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FIRST DETECTION OF HCN $J = 9$–8 (797 GHz) LINE EMISSION: VERY HIGH DENSITIES IN THE ORION CORE

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ABSTRACT

We report the first astronomical detection of HCN $J = 9 \rightarrow 8$ (797.433 GHz) emission. The line emitted from the Orion core shows two velocity components. One closely matches the low-velocity "plateau" component. The second probably originates in the "hot core" near IRc2. Both components have peak main-beam brightness temperatures of about 30 K in a 32″ beam.

We estimate the hydrogen density of the gas emitting the plateau component to be at least a few times 10^7 cm^{-3} and probably near 10^8 cm^{-3}, based on the assumption that the plateau HCN $J = 9 \rightarrow 8$ emission region has a spatial extent similar to high-density tracing mm-wave lines. If it is spatially more extended, the inferred densities are slightly lower. The very high density material in the plateau outflow is probably in a thin shell or in sheetlike structures. The plateau HCN $J = 9 \rightarrow 8$ emission thus probably traces highly compressed postshock material.

The hot core HCN $J = 9 \rightarrow 8$ emission confirms the interpretation of the hot core feature as emission from clumps of several hundred K with a density near 10^7 cm^{-3} or higher. Excitation by IR continuum photons can be ruled out for the observed HCN $J = 9 \rightarrow 8$ emission.

Subject headings: interstellar: matter — interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

HCN, a heavy linear rotor with a large dipole moment ($B = 44.594448$ GHz, $D = 87.24$ KHz, $\mu = 2.9845$ debye; Chantry 1979) is frequently used in its low-J millimeter-wave transitions as a high-density tracer in cold molecular cloud cores. Because of the J^3 increase of the Einstein A-coefficients with rotational quantum number, the high-J submillimeter transitions of HCN trace warm gas with even higher densities. The HCN $J = 9 \rightarrow 8$ (797.433 GHz) transition has an A-coefficient of 2.5×10^{-2} s^{-1} and a critical excitation density of $A/\gamma = 2 \times 10^9$ cm^{-3} (with the downward collision rate coefficient γ from below, § III*a*). The $J = 9$ level of HCN lies 191 K above ground state. The core region of the Orion molecular cloud and star-formation region, showing two emission features, the "plateau" and the "hot core," from warm and dense gas, is obviously an excellent candidate for the detection of a transition like HCN $J = 9 \rightarrow 8$.

II. OBSERVATIONS AND RESULTS

The HCN $J = 9 \rightarrow 8$ (797.433 GHz; 375.944 μm) detection was made on 1987 February 12 with the UC Berkeley/MPE cooled Schottky submillimeter heterodyne receiver mounted on the NASA IRTF on Mauna Kea, Hawaii. The instrument is described in detail in Harris *et al.* (1987*a*). The beamwidth at the IRTF was 32″ FWHM. The data were calibrated in the way described by Harris *et al.* (1987*b*) and Stutzki *et al.* (1988). The telescope secondary chopped 3′ E–W. Pointing was checked by a television camera aligned on the sub-mm boresight. We estimate the overall pointing error to be less than 10″.

The HCN $J = 9 \rightarrow 8$ line from the Orion core (Fig. 1) has a peak main-beam brightness temperature (T_{mb}) of 55 K at $v_{LSR} \approx 6$ km s^{-1}. Its width is about 25 km s^{-1} FWHM and the line centroid is near 10 km s^{-1}. Comparison with other lines shows that the wide wings closely match the low velocity "plateau" emission profile observed in high excitation mm-transitions like SO $2_3 \rightarrow 1_2$. The HCN $J = 9 \rightarrow 8$ profile is narrower than the high-velocity outflow in the sub-mm and far-IR CO lines, which require also high temperature, but more than two orders of magnitude lower densities for excitation than the HCN $J = 9 \rightarrow 8$ transition. The narrower feature at the line peak is at the velocity of the hot core emission. The cool gas from the molecular ridge at $v_{LSR} = 9$ km s^{-1} does not contribute to the HCN $J = 9 \rightarrow 8$ emission at a discernible level. The HCN profile is well fitted by two Gaussian components (Fig. 1) with parameters characteristic of the low-velocity plateau and hot core in other lines ($T_{mb} = 27$ K, $v_{LSR} = 6$ km s^{-1}, Δv(FWHM) $= 7$ km s^{-1} for the hot core, $T_{mb} = 32$ K, $v_{LSR} = 13$ km s^{-1}, Δv(FWHM) $= 30$ km s^{-1} for the plateau emission).

