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RATIOS OF MOLECULAR HYDROGEN LINE INTENSITIES IN SHOCKED GAS: EVIDENCE FOR COOLING ZONES

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ABSTRACT

Column densities of molecular hydrogen have been calculated from 19 infrared vibration-rotation and pure rotational line intensities measured at peak 1 of the Orion molecular outflow. The run of column density with energy level is similar to a simple cooling zone model of the line-emitting region, but is not well fitted by predictions of *C*-shock models current in the literature.

Subject headings: infrared: spectra — interstellar: molecules — molecular processes — shock waves

I. INTRODUCTION

The discovery of line emission from shocked molecular hydrogen in the Orion molecular cloud OMC-1 (Gautier *et al.* 1976) stimulated a series of theoretical studies (Kwan 1977; London, McCray, and Chu 1977; Hollenbach and Shull 1977) of the structure of molecular shocks. Observations of an extremely supersonic range of velocities in the H_2 1–0 *S*(1) line profile (Nadeau and Geballe 1979) prompted several workers (Draine 1980; Chernoff, Hollenbach, and McKee 1982; Draine, Roberge, and Dalgarno 1983) to develop magnetically moderated *C*-shock models.

In this *Letter* we present data from the brightest part of the OMC-1 outflow, peak 1 ($5^h32^m46^s$, $-5°24'02''$ [1950] Beckwith *et al.* 1978). The data consist of a set of molecular hydrogen line intensities observed between 2 μm and 4 μm, which cover a wide range of upper level energies (6500–25,500 K).

II. OBSERVATIONS

All of the observations of peak 1 were made at the United Kingdom 3.8 m Infrared Telescope on Mauna Kea. Most of them utilized the facility cooled grating spectrometer. The beam diameter of this instrument was set to 5″; the resolving power was typically 500. Standard chopping and nodding (60″ EW) practices were employed. The stars BS 1552 and BS 1713 were used for flux calibration. All of the 3 μm lines were measured in 1985 November; most of the 2 μm lines were observed in 1987 January and February. In addition, during the latter period a number of the strong lines in the 2 and 3 μm bands were measured in a single scan so that their relative intensities could be determined. The reduced 2 μm spectrum from 1987 January is shown in Figure 1. The 3 μm spectrum has been published elsewhere (Geballe 1986).

Several 2 μm H_2 lines, including the 4–3 *S*(3) and 3–2 *S*(2) (which had not previously been observed), were measured at peak 1 in 1988 January. These data were obtained using the facility CVF spectrometer in series with an ambient temperature Fabry-Perot interferometer. The beam diameter was 12″, and the velocity resolution was ~120 km s^{-1}. Chopping and nodding practices were as above. The 1–0 *S*(1) line was measured with this instrument, so that the former two line intensities could be scaled to previously measured H_2 lines and thus be included in the analysis. The 4–3 *S*(3) line is the highest excitation H_2 line yet observed in the 2 μm band; its spectrum is shown inset in Figure 1 together with that of the 3–2 *S*(2) line.

III. ANALYSIS AND RESULTS

The intensities of lines measured by the cooled grating spectrometer were determined by least-squares fitting Gaussian profiles to the observed lines, together with polynomials to the continua. Because of pointing and beam size differences between the different observations sets, the spectra were scaled to one another using the previously described spectrum that contained lines common to the various 2 and 3 μm spectra. The resulting line intensities are presented in Table 1. We note that the relative intensities of the 2 μm lines measured by us are consistent with those observed by Oliva and Moorwood (1988).

Of the approximately 30 H_2 lines detected, only those 19 lines whose intensities were believed to be free from significant uncertainties (e.g., due to attenuation by telluric absorption lines) were considered for further analysis. Observed column densities, N_0 (assuming no extinction), were determined from the observed intensities using transition probabilities from Turner, Kirby-Docken, and Dalgarno (1977). The extinction may be estimated by comparing intensities of lines which arise from a common upper energy level. In the present data set the 1–0 *S*(1), 1–0 *Q*(3), and 1–0 *O*(5) lines may be used. Assuming $A_\lambda \propto \lambda^{-1.5}$ we determine that $A_K = 0.8 \pm 0.3$. The dereddened column densities in the last column of Table 1 assume this form of the extinction law. If it is assumed that $A_\lambda \propto \lambda^{-1.0}$, the derived extinction is $A_K = 1.0 \pm 0.3$. However, the derived ratios of dereddened column densities are not changed significantly from those in Table 1.

