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OBSERVATIONS OF FAR-INFRARED LINE PROFILES IN THE ORION-KL REGION

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ABSTRACT

We report measurements of several far-infrared emission-line profiles in the Orion-KL region. The data were taken with a new high-resolution Fabry-Perot spectrometer ($\lambda/\Delta\lambda \approx 3 \times 10^4$) on the Kuiper Airborne Observatory.

Toward the BN-KL and H_2 peak 1 positions, the observed CO, OH, and [O I] emission lines (CO $J = 16 \rightarrow 15$ at 163 μm, OH $^2\Pi_{1/2}$, $J = 3/2 \rightarrow 1/2$ at 163 μm, and [O I] $^3P_1 \rightarrow ^3P_2$ at 63 μm) are well resolved with intrinsic line widths of 30–50 km s^{-1} (FWHM). The emission probably comes from dense, hot molecular and atomic gas in the Orion-KL shock. The CO and [O I] lines have similar profiles, suggesting that the high-velocity [O I] emission also arises in magnetohydrodynamic "cloud" shocks. The velocity centroids of the lines are somewhat blueshifted. The far-infrared data, therefore, support the interpretation that the blue asymmetry of the H_2 2 μm lines is not mainly caused by differential dust extinction, but by the kinematics and geometry of the shocked gas in the Orion-KL outflow. The [O I] and CO lines, however, have significantly less extreme blueshifted emission ($v_{LSR} < -60$ km s^{-1}) than the H_2 lines. Hence, the highest velocity dispersion H_2 emission may come from hotter gas than the emission at lower velocities. The OH emission width (~ 50 km s^{-1} FWHM) is larger than that of either the CO or [O I] lines (~ 30 km s^{-1}). The OH emission may come from very hot (T > 10^3 K) gas of high-velocity dispersion or may be highly optically thick.

We have also spectrally resolved the [O I] 63 μm and [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ 158 μm emission from UV photodissociated gas near Orion-Trapezium. Both lines have an intrinsic line width of 7 ± 2 km s^{-1} (FWHM) and an LSR velocity centroid of ~ 8 km s^{-1}, strongly supporting a common origin near the surface of the Orion molecular cloud. The high brightness temperatures of the [O I] and [C II] lines (150–180 K) indicate that the lines have significant optical depth ($\tau \approx 1$).

Subject headings: infrared: spectra — interstellar: matter — nebulae: Orion Nebula

I. OBSERVATIONS

The data were taken in 1985 February on the 91 cm telescope on board the Kuiper Airborne Observatory. To achieve the high spectral resolving powers required for velocity resolved measurements ($\lambda/\Delta\lambda \gtrsim 10^4$), we made major modifications to the UCB 50–200 μm tandem Fabry-Perot spectrometer (Storey, Watson, and Townes 1980). A brief description follows (for a detailed description, see Lugten, Crawford, and Genzel 1986): A precision stage allows tilt-free translation of one of the two metal mesh scanning Fabry-Perot mirrors. The stationary Fabry-Perot mirror immediately in front of the liquid He cooled chamber is cooled to liquid nitrogen temperature. This reduces the thermal background by factors between 3 and 4 and improves the sensitivity of the instrument by about a factor of 2. The separation between the two mirrors of up to 5 cm is accurately measured (to ~ 0.02 μm) by a Hewlett Packard Zeeman split laser interferometer and electronically controlled using a piezo electric element. This element is also used to scan one Fabry-Perot mirror over distances up to ~ 45 μm, resulting in spectral scans up to ~ 30 resolution elements. The maximum spectral resolving power of the new interferometer is limited in practice by the finite angular divergence of the rays through the Fabry-Perot. The limiting resolving power is $R_0 \approx 80{,}000\,(\theta/30'')^{-2}$, where θ is the FWHM focal plane aperture size. At spectral resolving powers approaching this "beam divergence" limit, the spectral response function is a convolution of a Lorentzian (the response of the Fabry-Perot to a plane wave) with a function depending on the angular illumination of the Fabry-Perot. We have found that measured profiles of absorption lines in a gas cell placed in front of the spectrometer are well fitted by theoretical response functions calculated from finesse and order of the Fabry-Perot and the known angular illumination of the Fabry-Perot. We use below the theoretical instrumental functions and a maximum entropy deconvolution routine (based on the work by Gull and Daniell 1978) to unfold the intrinsic line profiles from the measured profiles. This method substantially reduces the strong wings due to the instrumental response and allows a moderate "superresolution" of about a factor of 2.

