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DETECTION OF VIBRATION-ROTATION BAND LINES OF SHOCKED CO IN ORION

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ABSTRACT

Three lines of the fundamental (4.7 μm) vibration-rotation band of CO have been detected in emission toward H_2 Peak 1 in the Orion Molecular Cloud, OMC-1. Both the velocities of maximum line intensity and the linewidths appear to be similar to those of the H_2 $S(1)$ line, implying that the bulk of the line emission occurs in a shock within the molecular cloud. The relative line intensities, which are coupled to the populations of rotational levels in the ground vibrational state, yield average gas temperatures of ~ 1000 K. The luminosity of the CO fundamental band is nearly one-half of that from shocked H_2, a considerably larger fraction than has been predicted previously. A search for Brα line emission at Peak 1 produced an upper limit for that line flux which, including extinction, is less than one percent of the H_2 $S(1)$ flux.

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

I. INTRODUCTION

The effects of a shock front propagating through molecular gas are determined largely by the speed of the shock and the preshock density of the gas. In the simplest cases they determine the temperature range in the postshock region and the molecular, atomic, and ionic species which are major contributors to the postshock cooling. Studies of the bright H_2 $S(1)$ line in Orion (Nadeau and Geballe 1979; Scoville *et al.* 1982; Nadeau, Geballe, and Neugebauer 1982) indicated that shock speeds there might range from 10 to ~ 100 km s^{-1}. The wide range of velocities suggests that in Orion conditions might be favorable for intense line emission from ions, neutral atoms, and molecules other than H_2.

Chevalier (1980) suggested that the faster shocks in Orion would ionize hydrogen and lead to recombination line emission. He estimated that the Brα line at 4.05 μm would be one order of magnitude less intense than the 2.12 μm $S(1)$ line of H_2. If correct, Brα should be readily detectable. Scoville *et al.* (1982) obtained an upper limit for Brγ (2.17 μm), which corresponds approximately to Chevalier's prediction. Due to the large extinction to the shocked gas and to the difference in transition rates, Brα is expected to be an order of magnitude brighter than Brγ. Thus a detection of Brα or a meaningful upper limit should be obtainable.

Pure rotational line emission from shocked CO has been detected in Orion by Storey *et al.* (1981) in the far-infrared. The CO column density which they infer is large enough that one might expect to detect lines of the fundamental (1–0) vibration-rotation band near 4.7 μm. The magnetohydrodynamic shock models of Draine and Roberge (1984) also suggest this, although they predict that the lines are detectable at present only for rather high speed shocks ($v_s > 35$ km s^{-1} in very dense molecular clouds ($n > 10^6$ cm^{-3}). If shocked CO and H I were detected, a comparison of their intensities and line profiles could be very important to the understanding of the shock process in molecular clouds.

This *Letter* describes the results and implications of an initial search for shocked 4.7 μm CO and 4.05 μm Brα line emission. The search has demonstrated that the CO lines may be detected without difficulty and that they contain new and useful information concerning the shock structure. The description and discussion of the CO measurements make up the bulk of this *Letter*; the Brα search and results are briefly described in the concluding section.

II. OBSERVATIONS

Searches for three 1–0 band CO lines, the $P(8)$, $P(3)$, and $P(26)$ were made at the United Kingdom 3.8 m infrared telescope (UKIRT) on the night of 1987 January 8. Spectra were obtained using a scanning Fabry-Perot interferometer of resolution 40 km s^{-1} in series with the facility cooled grating spectrometer (CGS2), which isolated one order of the Fabry-Perot and was scanned simultaneously with it to maintain best rejection at all wavelengths. A 5″ diameter beam was used. Standard chopping and nodding practices were employed; the chopper throw was 40″EW. Peak 1 was observed at the coordinates, R.A. = $5^h32^m46^s.2$, decl. = $-5°24'02''$ (1950).