Figure 2 is a plot of the dereddened column density in each level divided by that predicted for a slab of gas at 2000 K. The data are presented in this way in order to show the deviation from such a constant temperature environment, which has often been considered to be characteristic of the H_2 line-emitting region. A Boltzmann distribution at any other temperature is a straight line in this diagram. The best-fit single excitation temperature for the data is ~2200 K, which is consistent with most previous observations of H_2 lines in OMC-1 (e.g., Knacke and Young 1981). However, it is clear that no straight line will be a satisfactory fit to all of the data points.

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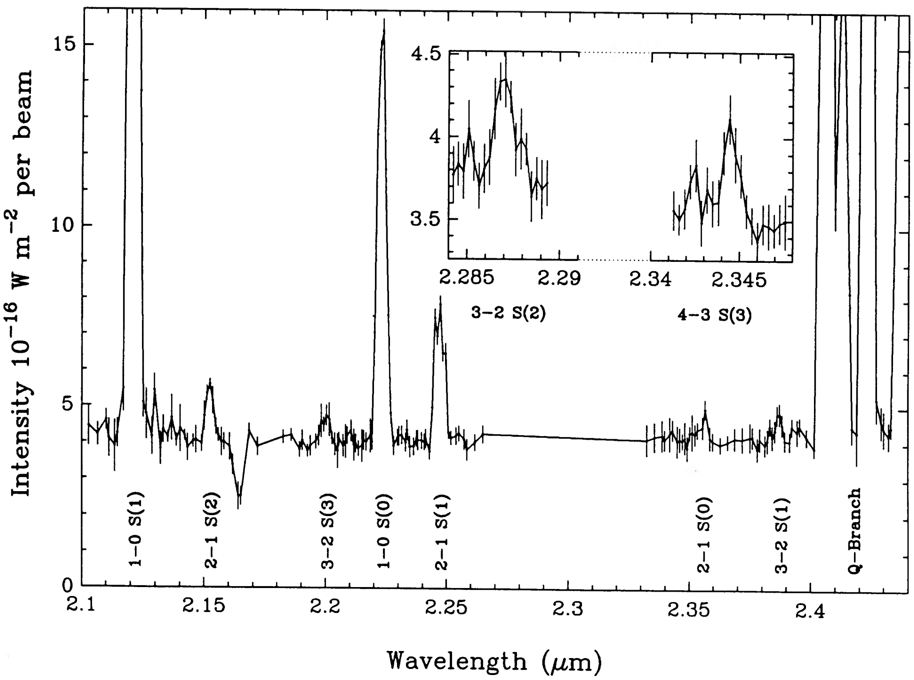

FIG. 1.—Raw 2 μm spectrum from 1987 January, obtained at a resolution of 0.004 μm. Lines used in the analysis are labeled. The feature at 2.166 μm is due to Brγ in the offset beam. The inset is the spectrum of the 3–2 $S(2)$ and 4–3 $S(3)$ lines, at a resolution of 0.0009 μm, and with the same flux scale as the main diagram.

