THE ASTROPHYSICAL JOURNAL, 385:240–243, 1992 January 20

DETECTION OF HCO^+ $J = 9 \rightarrow 8$ LINE EMISSION TOWARD ORION IRc2: MOLECULAR IONS IN HOT DENSE GAS

D. T. JAFFE,[1] U. U. GRAF,[2] A. I. HARRIS,[2] J. STUTZKI,[2,3] AND S. H. LEPP[4]

Received 1991 March 14; accepted 1991 August 1

ABSTRACT

We have detected the HCO^+ $J = 9 \rightarrow 8$ 802.458 GHz transition toward IRc2 in Orion. The line width implies that the emission originates in the low-velocity flow/doughnut most likely 10" or less from IRc2. If the line is optically thin, the density in the line-forming region is 10^7 cm^{-3} or higher. If the HCO^+ line arises in the same $\sim 10'' \times 20''$ source as other lines with similar width, the total column density of HCO^+ is 3×10^{14} cm^{-2} or higher, implying a line-of-sight averaged abundance 2×10^{-9} or more. This abundance is significantly greater than would be expected in a high-density region. Equilibrium chemical models predict an abundance more than an order of magnitude lower than observed. Enhancement of HCO^+ by local ultraviolet and X-ray fields is probably also insufficient to explain the observations. Time-dependent enhancement of the HCO^+ abundance in shocks may offer an explanation, if initial conditions are appropriate, but published models are not relevant to the conditions immediately around IRc2. Under some circumstances, mechanisms which lower the electron abundance may also be able to raise the HCO^+ abundance to the observed value.

Subject headings: line: identification — ISM: individual (Orion IRc2) — ISM: molecules

1. INTRODUCTION

Chemical models of dense ($n_{H_2} \sim 10^4$ cm^{-3}), cool ($T = 10$–20 K) molecular clouds accurately predict abundances for most common molecules (Langer & Graedel 1989). These models explain the production of molecules with extensive networks of ion-molecule reactions driven by cosmic-ray ionizations (Herbst & Klemperer 1973; Watson 1974; Prasad & Huntress 1980). A key prediction of these early ion-molecule chemical models is a high abundance of molecular ions. The formyl ion, HCO^+, is one of the most easily observable of these molecular ions. It has a high dipole moment, and its fundamental rotational transition lies in the 3 mm range. The detection of interstellar HCO^+ greatly strengthened arguments for ion-molecule chemistry. Klemperer (1970) had suggested that an unidentified line at 88.190 GHz (Buhl & Snyder 1970) could be a line of HCO^+. Laboratory spectroscopy of HCO^+ subsequently confirmed this identification (Woods et al. 1975).

Lines of HCO^+ are observable not only in cool clouds but also in hotter regions—both quiescent clouds around luminous protostars (Turner & Thaddeus 1977) and more dynamically active regions including high-velocity flows in star formation regions (Loren & Wootten 1980; Olofsson et al. 1982) and material impacted by the supernova-driven shocks in IC 443 (Dickinson et al. 1980). In warm, dense regions like the Orion core and in other regions where there may be shock heating, the chemistry differs considerably from the cosmic-ray–driven equilibrium models. Shocks will cause a wide range of changes in physical conditions—compression, heating, ion-neutral streaming—all of which will affect the abundance of various molecules. The equilibrium chemistry of warm, ultra-dense ($T \geq 100$ K, $n_{H_2} \geq 10^7$ cm^{-3}) regions will also differ from the classical cool cloud models. Some reaction rates have strong temperature dependences. Elemental abundances may be different as a result of evaporation of grain mantles.

In order to study HCO^+ selectively in warm, dense gas, we have observed the $J = 9 \rightarrow 8$ transition toward IRc2 in Orion. This transition is strong enough to be detectable only in the highest excitation material because of its high critical density (9×10^7 cm^{-3}; see below) and the high energy of its upper state ($E/k = 193$ K). We report the detection of this line and discuss the excitation required to produce the observed line strength, the abundance of HCO^+ in the warm, dense gas in the Orion–KL core, and the consequences for chemical models of this region.

