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THE DETECTION OF THE $J = 3$–2 LINES OF HCN, HNC, AND HCO^+ IN THE ORION MOLECULAR CLOUD

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ABSTRACT

We report the first measurements of the 1.1 mm ($J = 3$–2) lines of HCN, HNC, and HCO^+ in the Orion molecular cloud. The low-intensity broad velocity wings seen in the (1–0) lines of HCN and HCO^+ are greatly enhanced in the HCN (3–2) line but not in HCO^+ (3–2). No broad wings are seen in the HNC (3–2) line. The HCN observations suggest molecular hydrogen densities $\sim 10^6$ cm^{-3} in the broad wing source, and the differences between the lines of HCN and HCO^+ suggest that the lines may be formed in different regions within the source.

Subject headings: interstellar: molecules — line identifications — nebulae: Orion Nebula — radio sources: lines

I. INTRODUCTION

Comparison of several rotational transitions of interstellar molecules is an important diagnostic in determining the physical conditions in the regions of line formation. In this paper we report the first detections of the 1.1 mm $J = 3$–2 lines of HCN (265.9 GHz), HNC (272.0 GHz), and the molecular ion HCO^+ (267.6 GHz), in the Orion molecular cloud.

The spatially extended hot center of the Orion molecular cloud may be characterized by a radial velocity $V_{LSR} = 8$–9 km s^{-1}, molecular line widths $\Delta V \lesssim 6$ km s^{-1}, and a kinetic temperature $T_K \approx 90$ K. In addition, toward the center of the cloud in the direction of the Kleinmann-Low (KL) nebula and the Becklin-Neugebauer source, many molecular lines reveal a localized source with broad emission wings, $\Delta V \gtrsim 30$ km s^{-1}, and a radial velocity similar to the extended cloud. Mapping of this broad velocity source in the CO (3–2) line (Phillips *et al.* 1977) has shown it to be small ($37'' \times < 22''$) and situated at or near the front of the extended cloud, with a kinetic temperature $T_K \gtrsim 100$ K, and a density $n(H_2) \gtrsim 5 \times 10^5$ cm^{-3}. We discuss our observations of the $J = 3$–2 lines of HCN, HNC, and HCO^+ in relation to the equivalent $J = 1$–0 lines, in both the extended "spike" source and the localized, broad velocity "plateau" source (Zuckerman and Palmer 1975).

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II. OBSERVATIONAL TECHNIQUES

Observations were made in 1977 April and September at the prime focus of the Hale 5 m telescope on Mount Palomar. The telescope-receiver configuration has a theoretical beamwidth of 47″ at the observing frequencies, and positions could be determined to within ±10″.

The receiver used was an InSb hot electron bolometer detection scheme similar to that described by Phillips *et al.* (1977). It was operated in a single channel mode with a bandwidth of 1 MHz, corresponding to a resolution of 1.1 km s^{-1} at the observing frequencies. Spectra were obtained by frequency-scanning the single channel at a rate of 100 ms per frequency element, and by position-switching the telescope every 2.5 minutes. The system noise temperature was approximately 800 K, and atmospheric losses measured during the observations were typically 1.8 dB per air mass. Line temperatures are given in the form T_A^*, antenna temperatures corrected for all telescope and atmospheric losses, and the scale is estimated to be accurate to ±20%.

III. OBSERVATIONAL RESULTS

Figure 1 shows the HCN (3–2) spectrum obtained at the position of the KL nebula near the center of the Orion molecular cloud. All hyperfine components of the line are within 2.1 MHz (2.4 km s^{-1}) of the unsplit frequency and are unresolved by our observations. No