Several spectra, sampled approximately every 20 km s^{-1}, were obtained in the wavelength region of each of the above CO lines. The $P(3)$ scan was extended to include the strong 0–0 $S(9)$ line of H_2, which is also shown. Typical total integration times were 1 minute per point. The summed Peak 1 spectra were flux-calibrated by dividing them by similar

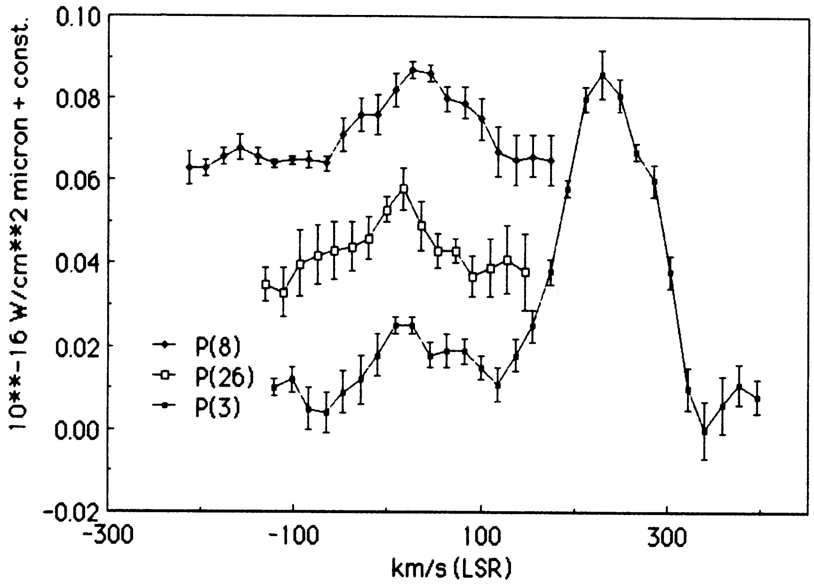

FIG. 1.—Spectra of three CO lines and the H_2 $S(9)$ line at Peak 1 in Orion. The spectra are plotted on a velocity scale appropriate for CO. The velocity resolution is 50 km s^{-1}. Error bars are ± 1 σ.

spectra of the bright star BS 1713 ($M = 0.02$ assumed). The spectral intervals of the $P(3)$ and $P(8)$ scans include strong absorption features due to telluric CO. However, the bulk of the line emission from Peak 1 was found to be redshifted beyond the half-power point of the telluric CO absorption; hence, the uncertainties in the CO emission line intensities are largely determined by factors other than telluric CO.

The final CO spectra are presented in Figure 1. Each spectrum has been Hanning-smoothed, resulting in a velocity resolution of 50 km s^{-1}. The velocity scale was determined from the telluric lines in the BS 1713 spectra and from lines observed in a CO absorption cell.

III. RESULTS

All three lines of CO are readily apparent in Figure 1. Relevant data pertaining to them and to the H_2 $S(9)$ line are summarized in Table 1. The strongest CO line of those observed, and the one for which the best signal-to-noise ratio was obtained, is the $P(8)$ line. This line has an observed FWHM of 120 ± 40 km s^{-1}. Allowing for the smoothed instrumental resolution of 50 km s^{-1}, we conclude that the intrinsic width is 70 ± 30 km s^{-1}. Both of the other lines appear to have narrower FWHMs, but all give the same result within the (large) uncertainties. By comparison the intrinsic FWHM of the H_2 $S(1)$ line at this position is ~ 60 km s^{-1} (Nadeau and Geballe 1979; Burton 1986).

The velocity of peak CO line emission is difficult to specify, because of the low signal-to-noise ratios of the spectra. Defined as the average of the velocity of the highest data point and the mean velocity of the two half-power points, and averaged over the three lines, it is $+15$ km s^{-1} (LSR) with an uncertainty of 10 km s^{-1}. This is very similar to the peak velocity of the H_2 $S(1)$ line emission at Peak 1 observed by Nadeau and Geballe (1979) and by Scoville *et al.* (1982). The profile of the $S(9)$ line in Figure 1 also appears to be similar to that of the $S(1)$ line. Thus, in the above two respects the description of the CO line profiles is quite like that of the H_2 lines. Obtaining additional details of the CO line shapes will require both better sensitivity and higher spectral resolution.