III. DISCUSSION

a) Dense Gas in the Orion Plateau Source

Because of the similarity of velocity centroids and line widths of the broad HCN $J = 9 \rightarrow 8$ emission with the mm-wave plateau emission we assume in the following that its spatial distribution is similar to the plateau gas a well. The beam-filling factor of the plateau emission estimated from SO interferometer maps (FWHM 11″ × 19″; Plambeck *et al.* 1982), is 0.17 in our 32″ beam. The observed main-beam bright-

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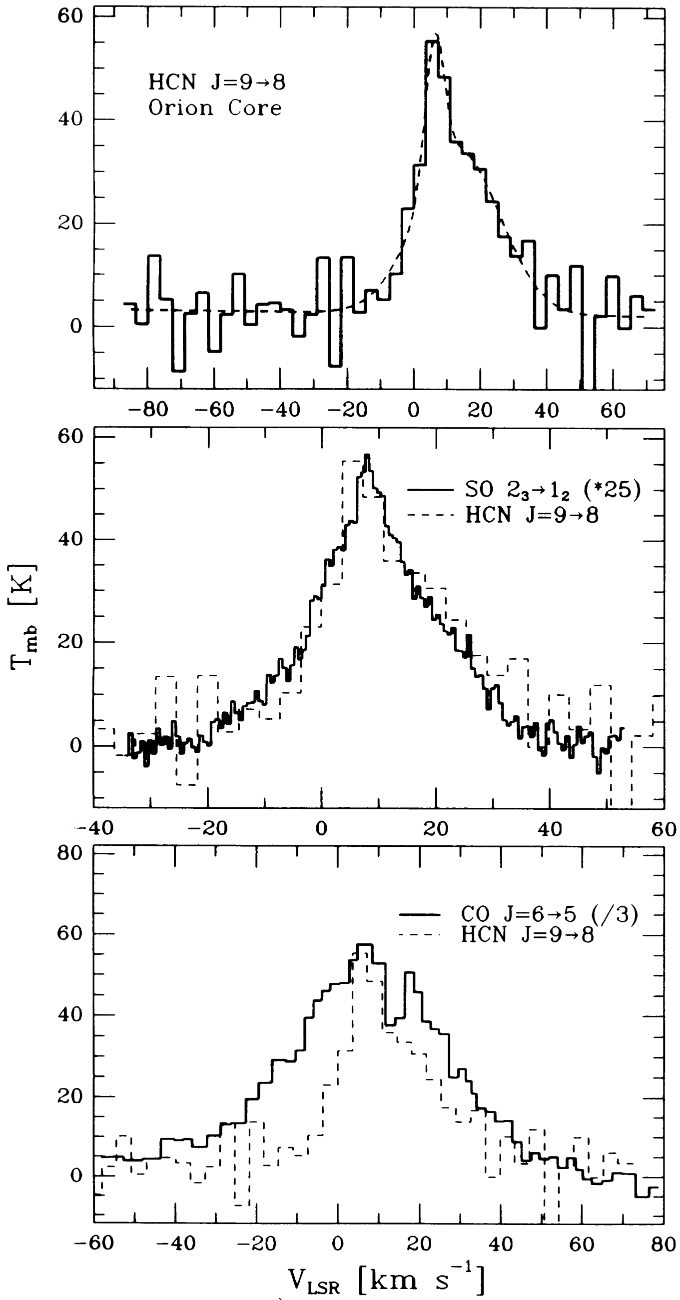