We observed the [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ line (rest wavelength 157.7408 μm: Cooksy, Blake, and Saykally 1986) with a 45″

aperture and effective spectral resolution of FWHM 25 km s^{-1}, the CO $J = 16 \rightarrow 15$ line (162.8116 μm), and the OH $^2\Pi_{1/2}$ $J = 3/2 \rightarrow 1/2$ line (163.1246 μm) with a 45″ aperture and resolution 33 km s^{-1}, and the [O I] $^3P_1 \rightarrow ^3P_2$ line (63.1837 μm) with a 30″ aperture and resolution 16 km s^{-1}.

The absolute CO/OH velocity scale was determined relative to CO absorption in a gas cell and is accurate to ± 3 km s^{-1}. The velocity centroid of the narrow component of the [O I] 63 μm line toward the Trapezium was assumed to be 8.5 ± 3 km s^{-1} LSR, the value measured by Werner *et al.* (1984). The velocity scale of the [C II] line was established relative to an H_2S line at 157.772 μm (Flaud, Camy-Peyret, and Johns 1983).

II. RESULTS

Figures 1 and 2 show the observed CO, OH, and [O I] line profiles. In addition to the CO and OH data shown in Figure 1, we also obtained a high signal-to-noise ratio sweep centered on the CO line (toward BN-KL) and two spectra of the [C II] line toward BN-KL and the Trapezium. Figure 3 gives the deconvolved profiles, together with the average 22 μm H_2 $S(1)$ profile toward the center of Orion-KL (Nadeau, Geballe, and Neugebauer 1982), and the CO $J = 6 \rightarrow 5$ 450 μm profile reported by Koepf *et al.* (1982). The main results are as follows:

All observed far-infrared line profiles are spectrally resolved. The new data provide the first opportunity to study the line profiles of far-infrared emission lines in Orion-KL.

The high-velocity CO, OH, and [O I] emission components have velocity widths of 30–50 km s^{-1} (FWHM), with significant emission ranging from -60 to $+40$ km s^{-1} (LSR). These widths are in good agreement with the best previous estimates from measurements at resolutions of 50–100 km s^{-1} (Watson *et al.* 1985; Werner *et al.* 1984). As has been discussed by Watson *et al.* (1985) and Viscuso *et al.* (1985) for CO and OH, and by Werner *et al.* (1984) for [O I], this high-velocity emission very likely comes from dense ($n_{H_2} \approx 2 \times 10^6$ cm^{-3}), hot ($T \approx 200$–1000 K) gas excited by shock waves. The far-infrared CO emission and possibly also the [O I] emission probably come from cooler gas in the shock ($T < 1000$ K), downstream from the region of vibrationally excited H_2 quadrupole emission (Storey *et al.* 1981; Chernoff, Hollenbach, and McKee 1982; Draine and Roberge 1982).

The velocity centroids of the CO, OH, and [O I] lines are somewhat blueshifted (~ 10 km s^{-1}) with respect to the velocity of the quiescent molecular cloud at 9 km s^{-1} (*thin vertical line* in Fig. 3). This is especially apparent for the CO $16 \rightarrow 15$ line. The asymmetry qualitatively is similar to, but not as strong as, the asymmetry of the near-infrared H_2 lines (Nadeau, Geballe, Neugebauer 1982; Scoville *et al.* 1982; Geballe *et al.* 1986).

