HCN rovibrational transitions, so they do not constrain the existence of hotter dust components that could dominate the dust emission at the wavelengths of the rovibrational lines of HCN. For example, a 12.5–20.3 μm color temperature map of the “minispiral” region interior to the CND indicates dust color temperatures ranging from 200 to 270 K (Cotera et al. 1999), significantly higher than the ~ 150 K dust temperatures derived by Lau et al. and others for the minispiral. Also, short wavelength emission from the hottest dust should originate from the inner edge of the CND, and given the orientation of the CND this emission from clump S2/SW should lie on the far side of the bulk of the gas in the southern emission peak of the CND (see, e.g., Lau et al.). Emission from hot dust in this source could then be significantly extinguished. If there are significant quantities of hot dust all along the inner edge of the CND, we predict that this hot dust component could be indirectly detected via the radiative excitation of HCN: the 14 μm rovibrational lines should be seen in absorption against the background dust continuum (where they are less extinguished by the dense CND torus), and emission from the $v_2 = 1$ rotational lines of HCN should also be present in other high-column density CND clumps lying along its inner edge.

We also note that it is not clear whether radiative excitation may also contribute to the excitation of HCO^+ . We do not detect the $v_2 = 1$ lines of HCO^+ ; however, this may not rule out radiative excitation as HCO^+ has a lower abundance than HCN in the CND (which we discuss in Section 7.4), making these lines too faint to be detected in our data. However, the rovibrational transitions of HCO^+ also occur at 12 μm , at which wavelength archival ISO spectra show the midinfrared emission from the CND to be a factor of 2–3 less intense than at 14 μm , so it is possible that radiative excitation is not important for HCO^+ .

In contrast, HNC should be more easily radiatively excited than HCN or HCO^+ , as the rovibrational transitions of its $v_2 = 1$ bending mode occur at 21.5 μm , where the background dust emission is stronger. For gas densities $\sim 10^6 \text{ cm}^{-3}$, HNC can be radiatively pumped by embedded dust with temperatures as low as 85 K (Aalto et al. 2007). As a result, HNC should be more sensitive to the presence of warm dust in the CND than in the HCN. Future observations of the HNC/HCN ratio and a search for the $v_2 = 1$ rotation-vibration lines of HNC would then provide a useful diagnostic of the distribution of warm dust in the CND and its resulting influence on the radiative excitation of molecules in the CND.

7.2. CND Densities

Comparing our RADEX-derived HCN and HCO^+ densities to those derived by RT12 using CO, we find that in general the best-fit densities from our fits to the majority of the line profile are consistent within the uncertainties with densities from RT12 toward the northern and southern emission peaks of the CND, although they tend to be slightly higher. However, the best-fit density for the south-1 pointing determined from our HCN observations, ($\log [n (\text{cm}^{-3})] = 6.5^{+0.5}_{-0.7}$), is higher than the CO-derived densities found by RT12 for the southern emission peak ($\log [n (\text{cm}^{-3})] = 5.2^{+0.4}_{-0.2}$) and does not agree within the uncertainties of both measurements. There is also some tension in the best-fit temperatures; the temperature determined from HCN line intensities toward south-1 (as well as the temperature determined from HCO^+ toward the north pointing) is lower than allowed by the RT12 CO fits to the high-density component of gas. There are two main scenarios that can explain this

discrepancy: either there truly is higher-density (and cooler) gas in the southern emission peak of the CND, or (as is the case for the separate southwest peak), radiative excitation contributes substantially to the excitation of the HCN lines, with the resulting alteration in the level populations mimicking a higher density than is actually present.