2. OBSERVATIONS AND RESULTS

We observed the $J = 9 \rightarrow 8$ transition of HCO^+ at 802.458 GHz (373.593 μm; Blake et al. 1987a) in 1988 February with the UC Berkeley/MPE laser heterodyne spectrometer (Harris et al. 1987) mounted on the UKIRT on Mauna Kea. The far-IR $^{15}NH_3$ laser local oscillator frequency was 802.986 GHz. For this experiment, we used a room-temperature corner cube mixer followed by a room-temperature IF amplifier and a dual acousto-optical spectrometer with 1200 resolution elements across a 1000 MHz band. The receiver temperature measured at the telescope ranged from 8000 to 10,000 K single sideband.

The HCO^+ $J = 9 \rightarrow 8$ spectrum shown in Figure 1 was taken toward IRc2 in the Orion–KL complex. The telescope secondary switched the 24" beam (full width at half-maximum) at ~2 Hz between the source and two reference positions 2'.5 east and west of IRc2. Total integration time (on and off source) was 75 minutes. The sky transmission at zenith varied from 0.16 to 0.20 during the observations. The vertical scale in Figure 1 is Rayleigh-Jeans main-beam brightness temperature (T_{MB}) determined from the line antenna temperature, sky transmission, and telescope main-beam efficiency ($\eta_{MB} = 0.31$) following Harris (1986). A single-component Gaussian fit to the

---

[1] Department of Astronomy, R. L. Moore Hall, University of Texas at Austin, Austin TX, 78712.

[2] Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, D-8046 Garching bei München, Germany.

[3] I. Physikalisches Institut, Universität zu Köln, Zülpicherstrasse 77, D5000 Köln 41, Germany.

[4] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

1992ApJ...385..240J

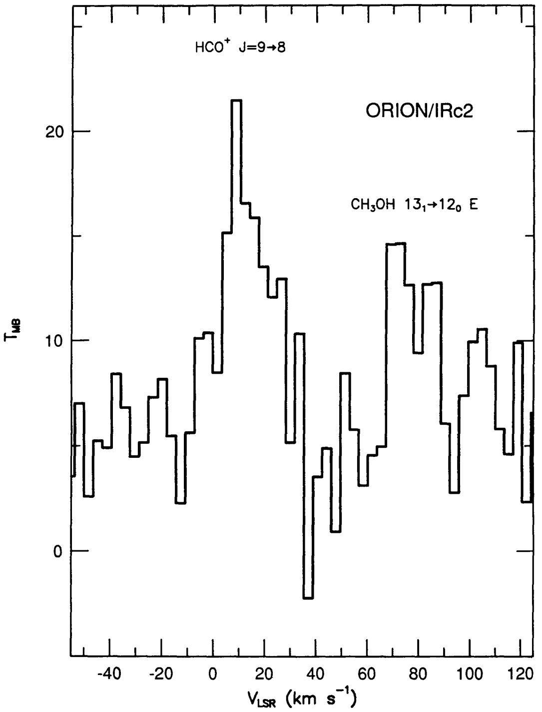

FIG. 1.—Spectrum of HCO$^+$ $J = 9 \rightarrow 8$ toward Orion IRc2. The LSR velocity scale is correct for the HCO$^+$ line.

HCO$^+$ $J = 9 \rightarrow 8$ line profile in Figure 1 gives a peak line temperature T_{MB} of 13.2 ± 1.6 K, a center velocity of 12.2 ± 1.3 km s^{-1}, and a line width of 23.2 ± 3.5 km s^{-1}. The methanol line appearing to the red of the HCO$^+$ $9 \rightarrow 8$ line has been discussed elsewhere (Stutzki et al. 1989).