The far-infrared emission is almost certainly not affected by dust extinction. The presence of excess blueshifted emission in the far-infrared lines, therefore, supports the interpretation that the asymmetry of the 2 μm H_2 lines is not caused by differential extinction of dust in an expanding source (obscuring redshifted H_2 emission more than blueshifted emission). The asymmetry is probably the result of the geometry and kinematics of the shocked gas in the Orion-KL outflow. This

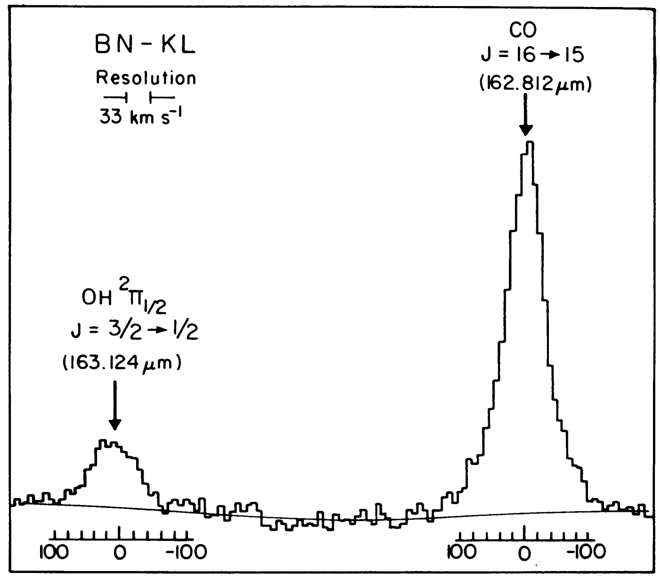

FIG. 1.—Spectrum of the 163 μm CO $J = 16 \rightarrow 15$ and OH $^2\Pi_{1/2}$, $J = 3/2^+ \rightarrow 1/2^-$ rotation lines at FWHM 33 km s^{-1} spectral and 55″ spatial resolution toward the BN-KL position. The LSR velocity scales are indicated below. The absolute integrated flux of the CO line is $6 \pm 1.8 \times 10^{-17}$ W cm^{-2} or $7.5 \pm 2.3 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}.

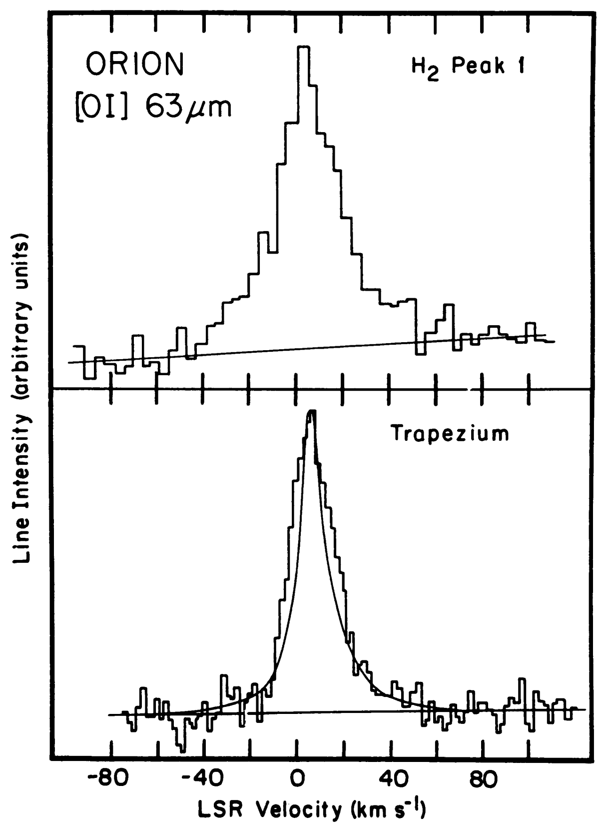

FIG. 2.—Spectra of the 63 μm [O I] $^3P_1 \rightarrow ^3P_2$ fine-structure line at FWHM 16 km s^{-1} spectral and 30″ spatial resolution toward H_2 peak 1 (Beckwith *et al.* 1978) and the radio continuum peak 10″ west of the Trapezium. The instrumental response function is given with the Trapezium spectrum. The absolute integrated flux of the [O I] line toward the Trapezium is $1.8 \pm 0.5 \times 10^{-16}$ W cm^{-2} or $6.6 \pm 2 \times 10^{-2}$ ergs s^{-1} cm^{-2} sr^{-1}. The flux of the line toward peak 1 is $\sim 15\%$ weaker.

