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DETECTION OF SHOCKED ATOMIC GAS IN THE KLEINMANN-LOW NEBULA

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ABSTRACT

We have mapped the 63 μm $^3P_1 \rightarrow {}^3P_2$ fine-structure line emission of neutral atomic oxygen at the center of the Orion nebula with a resolution of 30″. There are three main emission peaks. One is associated with the region of strongest thermal radio continuum radiation close to the Trapezium cluster and probably arises at the interface between the H II region and the dense Orion molecular cloud. The other two [O I] line emission peaks, associated with the Kleinmann-Low nebula, are similar in both distribution and velocity to those of the 2 μm $S(1)$ line of molecular hydrogen and of the high-velocity wings of rotational CO emission. The [O I] line profiles in the KL region are resolved at a resolution of 45 km s^{-1} and have an intrinsic width of about 50 km s^{-1}, while the line profile in the vicinity of the Trapezium is unresolved. We show that the [O I] emission from the KL nebula can be produced in the shocked gas associated with the mass outflows in this region and is an important coolant of the shocked gas.

Subject headings: infrared: sources — infrared: spectra — nebulae: Orion Nebula

I. INTRODUCTION

The Kleinmann-Low (KL) nebula in Orion is the site of a violent mass outflow associated with the formation of massive stars (cf. the review by Genzel and Downes 1982). Infrared emission lines from highly excited states of H_2, OH, and CO have been detected from this region (cf. Gautier *et al.* 1976; Storey *et al.* 1981; Beck *et al.* 1982); this emission is probably excited in shocks occurring where dense shells driven by the mass outflow strike the ambient molecular cloud material. In this *Letter*, we report mapping of the central 2′.5 of the Orion-KL region with 30″ resolution and show spectra taken at 45 km s^{-1} resolution which together reveal emission in the atomic oxygen $^3P_1 \rightarrow {}^3P_2$ ground-state fine-structure transition associated with the KL nebula. This transition is expected to be the dominant cooling transition for dense ($10^8 \geq n \geq 10^3$) *atomic* interstellar gas for temperatures between 100 and 5000 K.

II. OBSERVATIONS AND RESULTS

a) *Observations*

The observations were carried out with the 91 cm telescope of the Kuiper Airborne Observatory in 1983 February and 1983 October, using the UC Berkeley tandem Fabry-Perot spectrometer described by Storey, Watson, and Townes (1980). The beam had a FWHM of 30″, with an effective area of a 38″ diameter disk. In 1983 February the instrumental profile was Lorentzian with a FWHM of 170 km s^{-1}. A chopper spacing of 4′ in azimuth was used (approximately east-west). Spectral scans were obtained at approximately 40 points (typical integration time 1 minute per point) on a grid spaced by 20″ in both right ascension and declination. Each spectral scan included the line and the adjacent continuum, so that maps of line and continuum intensity were produced simultaneously with good relative positioning. Relative positions across the map are accurate to 5″. Absolute positions were obtained by assuming that the continuum peak is at R.A. = $5^h32^m46^s.8$, decl. = −05°24′25″ (1950; see Wynn-Williams *et al.* 1984). Repeated measurements of the line intensity at a point near the map center agreed to ±10%, and it is this reproducibility, rather than the signal-to-noise ratio, which is the limiting uncertainty in the quality of the map presented in Figure 1. Observations were made during two flights in 1983 October at velocity resolutions of 60 and 45 km s^{-1} toward several points on the map made in February; the 45 km s^{-1} spectra are shown in Figure 2. The beam size was again 30″, and the chopper spacing was 5′ in azimuth, which was again approximately east-west. Radial velocities were calibrated by measuring the relative wavelength separation between the [O I] lines in Orion (rest wavelength 63.18372 μm) and an H_2O line at 63.3236 μm. The line fluxes in Figures 1 and 2 were calibrated by measurements of the line to continuum ratio toward the continuum peak. We assumed a flux density of 7×10^4 Jy for the KL continuum in a 30″ beam (scaling by 0.6 the flux densities given by Werner *et al.* 1976). The overall calibration uncertainty is estimated to be ±25%.

b) *Spatial Distribution*

Figure 1 shows the spatial distribution of 63 μm line and continuum flux over the region mapped, compared with other relevant data. The [O I] line emission shows a peak 10″ SW of the Trapezium cluster and a double-peaked ridge near the KL nebula. The peak near the Trapezium is very similar in position and shape to the 5 GHz radio continuum emission. [O I]