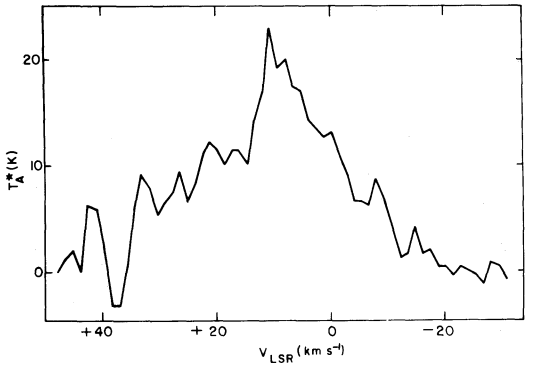

FIG. 1.—The HCN(3–2) spectrum at the position of KL, $\alpha = 5^h32^m46^s.7$, $\delta = -5°24'24''$ (1950.0). The velocity axis is with respect to the unsplit frequency of 265.8864 GHz given by Maki (1974). The data have been smoothed to an effective resolution of 3.8 km s^{-1}, and no baseline has been removed.

baseline has been removed from the data since emission probably extends over the whole range of velocities observed (80 km s^{-1}). Unlike the 1–0 line, the 3–2 line is not readily separable into broad and narrow velocity components due to the great enhancement of the high-velocity wings. We estimate a peak temperature for the broad velocity emission of about 10 K for the 3–2 line, compared with 3.8 K for the 1–0 line measured by Gottlieb *et al.* (1975). In contrast, Figure 2 shows the HCN (3–2) spectrum at a position away from the localized broad velocity source 2′ south of KL. There is no evidence of any broad velocity feature.

Figure 3 shows the HCO^+ (3–2) spectrum at the position of KL. The precise frequency of the line is not known, and the velocity axis here has been constructed by assuming that the 3–2 line center corresponds in velocity to that of the 1–0 line at this position (+8.66 km s^{-1}, Turner and Thaddeus 1977). The HCO^+ (3–2) spectrum shows some evidence of a weak, broad velocity emission feature ($T_A^* \approx 1.5$ K), extending about ± 25 km s^{-1} from the line center. This is similar in intensity to that observed for the 1–0 profile at this position; we estimate $T_A^* = 1.4$ K from the spectrum of Turner and Thaddeus (1977).

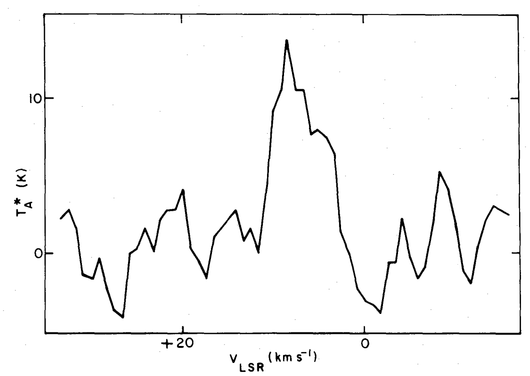

FIG. 2.—The HCN(3–2) spectrum at a position 2′ south of KL, smoothed to an effective resolution of 2.8 km s^{-1}. Linear baselines have been removed in Figs. 2–4.

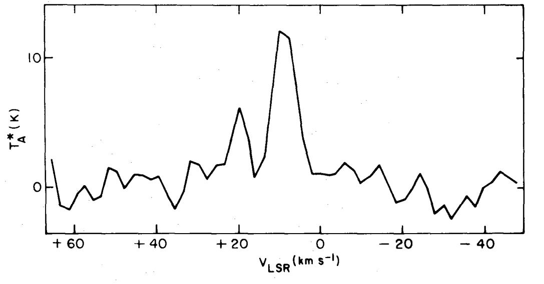

FIG. 3.—The HCO^+(3–2) spectrum at the position of KL. The velocity axis is appropriate to the adopted rest frequency of 267557.2 MHz, and the data have been smoothed to an effective resolution of 4.0 km s^{-1}.

Figure 4 shows the HNC (3–2) spectrum at the position of KL. The HNC (3–2) spectrum shows no broad velocity emission feature, but broad wings of peak temperature $\lesssim 4$ K cannot be precluded. We are not aware of detection of broad velocity wings in the HNC (1–0) line.