TABLE 1

PARAMETERS AND INTENSITIES OF OBSERVED H_2 LINES

Line	Wavelength[a] (μm)	Upper Level Energy[a] (K)	Flux Density[b] (10^{-16} W m^{-2})	Dereddened Column Density[c]/g_j (10^{18} m^{-2})
1–0 $S(7)$[d]	1.7480	12818	4.2 ± 0.4	...
1–0 $S(1)$	2.1218	6956	50.1 ± 0.5	326.3 ± 2.9
2–1 $S(2)$	2.1542	13150	1.6 ± 0.1	14.8 ± 1.2
3–2 $S(3)$	2.2014	19086	0.8 ± 0.1	1.9 ± 0.2
1–0 $S(0)$	2.2235	6471	12.2 ± 0.2	467.5 ± 11.1
2–1 $S(1)$	2.2477	12550	4.3 ± 0.1	18.8 ± 0.8
3–2 $S(2)$	2.2870	18386	0.8 ± 0.2	2.5 ± 0.6
4–3 $S(3)$	2.3445	23955	0.5 ± 0.1	0.6 ± 0.1
2–1 $S(0)$	2.3556	12095	0.9 ± 0.1	22.5 ± 4.5
3–2 $S(1)$	2.3846	17818	0.8 ± 0.1	3.1 ± 0.8
1–0 $Q(1)$[d]	2.4066	6149	40.0 ± 5.0	...
1–0 $Q(2)$[d]	2.4134	6471	16.5 ± 2.0	...
1–0 $Q(3)$	2.4237	6956	45.1 ± 5.0	367.0 ± 41.0
1–0 $Q(4)$[d]	2.4375	7585	16.0 ± 2.0	...
1–0 $O(4)$[d]	3.0039	6471	13.4 ± 2.0	...
1–0 $O(5)$	3.2350	6956	25.7 ± 2.1	299.0 ± 25.0
2–1 $O(5)$[e]	3.4378	12550	2.1 ± 0.3	16.9 ± 2.4
0–0 $S(17)$	3.4857	25541	1.5 ± 0.5	0.21 ± 0.07
1–0 $O(6)$	3.5007	7584	4.3 ± 0.6	167.0 ± 22.0
0–0 $S(16)$	3.5475	23461	0.8 ± 0.4	0.38 ± 0.18
0–0 $S(15)$	3.6261	21413	3.5 ± 0.6	0.74 ± 0.13
2–1 $O(6)$[d]	3.7236	13150 }	2.2 ± 0.3	{ ...
0–0 $S(14)$[d]	3.7244	19405 }		{ ...
1–0 $O(7)$	3.8075	8365	9.2 ± 0.8	145.0 ± 12.0
0–0 $S(13)$	3.8461	17445	8.4 ± 0.9	3.11 ± 0.03
0–0 $S(12)$	3.9960	15542	3.8 ± 0.4	5.8 ± 0.6
2–1 $O(7)$[d]	4.0540	13891	1.4 ± 0.4	...

[a] Obtained from Dabrowski 1984.

[b] In a 5″ aperture at peak 1, except for the 3–2 $S(2)$ and 4–3 $S(3)$ lines, which were in a 12″ aperture. These latter two fluxes need to be divided by 2.9 to scale with those in a 5″ aperture [based on a measurement of the 1–0 $S(1)$ line through the 12″ aperture]. The 2 μm line fluxes combine two sets of measurements. The 3 μm line fluxes have been multiplied by a factor of 1.07 from the observed values based on a composite 2 and 3 μm spectrum.

[c] Assumes $A_\lambda \propto \lambda^{-1.5}$ with $A_K = 0.8$. All values apply to a 5″ aperture.

[d] Line detected, but either contaminated by telluric absorption lines, blended with other lines, or observed with incomplete spectral coverage. Intensities not reliable enough to be included in the analysis.

[e] Blended with 0–0 $S(18)$, but we estimate the contamination is $<5\%$.

