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CO (v = 1–0) EMISSION IN THE MOLECULAR SHOCK REGIONS OF OMC-1[1]

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ABSTRACT

Using the new Aerospace spectrometer on the Kuiper Airborne Observatory, we have obtained observations of the molecular shocks associated with OMC-1. Unexpectedly these observations reveal (v = 1–0) emission from CO at 4.6 μm superposed on a strong continuum. Our observations strongly suggest that both the emission feature and the continuum are produced in molecular shocks. Since the (v = 1–0) band of CO is only excited in high-velocity shocks, we may be observing for the first time the primary driving mechanism in these regions. Even if these features are produced by scattering, the characteristics will provide new constraints on the conditions in and the geometry of the shock regions.

Subject headings: ISM: individual objects: Orion Nebula — ISM: molecules

1. INTRODUCTION

Since its discovery by Gautier et al. (1976) the molecular hydrogen emission observed in OMC-1 has resisted a convincing theoretical interpretation. There is reasonably little doubt that the H_2 emission arises in shock waves. The line profiles for the H_2 lines (e.g., Beck, Lacy, & Geballe, 1979) as well as the microwave CO lines (e.g., Kwan & Scoville 1976) exhibit *radial* velocities up to 90 km s^{-1}.

The difficulty is that theoretical calculations based on the assumption that ambient H_2 survives the shock have consistently produced models with relatively low velocities (Shull & Beckwith 1982). Early models based on purely hydrodynamic shocks (J-type) required velocities less than 20 km s^{-1}. Magnetohydrodynamic models (C-type shocks) have raised the shock velocities to 38 km s^{-1} (e.g., Draine & Roberge 1982). The standard picture is that the H_2 emission arises in low-velocity secondary shocks. The primary acceleration mechanism has remained undiscovered.

An analogous situation exists for the explanation of the optical emission lines observed in Herbig-Haro objects (e.g., Böhm & Solf 1985). The morphology of the H_2 emission associated with HH 1 and 2 by Harvey et al. (1986) strongly suggests that molecular shocks and HH objects are simply different facets of a single phenomenon.

Spectroscopic work on the molecular shock regions in OMC-1 has concentrated on individual lines of H_2, CO, or OH (e.g., Beckwith et al. 1983; Watson et al. 1985; Melnick et al. 1990). Spectrometers capable of surveying large portions of the spectrum at high sensitivity have not been available. The result is that we do not known what other spectroscopic features are present in the spectrum of the molecular shocks.

We report spectral mapping of the OMC-1 region from 3 to 14 μm using the Aerospace spectrometer.

2. OBSERVATIONS

Observations of OMC-1 were made on 1991 January 22 from the Kuiper Airborne Observatory using the Aerospace spectrograph (Warren & Hackwell 1989; Hackwell et al. 1990). This liquid helium cooled spectrograph uses two unique curved prisms to disperse the radiation onto two 58 element linear arrays of "Blocked Impurity Band" photoconductors. It covers the entire 3–13.5 μm spectral region at a resolving power of $\lambda/\Delta\lambda$ = 30–80 without scanning. Because all of the detectors view the field through the same aperture, telescope tracking errors and small shifts in position on extended objects do not result in spectral ambiguities such as those that can arise in scanning instruments. This makes it ideal for the current task of observing different positions in an extended region.

Observations were obtained at five positions in OMC-1 (Fig. 1) during a single 80 minute flight leg. Data were taken at the positions labeled Pk 1, NW, and Pk 2 with a chopper throw of 115″. Further data were obtained at the positions Pk 1, NE, and SW with a chopper throw of 238″. After the chopper throw was increased, the beam positions were reset by observing α Ori. The chop direction was in azimuth. Since the observations were made near transit, the direction of the chopper throw was within 10° of the exact east-west direction.

The data were reduced with respect to α Tau. The strength of the CO and SiO absorption features in α Tau, the star's continuum temperature, and its brightness were estimated by comparing α Tau spectra to those of α CMa taken during the flights of 1992 January 22 and January 24. For α CMa we assumed a color temperature of 10,000 K, and a magnitude of -1.36 at 12 μm. The resulting best-fit α Tau temperature is 7000 K with a 12 μm magnitude of -3.04. The data were reduced to units of flux by assuming that zero magnitude at 12 μm corresponds to 5.90×10^{-17} W cm^{-2} μm^{-1}. In our data, the CO absorption in α Tau covers the spectral region from ~4.5 to 6.0 μm and has a maximum depth relative to the continuum of 20%. The SiO absorption is seen between 7.5 and 9.0 μm with a maximum depth of ~10%. This is consistent with the results presented by Cohen (1991).