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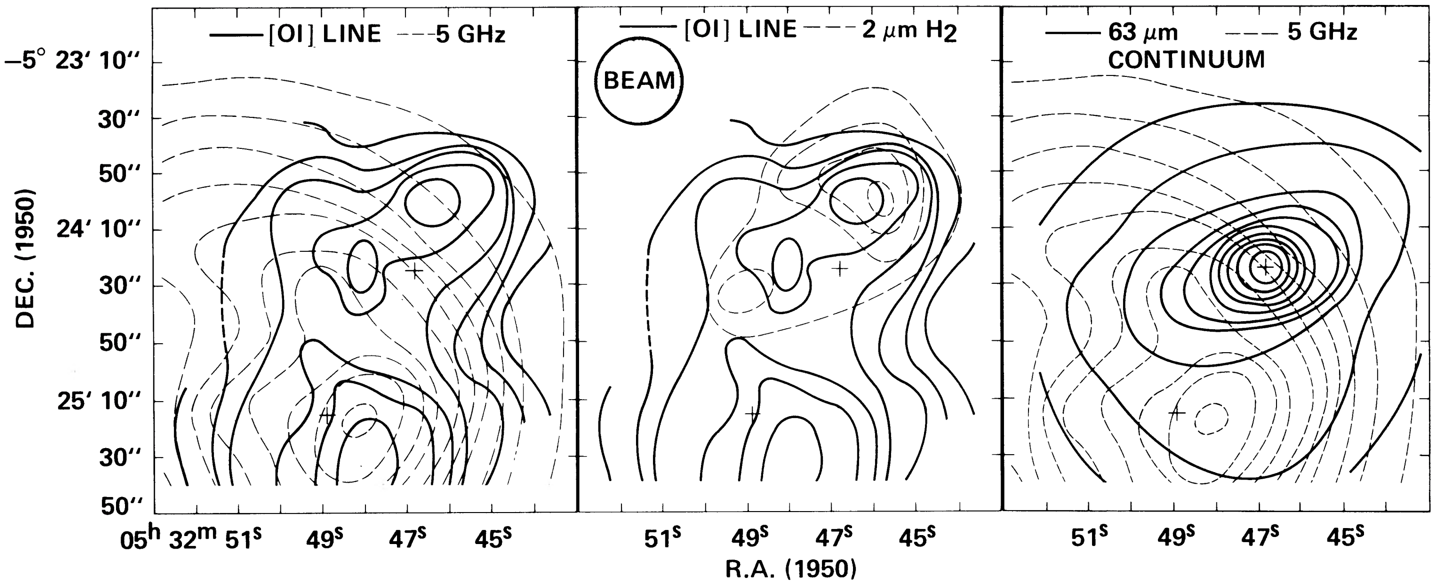

FIG. 1.—(*left*): Contours of integrated 63 μm [O I] line emission toward the Orion-KL region with a resolution of 30″ (*heavy lines*). Contour units are 2.5×10^{-17} W cm^{-2} (9.4×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}). The dashed lines are contours of 5 GHz radio continuum emission at a resolution of 28″ (from Johnston *et al.* 1983; contour unit 55 mJy per beam). The crosses mark the positions of the 63 μm continuum peak (the KL nebula, *upper*) and of Θ^1C Ori (*lower*), the brightest star in the Trapezium cluster. (*middle*): Contours of integrated [O I] emission (*heavy lines*), superposed on contours of $v = 1 \rightarrow 0$ $S(1)$ emission from H_2 at 2 μm (Gautier 1979), 30″ beam, contour unit 6×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}. The northwestern, stronger peak is H_2 peak 1; the southeastern peak is H_2 peak 2. (*right*): Contours of 63 μm continuum emission (*heavy contours* 1, 2, 4, 6, 8, 10, 12, 14, 16, 18 times 3.8×10^3 Jy or 1.6×10^{-17} W cm^{-2}), superposed on the 5 GHz radio continuum map.