It is possible that HCN (and HCO^+) trace gas that is preferentially excited in higher-density clumps of the CND, as the critical densities of the highest lines we measure (HCN 8–7 and HCO^+ 9–8) are $\sim 10^9 \text{ cm}^{-3}$, and $\sim 10^8 \text{ cm}^{-3}$, respectively, whereas the critical density of the highest line measured by RT12, CO 16–15, has a critical density of just a few times 10^6 cm^{-3} , three orders of magnitude lower. Our fits to limited velocity ranges corresponding to individual interferometrically detected clumps also tend to slightly indicate higher densities than fits to the entire line profile, which suggests that there may be denser clumps embedded in the CND, even though these higher densities may not be typical of conditions in the bulk of the CND gas, as traced by CO. However, if radiative excitation is important outside of clump S2/SW (where we detect the $v_2 = 1$ $J = 4-3$ line of HCN), and there is also a hot dust component in the southern emission peak, this could also lower the gas density we derive for this source, potentially bringing it into agreement with the lower density measured by RT12. As we do not detect $v_2 = 1$ $J = 4-3$ emission toward the CND’s southern emission peak, our current observations are not sufficient to distinguish between these scenarios; sensitive observations of the $v_2 = 1$ lines of HCN toward more positions in the CND should be conducted in order to determine whether the radiation from hot dust plays a role in the observed excitation of HCN throughout the CND.

7.2.1. Is CND Gas Virialized?

Previous interferometric observations of the CND with HCN and HCO^+ have suggested that, if virialized, the CND gas should have extremely high densities, on the order of 10^7 – 10^8 cm^{-3} (Christopher et al. 2005; Montero-Castaño et al. 2009). However, even the highest density we find (feature S1) is substantially lower than the large virial densities calculated by Montero-Castaño et al., which are on the order of a few times 10^8 cm^{-3} . In general, we find densities less than a few 10^6 cm^{-3} , suggesting that the clump densities determined by Montero-Castaño et al., Shukla et al. (2004), and Christopher et al. (2005) are overestimated, and CND clumps are not in virial equilibrium. We also compare our derived densities to the Roche limit for stability in the CND, which is $\sim 10^7 \text{ cm}^{-3}$. The densities we derive for all positions in the CND except one are lower than this value, meaning that the majority of the gas in the CND is not tidally stable. The densities allowed by our single-component HCN fit to feature S1 are $\log [n (\text{cm}^{-3})] = 7.2^{+0.4}_{-0.7}$, and so for this clump, we cannot rule out the possibility that this clump could be marginally stable against tidal disruption. Intriguingly, this is also the only CND clump that has a strong submillimeter counterpart (Liu et al. 2013). However, our overall analysis indicates that, consistent with the findings of RT12, the bulk, if not the entirety, of the CND gas is not tidally stable, and the observed clumps must be transient features.

7.3. Feature SW/S2

The most unusual properties from this analysis are associated with feature SW/S2, at a velocity of -20 km s^{-1} . This is the feature from which we detect the $J = 4-3$ $v_2 = 1$ line of HCN,

as well as the only feature from which we see significant self-absorption in the $J = 3-2$ and $4-3$ spectra of both HCN and HCO^+ (Figures 4 and 5).

RADEX fits to this feature indicate that it has the highest column density of all features we survey (the best-fit HCN columns are $10^{16.4} \text{ cm}^{-2}$ and $10^{15.9} \text{ cm}^{-2}$ toward SW and S2, respectively), and that extremely high opacities ($\tau \sim 10-50$) are needed to account for the observed self-absorption in the line profiles. However, this self-absorption could also be explained by multiple excitation components along the line of sight. In these scenarios, the opacities (and thus column densities) could be lower than those found by our RADEX fits. One way to test this is by looking for emission from rarer isotopologues of HCN and other species. Although the opacities from our RADEX fits are sufficiently high that the HC^{15}N lines should be detectable (with intrinsic line intensities of a few hundred mK, assuming a Galactic center $^{15}\text{N}/^{14}\text{N}$ ratio of 600 Wilson & Rood 1994), the large beam sizes of our observations dilute the expected signal so that it is still lower than our observed upper limits for the HC^{15}N lines. Higher-resolution observations of this region, with ALMA for example, would be useful in this regard, as well as for disentangling and successfully fitting the potentially multiple gas components in feature SW/S2 and for more precisely modeling the radiative excitation occurring in this region.