TABLE 1

LINES OBSERVED AT PEAK 1

Line Identification	Frequency (cm^{-1})	Peak Velocity (LSR km s^{-1})	Flux (10^{-20} W cm^{-2})
CO 1–0 $P(26)$......	2032.3	-7 ± 10	5 ± 1
CO 1–0 $P(8)$.......	2111.5	$+5 \pm 7$	9 ± 1
CO 1–0 $P(3)$.......	2131.6	0 ± 10	6 ± 1
H_2 0–0 $S(9)$	2130.1	$+8 \pm 10$	33 ± 3

No other CO lines were intentionally searched for. The frequency of the 2–1 $R(3)$ line occurs in the $P(3)$ scan, but is nearly coincident with the $P(3)$ line. The 2–1 lines are not expected to be detectable, because CO is almost certainly not in vibrational LTE (see below).

IV. DISCUSSION

The vibration-rotation band lines of CO are observed in emission from levels 3000–5000 K above the ground state. The lines have been detected far from any known starlike heating source and in positional coincidence with H_2 lines that are known to be excited by shock waves. In addition, the CO lines have peak velocities and widths comparable to the H_2 lines. Therefore, it is clear that the bulk of the CO line emission arises in the shocked gas. Some of the observed line emission at Peak 1 could be the result of resonant scattering of 4.7 μm photons from BN (and other embedded sources) off

CO in OMC-1. Such scattering would occur mainly in narrow velocity intervals centered on CO transitions involving low-J levels. Rough estimates suggest that resonant scattering might account for as much as 30% of the emission seen in the $P(3)$ and $P(8)$ lines but could not account for such a large percentage of the $P(26)$ line emission. Measurements of the polarization of 1–0 band CO lines might allow the contribution of resonant scattering to be determined.

It should be noted that the CO lines detected here and presumed to be extended over the entire region of shocked H_2 are too weak to be responsible for the CO fundamental band line emission observed toward BN by Scoville *et al.* (1983). A typical line flux seen by them in a 2".5 beam is 1×10^{-19} W cm^{-2}, which corresponds to a line surface brightness nearly an order of magnitude higher than that observed at Peak 1. Indeed, Scoville *et al.* conclude that the line emission at BN occurs at a radius of ~ 20 AU.

a) *Excitation Temperatures, Line Intensities, and Current Shock Models*

The shocked gas in OMC-1 has been modeled by many authors (most recently by Chernoff, Hollenbach, and McKee 1982 and Draine, Roberge, and Dalgarno 1983). There is agreement regarding its general behavior. In OMC-1 the preshock gas densities are thought to be ~ 10^5–10^6 cm^{-3}. The shock rapidly raises the gas temperature; if the temperature exceeds ~ 4000 K dissociation of H_2 cools the gas to that temperature, whereupon molecular line emission becomes the dominant cooling mechanism. Vibrational line emission from H_2 is thought to dominate the cooling until the vibrational levels cannot be excited by collisions, which occurs when the gas kinetic temperature falls below ~ 1000 K.

In the postshock gas ($10^6 < n < 10^7$ cm^{-3}, $1000 < T < 4000$ K) the H_2 is thought to exist close to or in rotational and vibrational equilibrium, due to the slow spontaneous decay rates of its excited rotational and vibrational levels (Turner, Kirby-Docken, and Dalgarno 1978; Beckwith *et al.* 1978). The situation is considerably different for CO. The $v = 0$ rotational levels with $J < 25$ are close to or in LTE (Storey *et al.* 1981). However, typical lifetimes in the $v = 1$ level are 1/20 s, whereas collisional vibrational relaxation times for the above density and temperature regimes are ~ 10^7 times longer (e.g., see Thompson 1973). Therefore, regardless of the kinetic temperature, the CO is confined to the ground vibrational state, except immediately after a vibration-exciting collision. The relative strengths of the fundamental band emission lines, which are optically thin, can be used to estimate the range of CO rotational temperatures in the ground vibrational state, which corresponds to the range of kinetic temperatures of the line-emitting gas if the CO rotational levels are in LTE.