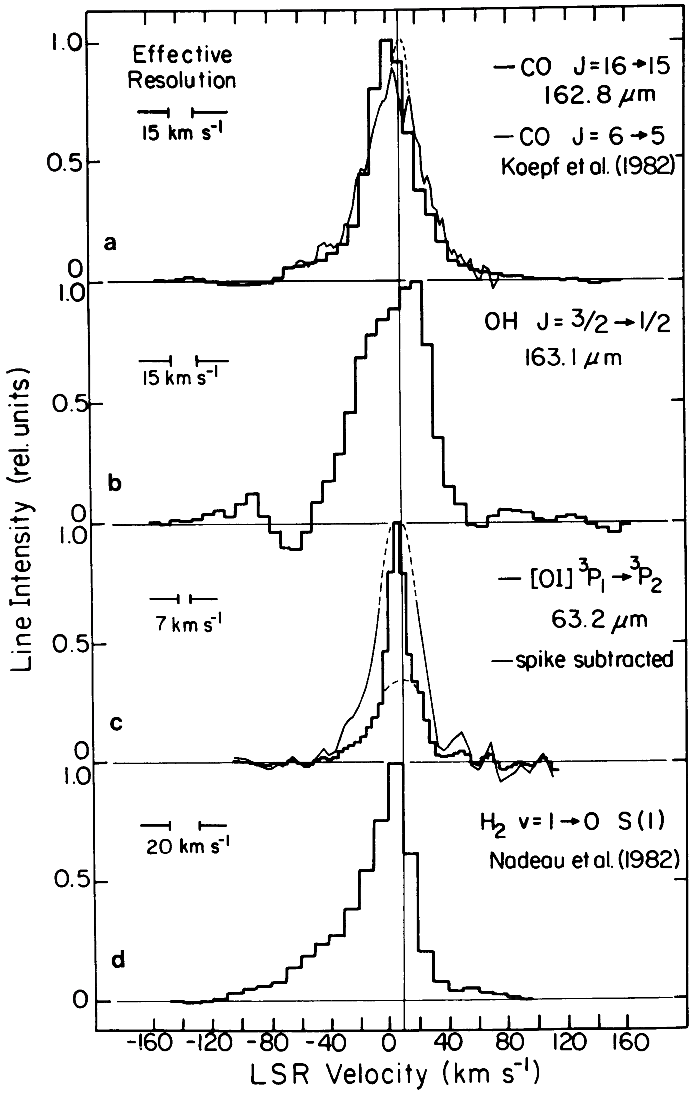

FIG. 3.—Comparison of line profiles in the Orion-KL shock. (*a*) Deconvolved CO $J = 16 \rightarrow 15$ line profile (*heavy*; *histogram*), compared to the CO $6 \rightarrow 5$ 450 μm submillimeter line (*thin*) (Koepf *et al.* 1982). The CO $16 \rightarrow 15$ data going into the deconvolution were the profile of Fig. 1 and a second spectrum at the same resolution, but centered on the CO line. The maximum entropy deconvolution procedure (cf. Gull and Daniell 1978) largely removes the influence of the broad Lorentzian wings of the instrumental response and allows moderate "superresolution." Note that the CO $6 \rightarrow 5$ line may be influenced by self-chopping due to insufficiently large spatial beam switching. (*b*) Deconvolved OH, $^2\Pi_{1/2}$, $J = 3/2^+ \rightarrow 1/2^-$ profile toward BN-KL. (*c*) Deconvolved [O I] 63 μm line profile toward H_2 peak 1 (*heavy*; *histogram*), and the profile of the underlying high-velocity emission (*thin*), after subtraction of the narrow "spike" component. To do so, a line of the width estimated from the Trapezium spectrum—showing no high velocity gas—was subtracted. (*d*) Spectrum of the 2 μm $S(1)$ $v = 1 \rightarrow 0$ line averaged over the "central region" in Orion-KL (from Nadeau, Geballe, and Neugebauer 1982).