7.4. *CND Chemistry*

Recent measurements suggest that the central 300 parsecs of the Galaxy (the central Molecular zone, CMZ) are subject to an elevated cosmic ray ionization rate, ranging from $\zeta \sim 10^{-16}$ to 10^{-14} s^{-1} (Oka et al. 2005; van der Tak et al. 2006; Goto et al. 2008, 2011, 2013) up to 10^{-13} s^{-1} (Yusef-Zadeh et al. 2007, 2013a, 2013b). For comparison, the typical interstellar cosmic ray ionization rate ζ_0 is estimated to be $3 \times 10^{-17} \text{ s}^{-1}$, although recent observations by Indriolo & McCall 2012 suggest that it may be an order of magnitude higher. A high flux of cosmic rays is suggested to be responsible for heating the molecular gas in the Galactic center, particularly for elevating the observed gas temperatures (50–200 K, e.g., Güsten et al. 1985; Hüttemeister et al. 1993) above the observed dust temperatures (15–30 K, e.g., Mezger et al. 1986; Molinari et al. 2011) in this region (Güsten et al. 1981; Ao et al. 2013; Clark et al. 2013). A predicted result of such a high ionization rate is a high fractional ionization of the molecular gas (Papadopoulos 2010; Ao et al. 2013; Yusef-Zadeh et al. 2013a): molecular ions such as HCO^+ should be more abundant, and this should be reflected in a lowered $[\text{HCN}]/[\text{HCO}^+]$ abundance ratio (Meijerink et al. 2006). A high flux of X-rays could also alter the gas chemistry in this region. As the CND gas is in close proximity to the central SMBH, which may have recently (within the past few hundred years) undergone an outburst several orders of magnitude stronger than its typical flares (Koyama et al. 1996; Murakami et al. 2000; Inui et al. 2009; Ponti et al. 2010; Clavel et al. 2013), it is also possible that molecular abundances in this environment have been affected by an enhanced X-ray flux.

The ratio of observed HCN and HCO^+ line intensities has been suggested to be a useful diagnostic for identifying gas in both X-ray-dominated (XDR) and cosmic-ray-dominated (CRDR) environments (Meijerink et al. 2006, 2007). We investigate the possibility that gas in the CND is subject to either a XDR or CRDR environment by comparing the observed ratio of the HCN and HCO^+ $J = 4-3$ transitions in the CND to those derived in the XDR and CRDR models of Meijerink et al. (2006,

2007). The observed ratios of HCN $4-3$ and HCO^+ $4-3$ in the CND are between 1.5 and 2.0 (and the ratios of the H^{13}CN and H^{13}CO^+ isotopologues of the same transition, which are free of opacity effects, are even higher, ranging from 2.5 to 5). The predicted HCN $4-3$ to HCO^+ $4-3$ ratio for a CRDR with a cosmic ray ionization rate of $5 \times 10^{-15} \text{ s}^{-1}$ and a density of 10^5 cm^{-3} is 0.85 (Meijerink et al. 2006). Predicted ratios for HCN $4-3$ to HCO^+ $4-3$ in an XDR with densities higher than 10^5 cm^{-3} are less than 0.4. As HCN $4-3$ is significantly stronger than HCO^+ $4-3$ in the CND, the environment of this gas is not consistent with predictions for molecular gas in a CRDR (at least for densities $\sim$ a few 10^5 cm^{-3}) or an XDR of any density. These observational constraints indicate either that cosmic ray ionization rates in the CMZ are lower than a few times 10^{-15} s^{-1} , or that the cosmic ray ionization rate varies strongly throughout the CMZ.

These observations then suggest that neither X-rays nor cosmic rays are responsible for heating the CND gas, consistent with recent findings by Goicoechea et al. (2013) for hot gas interior to the CND and the findings of Rodríguez-Fernández et al. (2004) for the CMZ as a whole. Another possible heating mechanism for the gas is photoelectric heating in photodissociation regions (PDRs): we find that the measured $[\text{HCN}]/[\text{HCO}^+]$ ratios are consistent with the model predictions of Meijerink et al. (2007) for a relatively high-density PDR ($10^5-10^6 \text{ cm}^{-3}$, similar to densities derived by our excitation analysis). However, PDR heating should be most effective at the surface of the CND surface and may not be sufficient to explain temperatures of $\gtrsim 200 \text{ K}$ found for the dense CND gas (Requena-Torres et al. 2012).