FIG. 1.—(*top*) The HCN $J=9\rightarrow 8$ (797.433 GHz) emission from the Orion core region [R.A. (1950) = $5^h32^m46\overset{s}{.}7$, decl. (1950) = $-5°24'17''$] observed with the 32″ beam of the IRTF. The total integration time was 20 minutes. No baseline corrections have been applied. The data are displayed at a velocity resolution of 3.624 km s^{-1} (16 AOS channels averaged). The dashed line is a two-component Gaussian fit. (*middle*) An overlay of the HCN $J=9\rightarrow 8$ line with SO $2_3\rightarrow 1_2$ (Phillips and White 1983; 65″ beam), and (*bottom*) with CO $6\rightarrow 5$ (Koepf *et al.* 1982; 35″ beam).

ness temperature of 30 K thus gives an intrinsic Rayleigh-Jeans brightness temperature of 170 K. The corresponding 190 K Planck brightness temperature is a lower limit to the gas temperature of the HCN emission region. This brightness temperature is in the upper range of kinetic temperatures estimated from mm-wave observations (Blake *et al.* 1987) and the far-IR OH plateau emission (Melnick, Genzel, and Lugten 1987). The HCN $J = 9 \rightarrow 8$ plateau emission is therefore probably near thermalization and the density must be close to the critical density of the $9 \rightarrow 8$ transition.

High-J, high-temperature collision rate coefficients for HCN are not available from the literature. We therefore calculated the $J \rightarrow 0$ collision rate coefficients in IOS approximation from the interaction potential given by Green and Thaddeus (1974), using the method described by Stutzki and Winnewisser (1985*a*). The resulting IOS $J \rightarrow 0$ cross sections are listed in Table 1. From these we calculated the $J \rightarrow J'$ cross sections including the energy correction factors according to DePristo *et al.* (1979), following the method described by McKee *et al.* (1982). The resulting collision rate coefficient for the $J = 9 \rightarrow 8$ transitions, for example, is $\gamma = 1.1 \times 10^{-11}$ cm^3 s^{-1} at 200 K.

Radiative pumping, either within the rotational ladder by the sub-mm radiation of the embedded warm dust, or via the first vibrationally excited states by mid-IR (14 μm) continuum radiation from IRc2, is of minor importance for the excitation of the observed HCN $J = 9 \rightarrow 8$ transition. The average dust opacity in the sub-mm ($\tau = 0.072$ at 400 μm; Keene, Hildebrand, and Whitcomb 1982) is much lower than the line opacity of the high-J rotational transitions. Its contribution to the total source function (the opacity weighted mean over line and continuum source function) is negligible. The dust optical depth at 14 μm in the Orion core is high. The continuum radiation from IRc2 thus can only affect the inside layers of the cloud toward IRc2 (cf. the discussion in Townes *et al.* 1983). Because of its large optical depth (see below) the observed HCN $J = 9 \rightarrow 8$ emission, however, originates only on the cloud surface toward the observer. If the emission arose on the inside cavity wall, the excitation gradient toward the observer would additionally produce a strong self-absorption feature, which is not observed.