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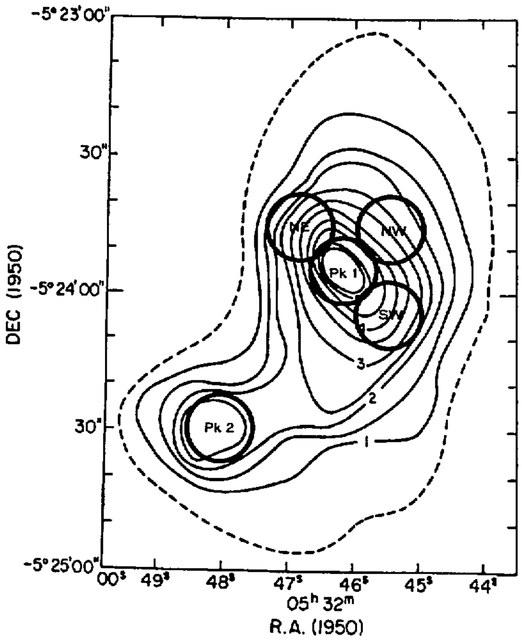

FIG. 1.—The 15" entrance aperture of the Aerospace spectrometer marks the positions at which spectra were obtained. The underlying contours show the intensity distribution of the H_2 (v = 1–0) $S(1)$ line at 2.12 μm (Beckwith et al. 1978). The smallest chopper throw that was used to make the observations was 115", so that all of our reference positions are beyond the east-west edges of this map.

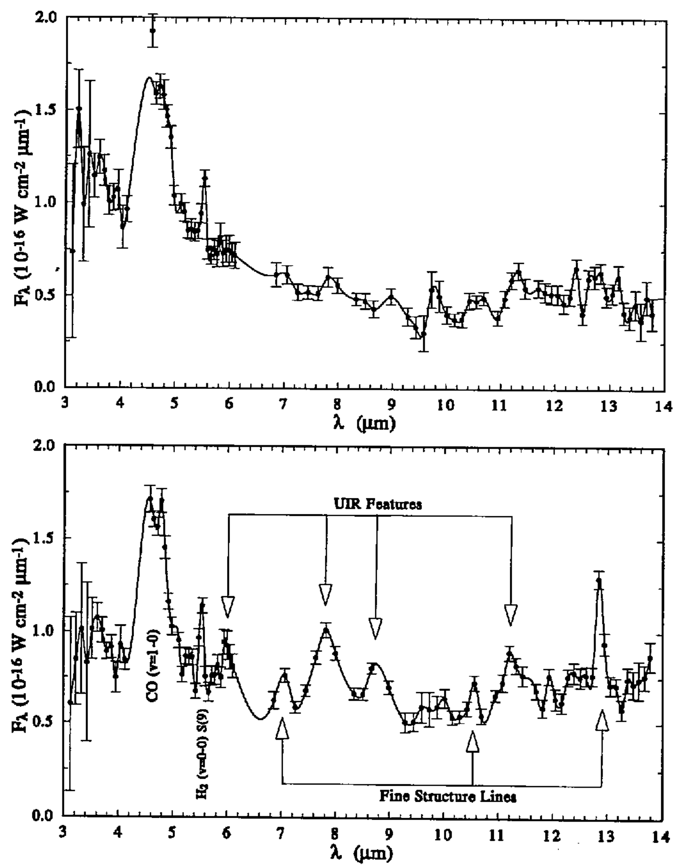

FIG. 2.—The upper panel contains the spectrum obtained on Pk 1 with a chopper throw of 115". The spectrum obtained at Pk 1 with a chopper throw of 238" is shown in the bottom panel. Useful observations near 4.4 μm could not be obtained because of the strong absorption by atmospheric CO_2. The gap in coverage around 6.5 μm results from an inefficient dichroic in the Aerospace spectrometer. The UIR features and the fine-structure lines grow dramatically with chopper throw and are therefore unlikely to be related to the molecular peak.

3. RESULTS

By comparing the spectra of Pk 1 taken with different chopper throws (Fig. 2) we are able to distinguish two groups of spectral features. The unidentified IR (UIR) features at 6.2, 7.7, 8.6, and 11.3 μm all increase in strength when the chopper throw is increased. It is difficult to see the UIR features in the small chopper throw data. Similarly the fine structure lines of [Ne II] at 12.8 μm, [S IV] at 10.5 μm, and [A II] at 7.0 μm are only seen with the large chopper throw. We interpret this result as indicating that these features are quite widely distributed in this part of the Orion Nebula and are unrelated to OMC-1.

As expected, the rotation line $S(9)$ of H_2 at 5.5 μm appears in both spectra of Pk 1 with the same strength, $I = 7 \pm 2 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}. The intensity agrees very well with the previous observations by Beckwith et al. (1983) of $I = 7.5 \pm 1.5 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}.