3. DISCUSSION

3.1. *The Line Formation Region*

The observed line width and velocity indicate that the HCO$^+$ $9 \rightarrow 8$ emission arises predominantly in the low-velocity plateau gas within 10″ (~0.02 pc) of IRc2. The line parameters ($\Delta V = 23$ km s^{-1}, $V = 12$ km s^{-1}) are similar to those measured for the broad component of the HCN $9 \rightarrow 8$ transition toward the same region ($\Delta V = 30$ km s^{-1}, $V = 13$ km s^{-1}; Stutzki et al. 1988). Blake et al. (1987b) have assigned the spectral components in Orion core molecular lines to four regions: (1) the extended 9 km s^{-1} "spike," (2) the broad plateau, (3) the narrow plateau, and (4) the hot core. HCO$^+$ is present in at least three of these components. HCO$^+$ $1 \rightarrow 0$ spectra show strong emission from the spike and some broad plateau emission (Olofsson et al. 1982; Vogel et al. 1984). Most of the low-velocity plateau HCO$^+$, however, is concentrated in a 10″ × 20″ region around IRc2 overlapping the SO$_2$ "doughnut" but not coincident in detail with the SO$_2$ or other molecular features (Vogel et al. 1984). HCO$^+$ $4 \rightarrow 3$ data taken with beam sizes similar to the $1 \rightarrow 0$ single-dish work (N. J. Evans II 1989, personal communication; Jewell et al. 1989) show a stronger, broad (50–60 km s^{-1}) component and a weaker spike than the narrow $1 \rightarrow 0$ feature, as well as a hump indicating the presence of the low-velocity flow.

3.2. *Column Density*

The integrated intensity of the HCO$^+$ $J = 9 \rightarrow 8$ line is 300 K km s^{-1}. The column density (averaged over the beam) is 8×10^{12} cm^{-2} in the $J = 9$ state, assuming that the line is optically thin. Given the coupling factor of our 24″ beam to the 10″ × 20″ low-velocity plateau source, $\eta \simeq 0.26$, the true $J = 9$ column density is 3.3×10^{13} cm^{-2} or greater. We can use a crude assumption about excitation in the plateau to estimate the lower limit to the total column density of HCO$^+$: If HCO$^+$ is thermalized at the plateau gas temperature (150–200 K; Blake et al. 1987b) up to $J = 9$ and then is totally unpopulated at $J > 9$, the total column density of the molecule is 3×10^{14} cm^{-2}. Assuming LTE for the entire rotational ladder would lead to a column density ~50% higher. Subthermal excitation of HCO$^+$ or optically thick $J = 9 \rightarrow 8$ emission would result in still higher total column densities. The limit $N(\mathrm{HCO}^+) \geq 3 \times 10^{14}$ cm^{-2} is therefore conservative.

3.3. *Collision Rates*

There are no HCO$^+$ collision rates available either for high-temperature gas or for transitions to and from states with high rotational quantum numbers. Monteiro (1985) has calculated HCO$^+$–H$_2$ rates for $T \leq 30$ K and $J \leq 4$. We can supplement these rates by scaling up the $T \leq 40$ K, $J \leq 6$ N$_2$H$^+$–He collision rates of Green (1975) by a factor of 2.9 to match the HCO$^+$–H$_2$ rates at low temperatures and densities. We have used these low-J, low-temperature rates to extrapolate HCO$^+$–H$_2$ collision rates to higher temperatures and rotational states using the energy-corrected sudden-power law (ECS-P) technique (Smith & Pritchard 1980; Brunner & Pritchard 1982). Specifically, we have calculated a basis set of downward rates for $T = 40$ K and $J \leq 15$ by extrapolating the Green N$_2$H$^+$–He rates (scaled up by the factor of 2.9) to higher J with a power law. From these rates, we calculated fundamental downward rates (γ_{J0}'s). Table 1 lists these rates. We derived the full matrix of downward rates using the energy-corrected sudden approximation (DePristo et al. 1979) and the upward rates from detailed balance (see McKee et al. 1982). As a check, we recalculated the full collision-rate matrix for $T = 40$ K. The ECS-P values agree with the original scaled Green (1975) values to within 15%. Overall, the rates should be good to better than ±50%.

The downward collision rate γ from $J = 9 \rightarrow 8$ is 4.9×10^{-10} cm^3 s^{-1} at 200 K. The spontaneous radiative rate for the same transition, A, is 4.35×10^{-2} s^{-1} ($\mu = 3.91$ debye; Botschwina 1989). The critical density for $J = 9$, A/γ, is therefore $n_{\mathrm{crit}} = 9 \times 10^7$, about a factor of 20 smaller than the critical density for the same transition in HCN (Stutzki et al. 1988).