Mechanical processes could also provide a mechanism to heat the gas in the dense and UV-shielded CND interior consistent with the observed abundances of HCN and HCO^+ . Where the gas in clump interiors is heated to temperatures $\gtrsim 100 \text{ K}$, HNC will be efficiently converted to HCN (Schilke et al. 1992; Talbi et al. 1996), enhancing the latter's abundance. Loenen et al. (2008) show, for somewhat lower densities than those likely to exist in the CND ($n = 10^{4.5} \text{ cm}^{-3}$), that including the effects of mechanical heating increases the relative abundance of HCN to HCO^+ by a factor of 2–3, consistent with our observed HCN/ HCO^+ ratios. A likely driver of mechanical heating in the CND gas is the cascade of turbulent energy (evident in the large line widths observed in the CND) to smaller size scales where it is dissipated. This turbulence could be injected by the accretion of material onto the CND (e.g., Amo-Baladrón et al. 2011; Liu et al. 2012) or possibly by the nearby Sgr A East supernova remnant (Rockefeller et al. 2005), although the interaction between the CND and Sgr A East has not been clearly demonstrated (Lee et al. 2008; Sjouwerman & Pihlström 2008). If the enhanced HCN abundance in the CND is due to mechanical heating in the dense clump interiors, the models of Loenen et al. (2008) predict a relatively low HNC/HCN ratio, which can be tested with future observations.

8. SUMMARY

In this article, we present observations of multiple lines of HCN and HCO^+ , including the ^{13}C isotopologues, toward four positions in the CND of molecular gas and dust in the central parsecs of the Galaxy. We use the measured main beam brightness temperature of each line over the majority of the line profiles (excluding velocity ranges where there is contamination from other nearby clouds) to constrain the H_2 volume densities,

kinetic temperatures, molecular column densities, and areal filling factors of dense gas in the CND. We also model the physical conditions over limited velocity ranges corresponding to single clumps identified in interferometric studies, in order to determine whether the conditions in individual clumps deviate from the average physical conditions in the CND gas. Our main findings are summarized as follows.

1. Using the RADEX radiative transfer code to fit the majority of the line profiles from HCN and HCO⁺, and assuming purely collisional excitation, we find typical densities of $\log[n(\text{cm}^{-3})] \sim 5.3\text{--}6.5$ and typical temperatures of $T \sim 100\text{--}400$ K for the dense gas in the CND, although in some cases the highest temperatures present are unconstrained by these fits. Fitting to limited velocity ranges in the profile corresponding to individual clumps, we derive slightly lower temperatures and slightly higher densities. This suggests conditions in individual clumps may deviate from the average physical conditions in the CND gas. However, from our RADEX models, we find only one feature (S1) that could have a density sufficiently high to be tidally stable; the bulk of the gas in the CND is not stable against tidal shearing.
2. The average HCN and HCO⁺ densities for the CND gas indicated by the RADEX fits are consistent within the uncertainties with results from other tracers including CO and dust for all positions except south-1 (for which we find a significantly higher density). In general, the best-fit HCN densities tend to be slightly higher than inferred by these other excitation analyses.
3. We also detect vibrationally excited HCN for the first time in the CND. We observe the $J = 4\text{--}3$ $v_2 = 1$ line toward the southern emission peak of the CND, at a velocity of -20 km s^{-1} , which is consistent with the SW/S2 clump. We model the excitation of this line by including radiative excitation of HCN due to hot dust in the CND, and we find that the observed brightness temperature of this line requires dust temperatures in this region to be $> 125\text{--}150$ K. If such hot dust is present in other clumps along the inner edge of the CND, this would have the effect of lowering the densities that we find with HCN. Dust temperatures of $T \sim 150$ K are sufficient to bring the densities we derive for the southern emission peak into agreement with those found using other tracers, such as CO and dust, and would then make it unlikely that *any* of the gas in the CND is tidally stable.

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