line emission in this region probably comes from dense ($n_H \approx 10^4$–10^5 cm^{-3}), warm ($T \approx$ a few hundred K) gas at the interface between the H II region and the molecular cloud. This interface region will be discussed in a forthcoming paper (Ellis and Werner 1984; see also Jaffe and Pankonin 1978). The [O I] peaks in the KL region are close to but somewhat interior to the emission lobes of hot molecular hydrogen (Fig. 1 [*middle*]) and are also similar to the distribution of high-velocity rotational CO emission (cf. Erickson *et al.* 1982). The lower resolution data of Naylor *et al.* (1982) and Ellis and Werner (1984) also clearly show an extension of the 63 μm emission from the Trapezium toward the BN-KL region but lack sufficient resolution to identify a separate peak.

c) *Kinematics*

Figure 2 shows [O I] spectra taken with a resolution of 45 km s^{-1} toward the radio peak west of the Trapezium, H_2 peaks 1 and 2, and the KL peak (the center of the 63 μm continuum emission). The line toward the radio peak is unresolved; the line shape is identical with the instrumental profile. The LSR velocity of the line is 8.5 ± 3 km s^{-1} which is in good agreement with the velocity centroid of the 6300 Å line of [O I] at this position (Münch and Taylor 1974). The line profiles near the KL nebula are resolved, and the lines are significantly blueshifted. The line width at H_2 peak 1 is 67 ± 5 km s^{-1} FWHM, and the peak of the line is at $v_{LSR} = 0 \pm 3$ km s^{-1}. The line widths at H_2 peak 2 and the KL peak are 61 ± 5 km s^{-1}, and they are centered at $v_{LSR} = +3 \pm 3$ km s^{-1}. Most of the difference between these line profiles and the unresolved line toward the radio peak is probably due to the influence of high-velocity [O I] emission, blueshifted by ~ 20–50 km s^{-1}. The presence of strong blueshifted wings is also characteristic of the H_2 2 μm lines toward peaks 1 and 2 (Nadeau, Geballe, and Taylor 1982). The intrinsic width of the [O I] line toward the KL region may be estimated, by comparing the line width observed at 45 km s^{-1} with that at 60 km s^{-1} resolution, to be about FWHM 50 km s^{-1} at H_2 peak 1 and 40 km s^{-1} toward the KL peak. These are lower limits to the width of the emission associated with the KL nebula itself since the profile probably includes a narrow component of line emission from the interface [O I] gas in front of KL.

III. DISCUSSION

a) *Properties of the* [O I]*-Emitting Gas in the KL Nebula*

The [O I]-emitting gas in the KL nebula has a large velocity dispersion, and its emission has a spatial distribution similar to that of the 2 μm emission from hot hydrogen. It is, therefore, likely that the 63 μm [O I] emission is produced in shocks due to the mass outflow from the center of the KL nebula. The [O I] line is of substantial importance to the gas cooling in the shocked region since its luminosity is of the same order of magnitude as the luminosities of the H_2 and CO lines. The peak surface brightness of the line near H_2 peak 1 is $3.3 \pm 1 \times 10^{-2}$ ergs s^{-1} cm^{-2} sr^{-1}, after subtraction of a background of about 2.5×10^{-2} ergs s^{-1} cm^{-2} sr^{-1} which may originate in the interface to the H II region. The total 63 μm line luminosity from the shocked region is 50 ± 25 $L_\odot$, which is only about 3–4 times smaller than the total luminosity of *all* H_2 infrared lines (~ 200 $L_\odot$; cf. Scoville *et al.* 1982, Beckwith *et al.* 1983), or the luminosity of the