conclusion has been reached earlier by Geballe *et al.* (1986) from a comparison of 2.2 μm, 3.7 μm, and 12.2 μm H_2 lines. A likely model is a bipolar outflow with a wide opening angle (Geballe *et al.* 1986; Erickson *et al.* 1982). In the framework of this model, most of the H_2 and far-infrared CO emission come from shock fronts at the outer edge of a cavity of radius ~ 0.1 pc, where the clumpy outflow from the infrared cluster interacts with the surrounding quiescent molecular cloud. The geometry is such that the line of sight toward BN-KL or H_2 peak 1 passes mainly through the blueshifted lobe. This model may also explain why the $6 \rightarrow 5$ submillimeter CO line profile (Koepf *et al.* 1982: Fig. 3*a*, similar beam size as in the $16 \rightarrow 15$ measurements) is less asymmetric than the $16 \rightarrow 15$ line, and why the $2 \rightarrow 1$ and $1 \rightarrow 0$ CO lines (Knapp *et al.* 1981; Zuckerman, Kuiper, and Rodriguez Kuiper 1976; Kwan and Scoville 1976) show no significant asymmetry. In comparison to the far-infrared CO emission, the $6 \rightarrow 5$, $2 \rightarrow 1$, and $1 \rightarrow 0$ CO lines probably come from cooler gas. This cooler gas may be located in the outflow itself, closer to the center of the source, and not at the interface between the outflow cavity and the surrounding cloud. The mm CO line shapes, by sampling a relatively larger range of angles in the outflow cone, thus appear more symmetric.

The same reasoning—relative contribution from gas at different radii and angles from the center for a given line of sight —may also be applied to explain the relative larger widths of the H_2 emission lines [~ 40 to 70 km s^{-1} for the 2 μm H_2 lines, and up to 100 km s^{-1} for the 3.8 μm O(7) line, Geballe *et al.* 1986] and the stronger extreme blueshifted emission ($v_{LSR} < -60$ km s^{-1}) relative to the CO/[O I] lines. The $16 \rightarrow 15$ CO line may not only be excited at the outer "cloud" shock, but also in lower velocity shocks closer to the center of the source. Alternatively, the difference between the H_2 and CO/[O I] lines may be an excitation effect. The high-velocity H_2 emission may come predominantly from very hot gas in high-velocity clump-clump collisions. Such hot gas would not be very effectively sampled by the lower excitation far-infrared lines.

With the exception of the relatively larger overall blueshift of the CO line, the CO and [O I] profiles are very similar. Werner *et al.* (1984) have shown that the spatial distribution of the [O I] emission near BN-KL is almost identical to the double-lobed 2 μm H_2 distribution (Beckwith *et al.* 1978). These two findings together strongly suggest that the high-velocity [O I] emission is coexistent with the CO and H_2 emission. Hence, the [O I] emission may also come from nondissociative, *C*-type shock fronts which best explain the hot molecular infrared lines (Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982). A separate, dissociative "wind shock" (Werner *et al.* 1984) is probably not necessary to account for the [O I] emission. To explain the observed strong [O I] emission in *C*-type shock models, a large pre- and postshock atomic oxygen abundance is required. The ratio of [O I] to total H_2 cooling (0.2–0.3) suggests the presence of relatively slow shocks ($v_s \lesssim 20$ km s^{-1}), in addition to the 30–40 km s^{-1} shocks which best fit the H_2 emission (Draine, Roberge, and Dalgarno 1983).