3.4. *Excitation*

The density in the HCO$^+$ $J = 9 \rightarrow 8$ line emission region must be $n_{\mathrm{H}_2} \geq 10^7$ cm^{-3} to produce the observed flux if the line

TABLE 1

HCO$^+$ COLLISION RATES

J_{upper}	$\gamma_{J0} \times 10^{10}$ (cm^3 s^{-1})	J_{upper}	$\gamma_{J0} \times 10^{10}$ (cm^3 s^{-1})
1..........	2.191	9..........	0.102
2..........	1.000	10..........	0.083
3..........	0.661	11..........	0.066
4..........	0.501	12..........	0.056
5..........	0.316	13..........	0.047
6..........	0.219	14..........	0.040
7..........	0.163	15..........	0.035
8..........	0.129		

is optically thin. We have used the collision rates derived from the fundamental rates in Table 1 to calculate the rotational population of HCO^+ and the line fluxes for 200 K gas over a range of densities, using the escape probability formalism to account for effects of radiative trapping. While the optically thin gas must have $n_{H_2} \geq 10^7$ cm^{-3}, optically thick 200 K gas with densities of 10^6 cm^{-3} or greater can reproduce the observed brightness. At $n_{H_2} = 10^6$ cm^{-3}, the required column density of HCO^+ is $\sim 2.3 \times 10^{15}$ cm^{-2}, about 7 times the column density needed to explain the optically thin emission.

3.5. *Abundance and Chemistry*

The abundance of HCO^+ is 2×10^{-9} or greater when the column density derived from $J = 9 \rightarrow 8$ observations is compared with the canonical low-velocity plateau H_2 column density of a few times 10^{23} (Blake et al. 1987b). This value agrees well with the previous estimate for the low-velocity flow/doughnut based on observations of HCO^+ $J = 1 \rightarrow 0$ (Vogel et al. 1984). In addition, the HCO^+/HCN abundance ratio based on observations of the $J = 9 \rightarrow 8$ transitions of both species toward this source agrees well with estimates based on observations of HCO^+ and HCN $J = 1 \rightarrow 0$ [$N(HCO^+)/N(HCN) \sim 0.01$: Stutzki et al. 1988; Vogel et al. 1984; this work]. The new result from the current HCO^+ measurement is that the high HCO^+ abundance persists in regions with high densities and temperatures. There is no satisfactory explanation for the high abundance of HCO^+, given these conditions.

What abundance should we expect for HCO^+ in the low-velocity flow? Elsewhere, observational estimates of HCO^+ abundances range from $\sim 8 \times 10^{-9}$ in the cold TMC-1 cloud down to $\sim 3 \times 10^{-9}$ in the warm ridge gas in OMC-1 (Irvine et al. 1984). Recent time-dependent models for dark clouds and for somewhat warmer regions like the Orion ridge agree well with these observations (Herbst & Leung 1986; Brown & Rice 1986; Langer & Graedel 1989). In quiescent gas, the dominant formation process for HCO^+ is the reaction

$$H_3^+ + CO \rightarrow HCO^+ + H_2 .$$

The principal destruction pathway is through dissociative recombination:

$$HCO^+ + e \rightarrow CO + H .$$

The dissociative recombination rate for HCO^+ depends roughly inversely on temperature and should therefore be smaller by about an order of magnitude in 250 K gas than in cold dark clouds (Adams, Smith, & Alge 1984). The dominant effect on the recombination rate in the low-velocity flow, however, is the increase due to the high density. We have constructed an equilibrium chemical model for the doughnut gas using a temperature of 250 K and an ionization rate of 10^{-17} s^{-1}, and setting the density to 10^8 cm^{-3} (based on the lower limit required by the HCN $9 \rightarrow 8$ observations; Stutzki et al. 1988). The predicted HCO^+ abundance (8×10^{-11}) is more than an order of magnitude lower than the observed abundance. The HCO^+ abundance in this equilibrium model is proportional to the ionization rate and inversely proportional to the electron density. For our model, the electron abundance is approximately equal to the abundance of metals (the model includes a generic metal ion representing all heavy elements with low ionization potentials), which we have taken as 3×10^{-8}. At very low metal abundances ($< 3 \times 10^{-9}$), the HCO^+ abundance will increase to 1×10^{-9}.