The temperature which best fits the relative intensities of the three observed CO lines is ~ 1000 K. However, a single-temperature fit is a very poor approximation; the excitation temperature of the two lower J lines is ~ 500 K, and that of the two upper J lines is ~ 1500 K. All of these temperatures may be too low (perhaps by ~ 500 K), because (1) the low-J lines may contain a significant resonant scattering component, and (2) the $v = 0$, $J = 26$ population may be subthermal. The existence of different excitation temperatures is not surprising, as the column of gas being observed is cooling behind a shock. It is also not surprising that excitation temperatures associated with the 1–0 CO emission are lower than those usually associated with the 2 μm H_2 line emission. Because the upper energy levels of the observed CO transitions are lower than those observed for H_2 at 2–5 μm, they can be collisionally excited, and hence observed, further downstream from the shock.

The intensities of the 1–0 CO band lines are considerably higher than are predicted in shock models which match the H_2 and far-infrared CO line emission. For example, the average of the surface brightnesses of the three 1–0 CO lines detected, 1.1×10^{-10} W cm^{-2} sr^{-1} (uncorrected for extinction), is 15 times higher than that calculated by Draine and Roberge (1982) for their best-fitting magnetohydrodynamic shock of speed 38 km s^{-1}. A higher speed MHD shock would produce the observed CO line brightness (Draine and Roberge 1984). However, most of the emission would then likely occur at high temperatures, in contradiction to the observed rather low excitation temperatures derived from the 1–0 band CO lines.

b) *Comparison of* 1–0 CO, 0–0 CO, *and* H_2 *Luminosities*

Direct comparison of the luminosities of the fundamental CO band and the H_2 lines at Peak 1 also implies a high CO luminosity. This comparison is facilitated by the concurrent observation of the H_2 $S(9)$ line (Fig. 1), which is 5 times more intense than the average of the three CO lines. In order to compare the total line fluxes in these molecules at Peak 1 we multiply the average observed CO fundamental band line flux by 60 to account for all P and R branch CO line emission, and we multiply the $S(9)$ flux by 30, as we calculate that at 2000 K (a typical temperature in the H_2 line-emitting region), the S(9) line accounts for 3.4% of the line flux emitted by H_2. We then obtain $L(1\text{–}0\ \mathrm{CO})/L(H_2) \approx 0.4$. The total H_2 line luminosity is estimated to be 280 $L_\odot$ for an extinction of 2.5 mag at 2.1 μm (Beckwith *et al.* 1983); thus, if we assume that the Peak 1 5" beam measurements apply to the entire shocked gas region the CO 1–0 band luminosity is ~ 100 $L_\odot$.

A luminosity comparison between the CO far-infrared and fundamental band luminosities is also of interest. A typical strong far infrared line observed by Watson *et al.* (1985) using a 44" beam centered on BN has 10 times the surface brightness of the average of the fundamental band lines observed by us at Peak 1. Assuming that the CO line intensities scale linearly with H_2 line intensities, the above ratio becomes ~ 25 for lines that are observed in the same region. The luminosity of the entire far-infrared band is perhaps 10 times that of a single line (Watson *et al.* 1985); for the fundamental band the factor is approximately 60 and there is an additional factor of 2 for extinction. Thus, the far-infrared CO band luminosity is roughly twice that of the fundamental band, or 200 $L_\odot$. An independent estimate of the CO far-infrared luminosity of 125 $L_\odot$ is obtained from the measured and extrapolated far-infrared line strengths and the estimate that the flux-weighted area of the entire shocked gas region is three times that of the far-infrared beam. The luminosities of the

H_2, 1–0 CO, and 0–0 CO (roughly 280 $L_\odot$, 100 $L_\odot$, and 160 $L_\odot$, respectively) appear consistent with the idea that H_2 dominates the cooling from 4000 K to ~1500 K, all three contribute equally between ~1500 K and ~1000 K, and pure rotational CO lines dominate below ~1000 K.