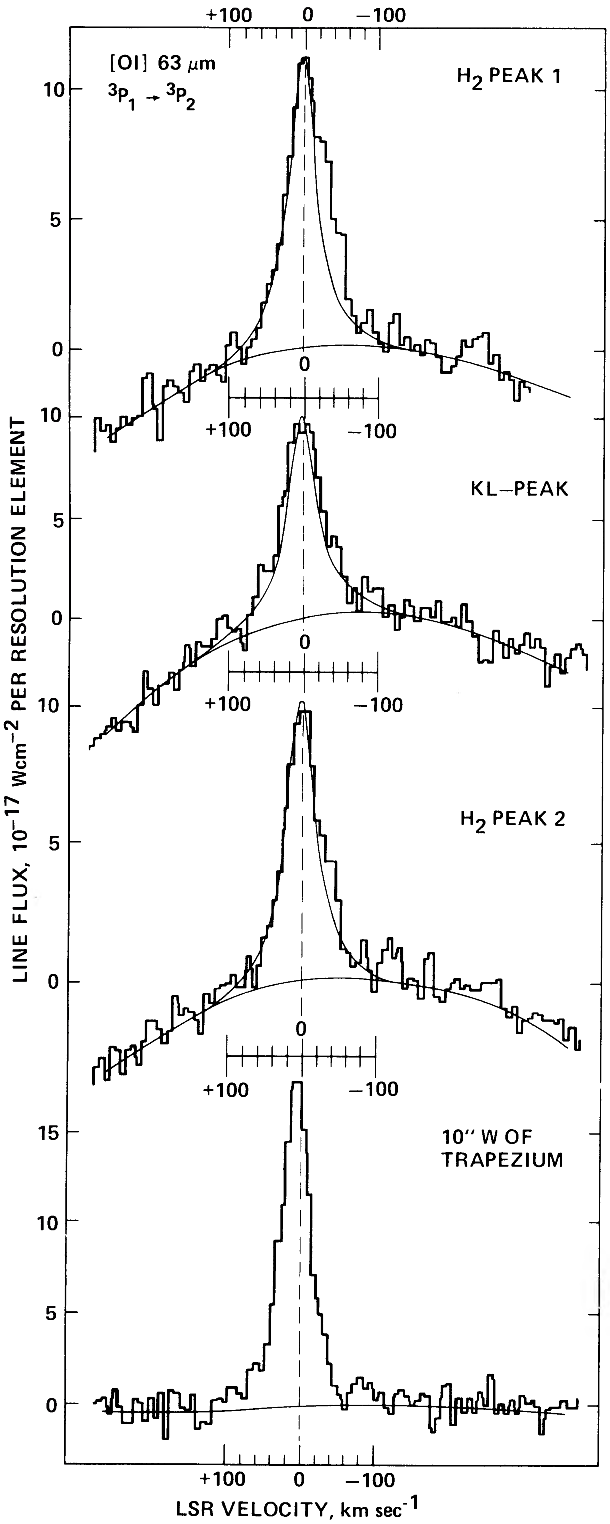

FIG. 2.—Spectra of 63 μm [O I] emission toward several positions in the Orion nebula region: 10″ west of Trapezium (*bottom*), H_2 peak 2 (*second from bottom*), 63 μm continuum peak (*third from bottom*), and H_2 peak 1 (*top*). Beam size is 30″, and the instrumental profile is a Lorentzian of FWHM 45 km s^{-1} (indicated by thin lines in the upper three spectra). The bottom line is unresolved. The curvature in the continuum on the left and right of the [O I] line is due to telluric H_2O absorption. The vertical scale is given separately on the y-axis for each spectrum. Typical integration times are 6 minutes per spectrum.

far-IR CO lines (150 $L_\odot$). The minimum column density of [O I] gas required to produce the observed surface brightness is 4.5×10^{17} cm^{-2}, assuming statistical equilibrium at high density ($n \geq 5 \times 10^5$ cm^{-3}) and $T \gg 230$ K. This is probably a good assumption for the parameters of the [O I] emitting gas in the KL nebula. The ratio of 63 μm intensity to that of the second [O I] line at 145 μm toward the center of the KL nebula is between 20 and 40 (Ellis and Werner 1984). This range is consistent with optically thin emission from dense gas ($n_H \approx 10^{5 \pm 1}$ cm^{-3}) at high temperature ($T \approx$ 300–1500 K) and is also characteristic of shocked gas. With a width of 50 km s^{-1}, the line has negligible opacity ($\tau_{63} \sim 10^{-2}$). Assuming all oxygen atoms are in the form of O I and a cosmic abundance of oxygen (O/H = 6.6×10^{-4}), the lower limit to the column density of hydrogen nuclei in the [O I]-emitting region is 7×10^{20} cm^{-2}, which corresponds to a mass of ~ 0.15 $M_\odot$. This is significantly larger than the amount of very hot hydrogen gas behind the molecular shock ($T \geq 2000$ K; $N_H \approx 5 \times 10^{19}$ cm^{-2}; cf. Beckwith *et al.* 1983) but less than the hydrogen column density estimated for the medium temperature molecular gas in this region ($T \approx 500 \rightarrow 1000$ K; $N_H \approx 2$–6×10^{21} cm^{-2} (cf. Watson *et al.* 1984).