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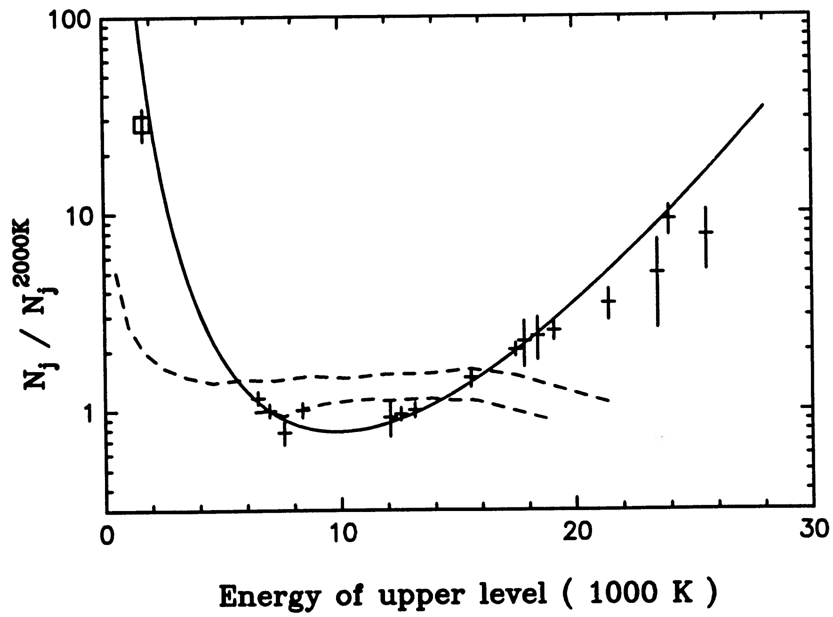

FIG. 2.—Plot of the ratios of observed, dereddened H_2 column densities to those from a Boltzmann distribution at 2000 K [normalized so that the 1–0 *S*(1) ratio is unity] vs. upper energy level. Error bars are $\pm 1\ \sigma$. The continuous line is from the cooling flow calculations described in the text, drawn through the 1–0 *S*(1) point. The dashed lines are the predictions of the *C*-shock models for OMC-1 by Draine and Roberge (1982) and by Chernoff, Hollenbach, and McKee (1982). The upper line is for pure rotational lines. The box represents the value of the 0–0 *S*(2) line observed by Beck *et al.* (1979).

The weak, high-excitation lines are considerably more intense than would be expected from a straight line fit based on the strong, low-excitation lines. Since weak and strong lines come from both the 2 and the 3 μm spectra and correspond to both ortho- and para-H_2, neither errors in scaling, errors in dereddening, nor any particular ortho-para ratio can be the cause of the curvature in the locus of data points in Figure 2.

A significant contribution to the high-v lines from fluorescence is highly unlikely at peak 1, since the intensity of the 3–2 *S*(2) line decreases with that of the 1–0 *S*(1) line just off-source, but within the ionized nebula. It is clear on theoretical grounds that intensities of the weak, high-*J* pure rotational lines at peak 1 cannot be significantly enhanced by fluorescent emission.

IV. DISCUSSION

The solid curve in Figure 2 is the prediction from a "toy" calculation (which nevertheless contains all the major features of the full calculation) of column density in the cooling zone behind a hydrodynamic shock. The cooling rate is taken to be $\Lambda = \Lambda_0 T^s$ W (H_2 molecule)$^{-1}$, with s set to 4.7 to match roughly the calculations (Hollenbach and McKee 1979; Burton 1986) of cooling by thermalized H_2. If the shock is strong enough, the H_2 column density per state at level j with energy T_j degrees Kelvin is approximately

$$N_j/g_j \propto \int e^{-T_j/T}(Q\Lambda)^{-1}\,dT \propto T_j^{-s} - (T_j + T_v)^{-s}\,, \qquad (1)$$

where the partition function Q is approximated by $AT(1 - e^{-T_v/T})$ with $T_v = 6000$ K.

A proper calculation of column density in a *J*-shock cooling zone, and a corresponding investigation of *C*-shocks, is being prepared for publication.

The cooling flow calculation described above provides a surprisingly good fit to the observed data. The apparent range of temperatures is naturally explained by the shape of the cooling function, independently of local conditions such as the shock velocity. This is consistent with other evidence (Brand *et al.* 1988) which shows that the ratio of a pair of H_2 lines with upper energy levels at 8365 K and 17,458 K respectively, is constant throughout the outflow.

In a calculation with the detailed shape of the cooling function properly treated, a better fit will result. Current *C*-shock models provide a poor fit to the wide range of H_2 data now available, and it appears that a superposition of several *C*-shocks may be required. The dashed curves are from the *C*-shock calculations by Draine and Roberge (1982) and Chernoff, Hollenbach, and McKee (1982).

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