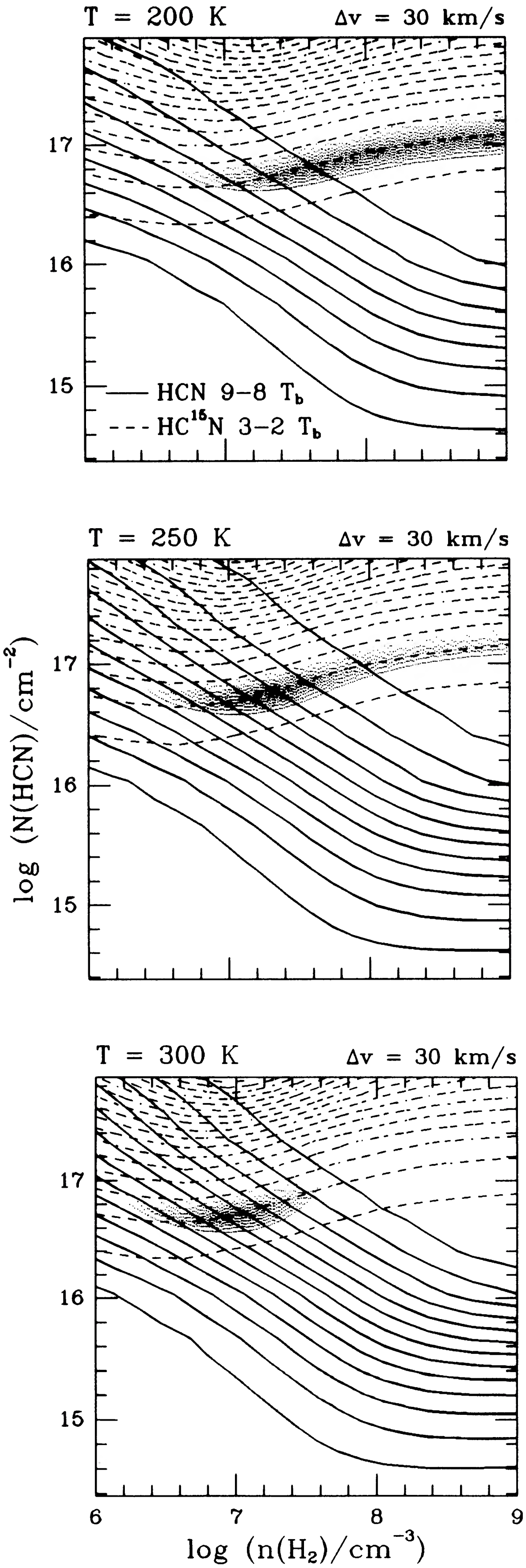
b) Model Calculations of the HCN *Excitation*

We used our numerical escape probability model (Stutzki and Winnewisser 1985*b*, slightly modified to account for the effect of IR pumping by embedded dust in a line averaged way) to study the HCN excitation conditions, expecially the effects of trapping, in more detail. We included the HCN vibrational ground state and a representative first excited state 1000 K above ground with rotational states up to $J = 14$ in both

TABLE 1

HCN $J \rightarrow 0$ IOS COLLISION RATE COEFFICIENTS (cm^3 s^{-1})

J	100 K	200 K	300 K
19..........	0.747E−15	0.234E−14	0.324E−14
18..........	0.737E−15	0.434E−14	0.106E−13
17..........	0.586E−15	0.401E−14	0.838E−14
16..........	0.934E−15	0.515E−14	0.177E−13
15..........	0.201E−14	0.689E−14	0.158E−13
14..........	0.322E−14	0.137E−13	0.298E−13
13..........	0.470E−14	0.307E−13	0.763E−13
12..........	0.941E−14	0.528E−13	0.129E−12
11..........	0.203E−13	0.948E−13	0.212E−12
10..........	0.500E−13	0.233E−12	0.521E−12
9..........	0.527E−13	0.217E−12	0.455E−12
8..........	0.183E−12	0.652E−12	0.127E−11
7..........	0.170E−12	0.519E−12	0.961E−12
6..........	0.716E−12	0.170E−11	0.265E−11
5..........	0.450E−12	0.101E−11	0.157E−11
4..........	0.344E−11	0.610E−11	0.811E−11
3..........	0.128E−11	0.216E−11	0.279E−11
2..........	0.211E−10	0.263E−10	0.287E−10
1..........	0.320E−11	0.425E−11	0.439E−11



vibrational states. Comparison between radiative transfer calculations, both with and without the excited vibrational state, as well as with and without radiative pumping at mid-IR and sub-mm wavelengths, shows that the emergent ground-state rotational line intensities, in the regime of parameters of interest, never change by more than a few percent. This confirms that radiative pumping is of minor importance for the excitation of the sub-mm rotational transitions in the vibrational ground state of HCN.