c) *Column Lengths and Densities*

In understanding the role of vibrationally excited CO in the postshock gas, it is instructive to estimate the column length of CO involved in fundamental band line emission. The total power in 1–0 band CO lines emitted by a 1 cm^2 column of shocked gas *at* Peak 1 is approximately 2×10^7 W. This estimate includes assumptions of a distance of 500 pc to OMC-1, 0.75 mag extinction at 4.7 μm (2.5 mag at 2.1 μm with $A \approx \lambda^{-1.5}$), no substantial contribution from resonant scattering, and that the total luminosity in CO fundamental band lines is 60 times the average of the observed line fluxes. Because for CO the radiative decay rate is much faster than the excitation rate, the above flux corresponds to a collisional excitation rate of 4×10^{12} s^{-1} cm^{-2}. For an H_2 postshock density of 10^7 cm^{-3}, the vibrational relaxation rate per CO molecule by collisions with H_2 and He at 1500 K is 2×10^{-6} s^{-1} (Millikan and White 1963; see also Thompson 1973). CO vibrational relaxation via collisions with atomic hydrogen (von Rosenberg, Taylor, and Teare 1971) is 4–60 times more rapid per particle than with molecular hydrogen in the temperature range 1000–2000 K. If no H_2 is dissociated the CO line emission requires a column density of hot CO of ~2×10^{18} cm^{-2} and a column length of 2×10^{15} cm, assuming that $CO/H_2 = 1.2 \times 10^{-4}$ (Watson *et al.* 1985). The associated column density of H_2, 2×10^{22} cm^{-2}, is considerably larger than the values derived by Watson *et al.* (1985) (although consistent to within the uncertainties). However, if a significant fraction ($\gtrsim 0.1$) of the H_2 is dissociated by the shock, the above column densities and lengths will be greatly reduced and in better agreement with Watson *et al.*

Beckwith *et al.*'s (1978) zero extinction estimate of the column density of hot H_2 is 2×10^{19} cm^{-2}. Allowing for 2.5 mag of extinction at 2.1 μm and again assuming $n(H_2) = 10^7$ cm^{-3} (which provides vibrational LTE for H_2), an H_2 column length of only 2×10^{13} cm is obtained. The much longer column of CO than H_2 confirms that the 1–0 CO line emission extends far into cool, postshock regions where H_2 vibrational line emission is not significant.

V. Brα SEARCH

A search for Brα at Peak 1 was made on the night of 1987 January 7. The observational technique was similar to that described previously for CO. The chopping and nodding effectively cancels out foreground Brα emission from the visible nebula, unless that emission has a significant east-west spatial second derivative. The Brα observations covered a velocity range of 425 km s^{-1}, centered at $v_{LSR} = -50$ km s^{-1}. Six spectra were obtained, each sampled every 20 km s^{-1}. The total integration time was 1 minute at each velocity. Velocity calibration was achieved by observing the Brα line in LkHα 101, which peaks at $v_{LSR} = -2$ km s^{-1} (Persson *et al.* 1984).

No Brα emission was observed toward Peak 1. The 3 σ limit on the total flux in the same velocity range as is emitted by the H_2 $S(1)$ line is 6×10^{-21}. This is approximately 50 times less than the $S(1)$ line flux from the same beam. When differential extinction is included, the Br$\alpha/S(1)$ ratio is further decreased by an additional factor of ~5. If postshock ionized gas exists in a sheet of thickness ~10^{13} cm, the above limit corresponds to a limit on the electron density, $n_e < 10^5$ cm^{-3}. It is clear that ionized gas can only be a minor component of the postshock molecular cloud gas.

Hasegawa and Akabane (1984) have reported a possible detection of H51α line emission associated with the shocked gas near Peak 1. They suggest that perhaps 4% of the observed 4.8 GHz radio continuum emission from this region (Johnston *et al.* 1983) may arise in shocked atomic gas. In a 5″ beam the Brα line emission associated with this radio continuum and extinguished by 0.75 mag is equal to the above 3 σ upper limit. McKee and Hollenbach (1987) argue that the H51α line intensity is consistent with a wind shock; their prediction of the associated Brα line intensity is also equal to our 3 σ upper limit.

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