The dominant feature in both spectra, a broad emission structure near 4.6 μm, was entirely unexpected. We identify this feature as the (v = 1–0) band of CO. The feature is superposed on a strong continuum. At the position of Pk 1, the H_2 line, the CO band and the underlying continuum do not change in intensity with chopper throw. We take this as prima facie evidence that all three features are related to the molecular shock region.

The spectrum of Pk 2 (Fig. 3) provides additional support for associating the CO feature and the continuum with the molecular shock regions. Although the spectrum beyond 6 μm has an entirely different character from that of Pk 1, the H_2, CO feature, and underlying continuum again appear with the same relative strength. The differences in the long wavelength spectra between Pk 1 and Pk 2 can be approximately understood. The stronger fine-structure lines are to be expected since Pk 2 is much closer to the Trapezium and is therefore more likely to be influenced by the compact H II region Orion A. Except for the possible presence of the 7.7 μm feature the UIR features are entirely masked by continuum emission which continues to rise to the limit of the spectrum at 14 μm. This is undoubtedly part of the Kleinmann-Low nebula as demonstrated by Grasdalen, Gehrz, & Hackwell (1981).

The hypothesis that the CO feature and underlying continuum arise in the molecular shocks is further strengthened by the spectra at positions NW, NE, and SW of Pk 1 (Fig. 4). These spectra demonstrate that all three features behave in the same way with position. It is particularly striking that all of the features disappear at the NW position.

4. DISCUSSION

Our identification of the feature near 4.6 μm as the (v = 1–0) band of CO is based on the wavelength coincidence and shape of the feature. In Figure 5 we compare the mean of the Pk 1 and SW position spectra with model CO spectra. The calculations were made assuming a Boltzmann distribution of populations. The Einstein A value were taken from Kirby-Docken & Liu (1978). The wavelength smearing of the spectrometer

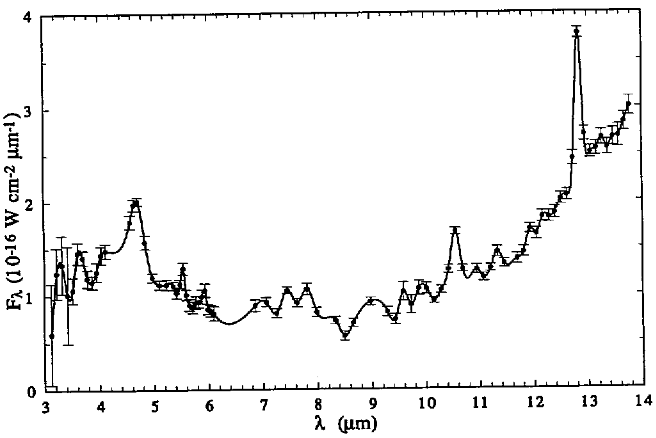

FIG. 3.—The observed spectrum of Pk 2 with a chopper throw of 115″. At long wavelengths this region is dominated by the Kleinmann-Low nebula. Since this position is relatively close to the Trapezium it is not surprising that the fine-structure lines (see Fig. 2) are quite strong. The H_2, CO band, and continuum near 4 μm all have approximately the same strength as at Pk 1.

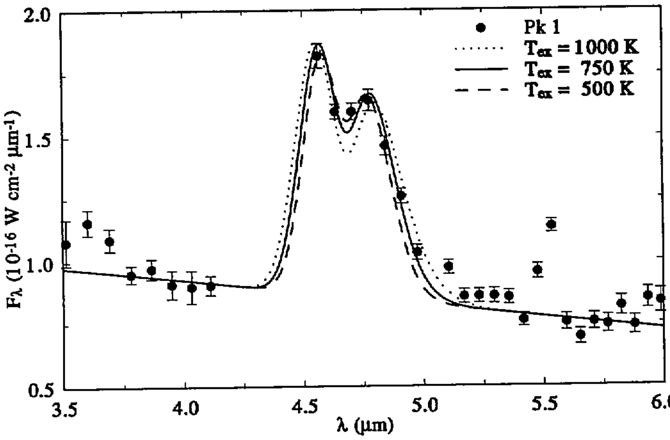

FIG. 5.—The mean spectrum near Pk 1 compared with predicted profiles for the CO (v = 1–0) band. The model predictions have been scaled and added to a linear continuum. The data are well represented by a model with T_{ex} = 750 K.

was modeled as a Gaussian with a FWHM of 0.13 μm. The resulting intensities were added to a linear model of the continuum. The agreement in position and shape with the observed feature is striking. The observations are reproduced almost exactly by a model with an excitation temperature of 750 K. The computed profiles for excitation temperatures of 1000 and 500 K are, respectively, broader and narrower than the observed profile.