The molecular parameters for the vibrational transition were determined as follows. From the measured integrated absorbance of the ν_3 band of 28.3 km mol^{-1} for the Q-branch (Kim and King 1979) we derive an Einstein A-coefficient of 3.6 s^{-1} (i.e., $\mu_{\rm vib} = 0.177$ debye) for the vibrational transition. The rovibrational dipole matrix elements are then given by (following Papousek and Aliev 1982)

$$|\mu_{\rm ro\text{-}vib}|^2_{J,\, v=1 \rightarrow J',\, v=0} = |\mu_{\rm vib}{}^2| \times \begin{cases} J/[2(2J+1)]\,, & J' = J+1 \\ (J+1)/[2(2J+1)]\,, & J' = J-1\,. \\ 1/2\,, & J' = J \end{cases} \quad (1)$$

Following Ziurys and Turner (1986), we approximated the vibrational collisional rate coefficients by those of CO_2 ($\gamma = 7.5 \times 10^{-12}$ cm^3 s^{-1}; Allen, Scragg, and Simpson 1980). We set the rovibrational collision rates equal to one-seventh of the purely vibrational rate for transitions with $|\Delta J| \leq 3$, and 0 otherwise.

To constrain the physical conditions in the HCN emission region, we use, in addition to the HCN $J = 9 \rightarrow 8$ transition, the HC^{15}N $J = 3 \rightarrow 2$ line observed by Blake *et al.* (1986) with a similar beam. Figure 2 shows the results of the radiative transfer calculations for the plateau emission. The HC^{15}N $J = 3 \rightarrow 2$ line mainly constrains the total HCN column density to a value close to 5×10^{16} cm^{-2} (assuming a HC^{15}N/HCN abundance ratio of 1/300). At this column density and a temperature of around 200 K the HCN $J = 9 \rightarrow 8$ transition is very optically thick ($\tau \approx$ several 100). Trapping thus reduces the density necessary for thermalization by 1–1.5 orders of magnitude below the critical density. This column density for a 30 km s^{-1} wide line corresponds to a velocity gradient of 2×10^4 km s^{-1} pc^{-1} at an HCN fractional abundance of 3×10^{-7} and molecular hydrogen density of 6×10^7 cm^{-3} in a large velocity gradient model with the same excitation conditions. We also note that the high HCN optical depth implies that the high-J sub-mm H^{13}CN lines will still have optical depths >1 and even the HC^{15}N will have τ around unity. Isotopic HCN sub-mm lines should consequently be very strong.

FIG. 2.—Peak main beam brightness temperature contours of the HCN $J = 9 \rightarrow 8$ and HC^{15}N $J = 3 \rightarrow 2$ transitions from radiative transfer calculations (see text; [HCN]/[HC^{15}N] = 300, Δv[FWHM] = 30 km s^{-1}, i.e., plateau emission) vs. H_2 density and HCN column density at kinetic temperatures of 200, 250, and 300 K. The contours increase in 20 K steps for the HCN $J = 9 \rightarrow 8$ transition (*heavy lines*) and in 3 K steps for the HC^{15}N $J = 3 \rightarrow 2$ transition (*broken lines*) from bottom to top. The gray shading is proportional to $\exp(-\chi^2)$ for the observed, beam dilution–corrected intensities of both transitions. The darkest regions therefore give the most likely parameters if all of the observed HC^{15}N $J = 3 \rightarrow 2$ emission comes from the very dense and warm gas traced by the HCN $J = 9 \rightarrow 8$ transition. If part of the HC^{15}N $J = 3 \rightarrow 2$ emission comes from less dense gas, the most likely values are to the right and below the dark areas.

The brightness of the broad component in the $J = 9 \rightarrow 8$ line by itself gives a lower limit on the kinetic temperature of around 190 K. For a gas temperature of 200 K the observed HCN $9 \rightarrow 8$ and $HC^{15}N$ $J = 3 \rightarrow 2$ brightness temperatures require a density of at least 6×10^7 cm^{-3}. At still higher temperatures the minimum possible density is lower (about 1×10^7 cm^{-3} at 300 K and 4×10^6 cm^{-3} at 600 K). However, only part of the gas in the plateau emission region probably has temperatures substantially higher than 200 K. If only a fraction of the total HCN column density contributes to the HCN $J = 9 \rightarrow 8$ emission the derived densities increase roughly proportionally (see Fig. 2), pushing the required densities up again (to several 10^7–10^8 cm^{-3} for a fraction of 10% of very warm gas). These densities and temperatures are still low enough that the emission from the rotational lines in the first vibrationally excited state from this gas component is well below the observational limit of about 0.4 K for the plateau emission derived from the data by Ziurys and Turner (1986).