If HCO^+ is not uniformly mixed with the bulk of the low-velocity flow, the local abundance may be significantly higher than our lower limit of 2×10^{-9} in some of the warm, dense gas. What causes the abundance to exceed the values predicted by the quiescent models by such large factors? One possible explanation would be an ionizing source in addition to the cosmic-ray ionization included in the models. (The cosmic-ray rate itself would have to increase by a factor of 200 over the value used in our model to raise the HCO^+ abundance to 2×10^{-9}.) A less extreme enhancement of the cosmic-ray ionization rate (to $\sim 10^{-16}$ s^{-1}) can reproduce the observed HCO^+ abundance if grains can remove the electrons from gas so they cannot participate in dissociative recombination (Lepp & Dalgarno 1988). A grain abundance of 10^{-9} will yield an HCO^+ abundance of 2×10^{-9} at this cosmic-ray rate. The high X-ray flux from the dense Orion star cluster (Ku & Chanan 1979) has led to an analysis of how X-ray ionization influences the chemistry of dense molecular clouds (Krolik & Kallman 1983). High X-ray ionization rates can enhance the HCO^+ abundance by factors of up to ~ 3 in these models—significant but insufficient to account for the observed abundance.

Another possibility is that shocks may enhance the HCO^+ abundance. The HCO^+ abundance appears somewhat (factors of 1–10) elevated over quiescent cloud values in high-velocity gas in bipolar flows (Kuiper, Zuckerman, & Rodriguez-Kuiper 1981; Loren et al. 1984; Wootten et al. 1984). Early observational arguments for a greatly enhanced HCO^+ abundance in disturbed gas near the supernova remnant IC 443 (Dickinson et al. 1980; DeNoyer & Frerking 1981) may have been overstated (Ziurys, Snell, & Dickman 1989). Models of the IC 443 gas predicted a decrease in HCO^+ abundance as a result of the higher postshock densities (Iglesias & Silk 1978; Elitzur 1983). A temporary but significant increase in the abundance of HCO^+ is possible, however, if the preshock C^+ density is high enough, through the reaction

$$H_2O + C^+ \rightarrow HCO^+ + H$$

(Mitchell & Deveau 1983). A short time after the passage of the shock, however, the abundance of HCO^+ drops substantially. In models for high-velocity, dissociative shocks in dense gas (Neufeld & Dalgarno 1989), additional ionizing radiation produced by the immediately postshock gas results in HCO^+ column densities of up to $\sim 10^{14}$ cm^{-2}. The narrow HCO^+ $9 \rightarrow 8$ line width in Orion–KL makes it unlikely that a shock of this type is directly responsible for the observed HCO^+. However, shock-ionized material observed in hydrogen recombination line emission (Hasegawa & Akabane 1984; McKee & Hollenbach 1987) may increase the ionization rate in the doughnut gas. Further shock models with initial conditions more appropriate to the environment in the low-velocity flow are needed.

We would like to thank Reinhard Genzel and Herman Rothermel for help with the observations, and Neal Evans and Sheldon Green for helpful suggestions. This work was supported in part by NSF grant AST88-15801 to the University of Texas. D. J. acknowledges support from the David and Lucile Packard Foundation. S. L. was supported in part by NSF grant AST89-21939.