There are two plausible mechanisms for the production of the CO feature and the associated continuum: scattering or collisional processes in the molecular shocks. The CO emission could be continuum radiation from the Becklin-Neugebauer (BN) object that was absorbed and then reradiated by ambient CO. The excitation temperature would then be a measure of the excitation temperature of the ambient CO. Similarly, the continuum radiation could be light from the BN object scattered by dust grains in the ambient medium. Over the wavelength interval from 3 to 8 μm the energy distribution of the

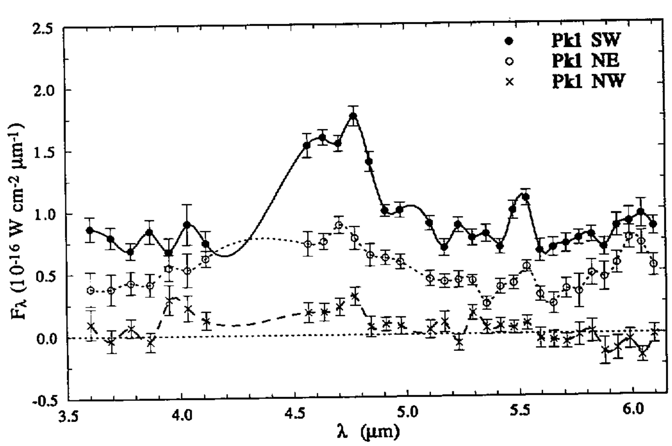

FIG. 4.—The 3–6 μm spectra at three positions around Pk 1. The two dominant spectral features are the H_2 $S(9)$ (v = 0–0) line at 5.5 μm and the CO (v = 1–0) band around 4.6 μm. These spectra demonstrate that the features and the underlying continuum are highly correlated in their spatial distribution.

BN object is approximately constant in F_λ units. The observed continuum rises from 6 μm to the limit of our data at 3 μm. Thus the continuum is bluer than the BN object as predicted by the scattering hypothesis. The correlation of the CO feature and continuum with the H_2 emission would be largely fortuitous. There is no reason to expect that the illumination from the BN object would be correlated with the strength of the secondary shocks that are thought to be responsible for the excitation of the H_2 emission. Since both the reradiated CO emission and the dust scattered continuum would be highly polarized, the hypothesis is subject to direct observational test.

The other possibility is that the CO band and the continuum are directly related to the molecular shocks. The excitation temperature fits directly into the trend of excitation temperature with excitation energy seen in the molecular hydrogen emission and the excitation inferred from the high J rotational lines of CO and OH (Watson et al. 1985). For levels below 2000 cm^{-1} the observed excitation temperature of the H_2 is $\leq$ 1000 K (Beckwith et al. 1983).

Unlike molecular hydrogen, the $v = 1$ level of CO is connected to the ground state by permitted transitions. Therefore predictions of the intensity of the band requires knowledge of the number densities of CO, and the colliding particles as well as the relevant collisional cross sections. Calculations by Draine & Roberge (1984) for magnetohydrodynamic shocks indicate that the emission in the (v = 1–0) band is an extremely strong function of shock velocity, increasing by approximately an order of magnitude with every 5 km s^{-1} increase in the shock velocity. They predicted measurable emission for shock velocities above 25 km s^{-1}. They only carried out calculations for shocks with velocities $\leq$40 km s^{-1}. At that velocity the strongest CO lines had predicted strengths of $\sim 4 \times 10^{-4}$ ergs cm^{-2} s^{-1} sr^{-1} for a preshock density of $n_H = 10^6$ cm^{-3}. The observed intensity inferred for an individual CO line is $\sim 3 \times 10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1}. Unfortunately, recent calculations by Neufeld & Dalgarno (1989a, b) for fast dissociative shocks have not included predictions for the (v = 1–0) band of CO.

The total luminosity in the 15″ beam at Pk 1 is 3 $L_\odot$ (assuming a distance of 450 pc to OMC-1). If we assume that the CO emission is distributed similarly to the H_2 emission we infer a total observed luminosity in the CO feature of $\sim 15\ L_{\odot}$. This is about an order of magnitude less than the $200 \pm 80\ L_{\odot}$ due to H_2 emission (Beckwith et al. 1983). If the CO emission arises in the same shocks as the H_2 emission the logical inference is that only a small fraction of the hydrogen is still in molecular form.

If the continuum does arise directly in the molecular shock region it is unlikely to be due to p-e^- bremsstrahlung. We have not observed H I recombination lines that would be expected in that case. Of course, more exotic forms of bremsstrahlung, e.g., H^--e^- or H_2-e^-, cannot be ruled out.

If the observed CO ($v = 1$–0) emission and continuum arise in the molecular shock regions we may finally have a direct observational probe of the primary shock phenomenon in the OMC-1 region. If these features are the result of scattering processes they will be useful probes into the physical conditions in the molecular shock regions but the central puzzle will remain unresolved.

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