IV. DISCUSSION

a) The Extended Cloud

While the extended Orion molecular cloud, which gives rise to the narrow velocity component, has been observed in numerous molecular lines, there is no generally accepted simple kinematic and radiative transfer scheme that explains all the observations. Here we adopt the expedient of using the peak line temperatures to estimate molecular densities in a collapsing-sphere velocity gradient model (Goldreich and Kwan 1974). Using this model, together with the assumption of collisional excitation by molecular hydrogen, and a given value of the velocity gradient (V/R) and kinetic temperature (T_K), the intensity of each line of each molecular species (M) may be computed as functions of the density of the molecular species, $n(M)$, and $n(H_2)$. By simultaneously matching the observed and computed intensities for both the 1–0 and 3–2 lines, estimates for both $n(H_2)$ and $n(M)$ can be made. Given the assumptions, the resulting molecular density estimates are generally constrained by the observational uncertainties to within a factor

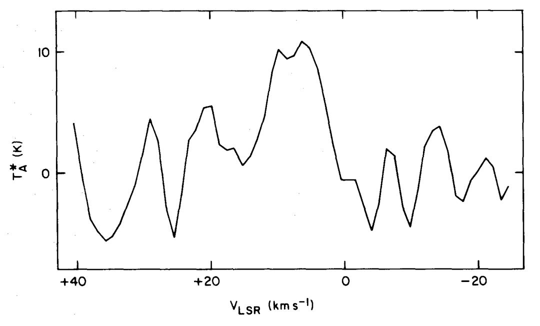

FIG. 4.—The HNC(3–2) spectrum at the position of KL. The velocity axis is appropriate to a rest frequency of 271982.6 MHz, and the data have been smoothed to an effective resolution of 2.2 km s^{-1}.

of 3. The estimates for $n(H_2)$ and $n(M)$ vary, respectively, independently and linearly with the adopted value of V/R; both are insensitive to the precise value adopted for T_K. For the extended cloud we adopt $V/R = 5$ km s^{-1} pc^{-1} and $T_K = 100$ K.

For HCO^+ we use the collisional rates suggested by Green (1975), and the 1–0 intensity given by Turner and Thaddeus (1977), assuming the source is extended over the 1–0 main beam, but with a 30% correction for error pattern losses. By matching the computed and observed intensities of both the 3–2 and 1–0 lines we derive a molecular hydrogen density $n(H_2) \approx 3 \times 10^5$ cm^{-3}, and an abundance ratio $n(HCO^+)/n(H_2) \approx 2 \times 10^{-10}$.

For HCN the situation is complicated by the highly developed 3–2 broad wings and by the hyperfine splitting of the line. First we note that the intensities of the HCN (1–0) narrow velocity features at the position of KL and 2′ south are essentially the same (Gottlieb *et al.* 1975). Within the noise level this also holds for the observed 3–2 lines ($T_A^* \approx 11$ K) if the intensities of the broad and narrow velocity features at the position of KL are simply additive. This will be the case if the broad velocity source is at or near the front of the extended cloud, and is optically thin or small compared with the observing beam. Observations of the CO line (Phillips *et al.* 1977) show that the broad velocity source is either near the front or in front of the extended cloud and is small, which suggests that $T_A^* \approx 11$ K is a reasonable estimate of the actual spike temperature of the 3–2 line at KL. A detailed treatment of the resolved hyperfine structure of the 1–0 line by Gottlieb *et al.* (1975) yields the molecular abundances $n(H_2) = 1$–3×10^5 cm^{-3} and $n(HCN)/n(H_2) = 2$–6×10^{-10}. At the 3–2 line the hyperfine splitting is smaller than the line width and is not resolved by our observations. A simple velocity-gradient calculation for the 3–2 line, using $n(H_2) = 3 \times 10^5$ cm^{-3} from the HCO^+ lines, and ignoring any hyperfine effects, yields $n(HCN)/n(H_2) \approx 3 \times 10^{-10}$, in agreement with the results of Gottlieb *et al.* (1975).