The total H_2 column density derived from dust sub-mm and mm-wave continuum data (Keene, Hildebrand, and Whitcomb 1982; Wright and Vogel 1985; Masson *et al.* 1985) and NH_3 observations (Genzel *et al.* 1982) is one to a few times 10^{24} cm^{-2}. Most of this material is located within $\approx 10''$ around IRc2. The low-velocity outflow or plateau gas probably has a total H_2 column density of a few times 10^{23} cm^{-2} (Blake *et al.* 1987; beam dilution correction applied). The HCN column density derived from the comparison of several rotational and isotopic lines implies a rather high HCN fractional abundance of $\sim 3 \times 10^{-7}$ (Blake *et al.* 1987). The area filling factor of the very high density material must be close to unity within the core region, so that the observed HCN $J = 9$–8 brightness temperature is consistent with the temperatures inferred in the core region. The length scale derived by dividing the total H_2 column density by a density of 10^8 cm^{-3} is a few times 10^{15} cm, almost two orders of magnitude smaller than the probable linear extent of the region. Assuming that the H_2 column density quoted above does not substantially underestimate the true column density, we conclude that the very high density material is located in a thin shell or sheetlike structures around IRc2 which fill only a small fraction of the volume.

The derived density, temperature, and velocity gradient, as well as the inferred sheetlike geometry, suggest that the sub-mm HCN emission may come from highly compressed postshock gas in shock fronts created either by the outflow hitting the surface of dense, cooler molecular material at the boundary of the cavity around IRc2, or clumps in the outflow colliding with each other. The derived physical parameters are similar to those inferred from the OH far-IR line emission (Melnick, Genzel, and Lugten 1987). The situation is somewhat puzzling, as on the other hand the wider OH line profiles seem to be more similar to that of the shocked gas traced in CO. The CO emission, however, probably traces gas with substantially lower densities ($\sim 10^6$ cm^{-3}), but much higher temperatures (up to 1000 K) than either the HCN or OH lines.

c) The Hot Core Component

The narrow emission component at $v_{LSR} = 6$ km s^{-1} has line parameters very similar to the typical hot core emission. If this emission component is a local high-density clump near IRc2, it has to be very bright. If the source size is 6″, comparable to the one derived for vibrationally excited HC_3N emission (Goldsmith, Krotkov, and Snell 1985), the beam-filling correction gives an intrinsic brightness temperature of 790 ± 260 K for the HCN $J = 9 \rightarrow 8$ line (the error combines the calibration uncertainty and the ambiguity in the two component Gaussian decomposition). The 14 μm continuum emission from IRc2 (approximated by a 700 K blackbody of 1″ diameter; Wynn-Williams *et al.* 1984), diluted by a factor ~ 36 in a source of $\sim 6''$ extent, cannot provide enough photons for IR pumping. Collisional excitation of the observed HCN $J = 9 \rightarrow 8$ emission would require a substantial amount of many hundred K gas with very high densities, not detected in any other molecular transition.

The excitation constraints are less severe if the HCN $J = 9 \rightarrow 8$ hot core emission is more extended, e.g., on the order of 10″, similar to the ammonia metastable lines (Genzel *et al.* 1982; Pauls *et al.* 1983). For this size, the beam dilution correction gives an intrinsic brightness temperature of 300 ± 90 K. This temperature is in the upper range, but consistent with, those derived from other molecular line observations. The excitation requirements in the hot core derived from the radiative transfer calculations are similar to those in the plateau. The higher total column density combined with the narrower linewidth pushes the optical depth up. This is partly outweighed by the higher temperature. Trapping is thus slightly more important than for the plateau gas. The almost thermalized HCN $J = 9 \rightarrow 8$ emission requires hot core densities between 10^7 and 10^8 cm^{-3} for excitation.

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