b) [O I] *Emission from the Cloud Shock*

The mass outflow in the KL nebula drives shocked, neutral gas into the ambient interstellar medium. As pointed out by Castor, McCray, and Weaver (1975), Hollenbach (1982), and Chernoff, Hollenbach, and McKee (1982, hereafter CHM), two separate shock fronts will exist under these circumstances. The "wind shock" occurs at the point where the stellar wind collides with the inner edge of the shocked, expanding material. A second shock (the "cloud shock") occurs where the outer edge of the expanding material strikes the ambient molecular cloud. Draine and Roberge (1982) and CHM have modeled the cloud shock as a C-type shock in which the magnetic field effectively "cushions" the shock front. These models have successfully reproduced the intensities of the high-excitation molecular lines of H_2, OH, and CO observed in the KL region. In such a shock, the [O I] 63 μm line is predicted to be two or more orders of magnitude fainter than the integrated H_2 emission, because any preshock atomic oxygen is rapidly converted to H_2O in the hot postshock region. By contrast, the present observations show that the 63 μm line is within an order of magnitude as intense as the total H_2 emission. The column density of medium temperature ($T > 500$ K) C-shocked gas, however, is sufficient to produce the [O I] emission if $\sim 10\%$ of the oxygen could be maintained as [O I]. Thus, if our present understanding of the chemistry in this region is inadequate, it is possible that the [O I] emission could in fact be produced in the molecular shock.

c) *The Wind Shock*

Alternatively, the [O I] emission may come from the wind shock (Hollenbach 1984; Draine and Roberge 1982). If the outflow has a characteristic speed in excess of 100 km s^{-1}, it strikes the inner surface of the compressed shell at a speed in excess of 50 km s^{-1}. This is sufficient to dissociate and significantly ionize the wind material, which leads to formation of a J-type wind shock front with sharp density and temperature discontinuities and high postshock temperatures ($T \gg 10^4$ K). As the gas behind the shock front cools and recombines, it passes through a range of temperatures from approximately 5000 K to 100 K in which [O I] 63 μm emission is the dominant coolant for the largely atomic gas. Because the 63 μm line is the dominant coolant in this temperature range, about 5000 k of energy ($k = 1.38 \times 10^{-16}$ ergs K^{-1}) is radiated in the line for each nucleon which crosses the shock front. Thus the flux of material into the shocks, $n_H v$ (cm^{-2} s^{-1}), is related to the surface brightness, I, of the 63 μm line by:

$$I = 5000 \frac{k}{4\pi} n_H v \text{ ergs s}^{-1}\text{cm}^{-2}\text{ sr}^{-1}, \quad (1)$$

where n_H (cm^{-3}) is the preshock hydrogen density in the wind, and v is the relative velocity between wind and shell. Detailed calculations over the range 40 km $s^{-1} < v <$ 200 km s^{-1} and 10 $cm^{-3} < n_H < 10^{+5}$ cm^{-3} show that the [O I] 63 μm intensity lies within a factor of 2 of this linear relationship for $n_H v \lesssim 10^{12}$ cm^{-2} s^{-1} (Hollenbach 1984). Assuming that the wind shock in the Orion-KL region falls within this parameter range, the observed [O I] 63 μm intensity corresponds to a value of $n_H v = (6 \pm 2) \times 10^{11}$ cm^{-2} s^{-1}. In this limit, the total luminosity of the 63 μm line gives a direct estimate of the mass loss rate $\dot{M}$ from the central object and is about 7 $L_\odot$ if $\dot{M} = 10^{-3}$ $M_\odot$ yr^{-1}. For the observed total [O I] luminosity of 50 $\pm$ 25 $L_\odot$, the corresponding mass loss rate is $(7 \pm 3.5) \times 10^{-3}$ $M_\odot$ yr^{-1}, which is comparable with or somewhat higher than other estimates of the mass loss rate in the KL region. If the [O I] emission arises predominantly in the wind shock, while the H_2 and CO infrared emission lines arise in the molecular shock, differences in the details of the line profiles and spatial distribution are expected. The [O I] data presented above are consistent with these expectations but do not exclude the possibility that the [O I] emission comes from the cloud shock. The [O I] 63 μm emission line may be one of the few direct observational probes of J-type wind shocks in embedded infrared sources. If [O I] emission from the wind shock can be unambiguously identified, its intensity may be an important measure for determining mass loss rates in outflow sources.

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