The OH $^2\Pi_{1/2} J = 3/2 \rightarrow 1/2$ line is significantly wider than either the CO or the [O I] lines (50 vs. 30 km s^{-1}). The excitation requirement for the OH line ($n_{crit} \approx 10^{10}$ cm^{-3}) is significantly higher than for the latter two ($n_{crit} \approx 10^6$ cm^{-3}). To account for the relative intensities of the far-infrared OH lines observed, a clumpy, high-density ($n_{H_2} \approx 10^6$–10^7 cm^{-3}) medium is required (Watson *et al.* 1985; Viscuso *et al.* 1985; Melnick *et al.* 1986). The far-infrared OH optical depths in this medium may be substantial. Hence, the large width and flat-topped profile of the OH line may be the result of a combination of the high-excitation requirements (selecting hot, highly compressed clumps of large velocity dispersion) and radiative transport in an optically thick medium.

The [C II] 158 μm lines toward Trapezium and BN-KL presently do not indicate any significant high-velocity emission, consistent with the non-ionizing nature of the shocks in Orion-KL. The [C II] and [O I] lines toward the Trapezium and BN-KL are dominated by a narrow, barely resolved "spike" line (Fig. 2). Cooksy, Blake, and Saykally (1986) have recently measured the rest wavelength of the [C II] line in the laboratory to be 157.7408 μm, improving the value of 157.737 μm reported by Crawford *et al.* (1985). With this new rest wavelength, the measurements reported here give an LSR velocity centroid of 7.5 $\pm$ 2 km s^{-1} of the [C II] lines toward the Trapezium and BN-KL. This value is identical within the uncertainties with the velocity centroid of the [O I] lines (7 $\pm$ 3 km s^{-1} at BN-KL, 8.5 $\pm$ 3 km s^{-1} at Trapezium), and the LSR velocity of the Orion molecular cloud (8–9 km s^{-1} LSR). The intrinsic FWHM width of the [C II]/[O I] "spike" is 7 $\pm$ 2 km s^{-1}. The velocity information adds strong support to the interpretation that the [C II]/[O I] emission originates at the surface of the Orion molecular cloud where it is exposed to UV radiation from the OB stars in the Trapezium H II region (cf. Crawford *et al.* 1985; Ellis and Werner 1986; Stacey 1985). For comparison, radio recombination lines toward the Orion H II region have velocity centroids of about -6 to 0 km s^{-1} LSR (Jaffe and Pankonin 1978). The width of the C109α carbon recombination line toward the same position is 7.6 $\pm$ 1.5 km s^{-1}, consistent with our estimate (Jaffe and Pankonin 1978), although a more typical width of the C109α line toward other positions in Orion is somewhat smaller (3–5 km s^{-1}). With $\Delta v = 7 \pm 2$ km s^{-1}, the Planck brightness temperature corresponding to the total intensity of the [O I] 63 μm line (6.6×10^{-2} ergs s^{-1} cm^{-2} sr^{-1}) is 180 $\pm$ 40 K. The brightness temperature of the [C II] line (5.5×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}) is 150 $\pm$ 40 K. The kinetic temperature in the [O I]/[C II] region probably lies between 300 and 1000 K (Tielens and Hollenbach 1985; Stacey 1985; Genzel and Stacey 1985). For thermalized emission at $T = 300$ K, the observed brightness temperatures indicate optical depths $\lesssim 0.6$ for both lines. If the emission is clumped, or if the levels are subthermally excited (as may be the case for the O I fine-structure levels), the optical depth could be significantly larger. If the gas temperature is > 300 K, the optical depth would be smaller. We conclude that the optical depths of the 63 μm [O I] and 158 μm [C II] lines are likely moderately large ($\tau \approx 1$). The case of optical depth greater than about 2 can be excluded for the [C II] line, since no [^{13}C II] hyperfine components were detected.

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