For the HNC line the data are less secure. The available 1–0 data (Snell and Wootten 1977) have been obtained with a large (2ʹ.9) beam which is comparable with the extent of the lines of some high-dipole-moment molecules; the actual extent of the HNC emission has not been measured, and we adopt a simple beam dilution of a factor of 2 for the 1–0 line. In addition, our 3–2 spectrum was obtained under uncertain atmospheric conditions, and the uncertainty in the temperature scale exceeds the value given in § II. A velocity gradient calculation using $n(H_2) = 3 \times 10^5$ cm^{-3}, assuming collisional rates equal to those for HCN and ignoring hyperfine effects, yields $n(HNC)/n(H_2) \approx 0.5 \times 10^{-10}$ and 3×10^{-10} for the 1–0 and 3–2 lines, respectively. In view of the uncertainty in the data the difference is not considered significant.

At this stage, detailed discussion of the radiative transfer scheme used here to interpret the lines seems unwarranted. However, we note that similar analysis of the CO isotopic lines at the center of the extended cloud (Phillips and Huggins 1977; Goldsmith, Plambeck, and Chiao 1975) yields much lower densities for molecular hydrogen. This may suggest that a simple velocity-gradient analysis of the lines is not appropriate, and that other effects including turbulence and fragmentation may influence the line intensities. Several models have recently been discussed by Kwan (1978), where some indication of the differences to be expected are given.

b) *The Broad Velocity Source*

The small size of the broad velocity source ($\sim 37'' \times < 22''$, in the CO (3–2) line; Phillips *et al.* 1977) presents severe beam dilution problems, particularly at lower frequencies; at the frequencies of the 1–0 lines of HCN and HCO^+, the highest available resolution is with a main beam of width $\sim 75''$, indicating dilution factors $\gtrsim 7$.

Because of the close coincidence in the frequency the HCO^+ and HCN lines, the result in these lines can be compared independently of details of the source size and differential beam dilution effects, provided the lines are formed cospatially within the source. We note that the intensity of the broad velocity emission of HCN (3–2) is considerably enhanced over that in the HCN (1–0) line, while the broad velocity emission of HCO^+ (3–2) is not enhanced over that in the HCO^+ (1–0) line. The difference in the behavior of the lines is significant and surprising in view of their similar dipole moments ($\mu_{HCN} = 3.0$ D and $\mu_{HCO^+} \approx 3.3$ D, estimated by Woods *et al.* 1975), and the increased molecular hydrogen collisional rates of HCO^+ over HCN by a factor of about 2 (Green 1975; Green and Thaddeus 1974). HCO^+ should therefore be slightly more easily excited into the upper levels, in contrast to our observations.

In an attempt to estimate the general level of molecular densities within the broad velocity source, we adopt as parameters for the region, $T_K = 100$ K, a simple Gaussian spatial distribution of width 29″ to estimate beam dilution effects, and a velocity gradient model with $V/R = 500$ km s^{-1} pc^{-1}; these values correspond approximately to the maximum size and minimum temperature of the region inferred from the CO (3–2) results (Phillips *et al.* 1977). After due allowance for the beam and error patterns of the observations, we can estimate the intrinsic line temperatures of the 1–0 line and 3–2 lines of HCN and HCO^+, and derive molecular abundances by simultaneously matching the observed and computed line intensities. Collisional excitation by molecular hydrogen is assumed, and the hyperfine splitting of HCN is ignored since it is much smaller than the observed line width.

From the HCN lines we obtain $n(HCN)/n(H_2) \approx 2 \times 10^{-8}$ and $n(H_2) \approx 2 \times 10^6$ cm^{-3}. From the HCO^+ lines we obtain $n(H_2) \approx 1 \times 10^5$ cm^{-3} and $n(HCO^+)/n(H_2) \approx 6 \times 10^{-8}$. These values may be compared with the value $n(H_2) \gtrsim 5 \times 10^5$ cm^{-3} derived by Phillips *et al.* (1977) from CO observations. In view of our highly simplified picture of the plateau region, the differences in the general level of the molecular abundances estimated from the HCN and

HCO^+ lines are probably not significant. However, the differences in the derived values for $n(H_2)$ do reflect the different behavior of the lines of the two molecular species. As noted above, these could be accounted for by spatial variations in the physical conditions or chemical abundances within the source. In particular HCO^+ may be preferentially found within the lower-density regions of the source. We also note that the abundance ratios of both HCN and HCO^+ relative to molecular hydrogen may be greater in the broad velocity source than in the extended cloud. A similar examination of the CO data of Phillips and Huggins (1977) and Phillips *et al.* (1977) suggests that this may not be true for CO, although the situation is obscured by the anomalous behavior of the isotopic lines in the extended cloud, as discussed in § IV*a*.