1992ApJ...385..240J

REFERENCES

Adams, N. G., Smith, D., & Alge, E. 1984, J. Chem. Phys., 81, 1778

Blake, G. A., Laughlin, K. B., Cohen, R. C., Busarow, K. L., & Saykally, R. J. 1987a, ApJ, 316, L45

Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987b, ApJ, 315, 621

Botschwina, P. 1989, in Ion and Cluster Ion Spectroscopy and Structure, ed. J. P. Maier (Amsterdam: Elsevier), 59

Brown, R. D., & Rice, E. H. N. 1986, MNRAS, 223, 405

Brunner, T. A., & Pritchard, D. 1982, in Dynamics of the Excited State, ed. K. P. Lawley (New York: Wiley), 589

Buhl, D., & Snyder, L. E. 1970, Nature, 228, 267

DeNoyer, L. K., & Frerking, M. A. 1981, ApJ, 246, L37

DePristo, A. E., Augustin, S. D., Ramaswamy, R., & Rabitz, H. 1979, J. Chem. Phys., 71, 850

Dickinson, D. F., Rodriguez-Kuiper, E. N., Dinger, A. S., & Kuiper, T. B. H. 1980, ApJ, 237, L43

Elitzur, M. 1983, ApJ, 267, 174

Green, S. 1975, ApJ, 201, 366

Harris, A. I. 1986, Ph.D. thesis, University of California, Berkeley

Harris, A. I., Jaffe, D. T., Stutzki, J., & Genzel, R. 1987, Int. J. Infrared Millimeter Waves, 8, 857

Hasegawa, T., & Akabane, K. 1984, ApJ, 287, L91

Herbst, E., & Klemperer, W. 1973, ApJ, 185, 505

Herbst, E., & Leung, C. M. 1986, MNRAS, 222, 689

Iglesias, E. R., & Silk, J. 1978, ApJ, 226, 851

Irvine, W. M., Schloerb, F. P., Hjalmarson, Å., & Herbst, E. 1984, in Protostars and Planets II, ed. D. C. Black & M. S. Mathews (Tucson: Univ. Arizona Press), 589

Jewell, P. R., Hollis, J. M., Lovas, F. J., & Snyder, L. E. 1989, ApJS, 70, 833

Klemperer, W. 1970, Nature, 227, 1230

Krolik, J. A., & Kallman, T. R. 1983, ApJ, 267, 610

Ku, W. H.-M., & Chanan, G. A. 1979, ApJ, 234, L59

Kuiper, T. B. H., Zuckerman, B., & Rodriguez-Kuiper, E. N. 1981, ApJ, 251, 88

Langer, W. D., & Graedel, T. E. 1989, ApJS, 69, 241

Lepp, S., & Dalgarno, A. 1988, ApJ, 324, 553

Loren, R. B., & Wootten, H. A. 1980, ApJ, 242, 568

Loren, R. B., Wootten, H. A., Sandqvist, A., Friberg, P., & Hjalmarson, Å. 1984, ApJ, 287, 707

McKee, C. F., & Hollenbach, D. J. 1987, ApJ, 322, 275

McKee, C. F., Storey, J. W. V., Watson, D. M., & Green, S. 1982, ApJ, 259, 647

Mitchell, G. F., & Deveau, T. J. 1983, ApJ, 266, 646

Monteiro, T. S. 1985, MNRAS, 214, 419

Neufeld, D. A., & Dalgarno, A. 1989, ApJ, 340, 869

Olofsson, H., Elldér, J., Hjalmarson, Å., & Rydbeck, G. 1982, A&A, 113, L18

Prasad, S. S., & Huntress, W. T. 1980, ApJS, 43, 1

Smith, N., & Pritchard, D. E. 1981, J. Chem. Phys., 74, 3939

Stutzki, J., Genzel, R., Graf, U. U., Harris, A. I., & Jaffe, D. T. 1989, ApJ, 340, L37

Stutzki, J., Genzel, R., Harris, A. I., Herman, J., & Jaffe, D. T. 1988, ApJ, 330, L125

Turner, B. E., & Thaddeus, P. 1977, ApJ, 211, 755

Vogel, S. N., Wright, M. C. H., Plambeck, R. L., & Welch, W. J. 1984, ApJ, 283, 655

Watson, W. D. 1974, ApJ, 188, 35

Woods, R. C., Dixon, T. A., Saykally, R. J., & Szanto, P. G. 1975, Phys. Rev. Lett., 35, 1269

Wootten, H. A., Loren, R. B., Sandqvist, A., Friberg, P., & Hjalmarson, Å. 1984, ApJ, 279, 633

Ziurys, L. M., Snell, R. L., & Dickman, R. L. 1989, ApJ, 341, 857