While our discussion of the broad velocity source has been necessarily tentative, it may relate to other aspects of the source.

First, the strong, broad velocity features seen in H_2S, SiO, SO, and SO_2 (Thaddeus *et al.* 1972; Buhl *et al.* 1975; Dickinson *et al.* 1976; Gottlieb and Ball 1973; Wannier and Phillips 1977) may be indicative of real abundance differences in the gas phase between the broad velocity source and the extended cloud.

Second, the broad velocity molecular emission may arise in cooled gas behind shock fronts (Kwan and Scoville 1976). The observed molecular abundances would then be dependent on the details of the post-shock chemistry. In addition, the presence of shocks can lead to the destruction of grains by sputtering and collisions (Aannestad 1973; Shull 1977) which can result in a substantial release of the elements locked therein. The depletions of C, N, and O by factors of about 5 seen toward unreddened stars (Spitzer and Jenkins 1975) may indicate a potential reservoir of these elements available to shock release in quiescent dense clouds.

That the abundances of HCN and HCO^+ can vary widely within the broad velocity source is clearly a possibility. How they depend on the local conditions could be a question for detailed modeling of the post-shock regions.

c) *Molecular Line Frequencies*

The $J = 3\text{–}2$ lines of both HCO^+ and HNC have not previously been observed in the laboratory, and their precise frequencies are not known. Both molecules were first identified in interstellar clouds by their $J = 1\text{–}0$ lines. Our detection of the $J = 3\text{–}2$ lines of both HCO^+ and HNC near the expected frequencies is in agreement with these identifications, and allows the measurement of astronomical rest frequencies for these lines.

For HNC, if we assume the observed 3–2 line corresponds in velocity to that of the 1–0 line at the same position ($+8.8$ km s^{-1}, Snell and Wootten 1977), we derive an astronomical rest frequency of 271982.6 ± 1.1 MHz for the 3–2 line, which is consistent with the value of 271981.1 ± 0.6 MHz inferred from the laboratory constants measured by Pearson *et al.* (1976).

Similarly, for HCO^+, if we assume the observed 3–2 line corresponds in velocity to that of the 1–0 line at the same position ($+8.66$ km s^{-1}, Turner and Thaddeus 1977), we derive an astronomical rest frequency of 267557.20 ± 0.46 MHz for the 3–2 line of HCO^+. Combining this with the laboratory frequency of the 1–0 line (Woods *et al.* 1975), and ignoring small systematic uncertainties in that measurement due to ion drift velocities, we derive the following rotational constants for HCO^+: $B_0 = 44594.448 \pm 0.015$ MHz and $D_0 = 87.9 \pm 4.8$ kHz. The stretching constant for the isoelectronic HCN is 87.24 kHz (Maki 1974).

V. CONCLUSION

We have made the first measurements of the 1.1 mm $J = 3\text{–}2$ lines of HCN, HNC, and HCO^+ in the Orion molecular cloud. Comparison of these lines with the equivalent 1–0 lines in the extended cloud indicates abundances for these molecular species in the range 10^{-10} to 10^{-9}, relative to molecular hydrogen, and a molecular hydrogen density $\approx 3 \times 10^5$ cm^{-3}. This latter value is consistent with values of $n(H_2)$ derived from observations of CS, DCN, and H_2CO, but not from CO (Phillips and Huggins 1977; Goldsmith, Plambeck, and Chiao 1975). The CO results may indicate that a simple velocity-gradient interpretation of the lines may not be correct.

Our observations of the broad velocity source show that the 3–2 lines of HCN and HCO^+ are not similarly enhanced over the 1–0 lines, and may indicate that the lines are formed within different regions of the source. In addition, HCN and HCO^+ may be more abundant relative to molecular hydrogen than in the extended cloud.

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