SPECTROSCOPY OF THE ORION MOLECULAR CLOUD CORE

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ABSTRACT

Recent infrared and radio spectroscopic data pertaining to the Orion BN-KL infrared cluster are reviewed. A new, high resolution CO map shows that the thermal structure over the central 10'(1.5 pc) in the Orion molecular cloud is dominated by energy sources in the infrared cluster and M42. Peak CO brightness temperatures of 90 K occur on KL and near the bar at the southern edge of M42.

Within the central 45" of the infrared cluster, both radio and IR data reveal a highly energetic environment. Millimeter lines of several molecules (e.g. CO, HCN, and SiO) show emission over a full velocity range of 100 km s^{-1}. These supersonic flows can be modeled as a differentially expanding envelope containing a total of $\sim 5\ M_\odot$ of gas within an outer radius of $r \simeq 1.3 \times 10^{17}$ cm. Over the same area emission is seen from vibrationally excited molecular hydrogen at an excitation temperature of 2000 K. The high velocity mm-line emission and the NIR H_2 lines are clearly related since they exhibit similar spatial extents and line widths. Comparison of the total cooling rate for all the H_2 lines with the estimated kinetic energy and expansion time for the mm-emission region indicates that the H_2 emission probably arises from shock fronts where the expanding envelope impinges on the outer cloud.

Near IR spectroscopy also probes ionized and neutral gas closely associated with BN. Br α and Br γ emission is detected from an ultracompact HII region of mass $M_{HII} \lesssim 10^{-4}\ M_\odot$. Full widths for the HII lines are $\sim$400 km s^{-1}. CO bandhead emission detected in BN at $\lambda \simeq 2.3$ μm is probably collisionally pumped in a high excitation zone ($n_{H+H_2} > 10^{10}$ cm^{-3} and $T_K \simeq 3000$ K) at only a few AU from the star. The velocity of both the HII and CO emission is $V_{LSR} \simeq +20$ km s^{-1}; thus BN appears to be redshifted by 11 km s^{-1} with respect to OMC-1.

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I. INTRODUCTION

In the last few years we have witnessed a remarkable change in our comprehension of the evolution of active star formation regions like the Orion nebula. Far from the initial picture of an interstellar cloud gently condensing to form stars, recent mm and near infrared spectroscopic data attest to an extraordinary level of activity at the cloud core. Within the BN-KL infrared cluster, NIR emission lines are detected from vibrationally excited H_2 and CO, indicating dense, neutral gas at temperatures of several thousand degrees, and high velocity wings are observed on many of the mm-wavelength rotational transitions (e.g. $J = 1 \rightarrow 0$, CO), indicating hypersonic gas motions over a range of 100 km s^{-1}. Similar phenomena have now been detected in almost a dozen other cloud core regions; it is therefore evident that a thorough study of the events in Orion can contribute to our understanding of cloud evolution, specifically the disruptive phases following an internal episode of star formation. The near infrared spectroscopy is also yielding important constraints on the nature of the embedded sources like BN and their immediate environs. Most helpful to observations of continuum sources has been the recent development of Fourier transform spectrometers with sufficient resolution ($\Delta K \lesssim 0.2$ cm^{-1}) to remove absorption features in the earth's atmosphere and to resolve both "stellar" and interstellar features.

In this review of spectroscopic results, our focus is upon the active central region ($r \leq 2 \times 10^{17}$ cm) of the Orion molecular cloud encompassing infrared continuum sources and the excited, high velocity molecular gas. The two phenomena are very likely to be related since several of the continuum sources are presumably very young stars and the gas disturbances may ultimately be traced back to the evolution of such stars trapped within a cloud. In studying this activity we find a convenient marriage of the complementary radio and IR data. The former generally provides an excellent view on the lower excitation, more extended gas phases; the latter is uniquely capable of sampling trace quantities of gas with high excitation conditions or the small volumes immediate to the embedded stars. To gain some perspective on the central core region we start the discussion below with a brief description of the very extended Orion molecular cloud as gained from millimeter line data.

II. THE ORION GIANT MOLECULAR CLOUD

The full extent of the Orion molecular cloud is best appreciated from maps of the $J = 1 \rightarrow 0$ (2.6-mm) CO line on account of the ubiquity of CO and the very modest requirements ($n_{H_2} \gtrsim 300$ cm^{-3}) for excitation of this transition above the 2.7 K background. The first complete, low resolution map of this emission by Kutner et al. (1977) showed the cloud strung out roughly parallel to the galactic plane (SE-NW) with dimensions of $1 \times 5^{\circ}$ or 10×45 pc. The overall mass estimated from a virial analysis and from the calculated CO column densities is about 1×10^5 $M_{\odot}$, most of which is presumably H_2 at a mean density $n_{H_2} \sim 300$ cm^{-3}.

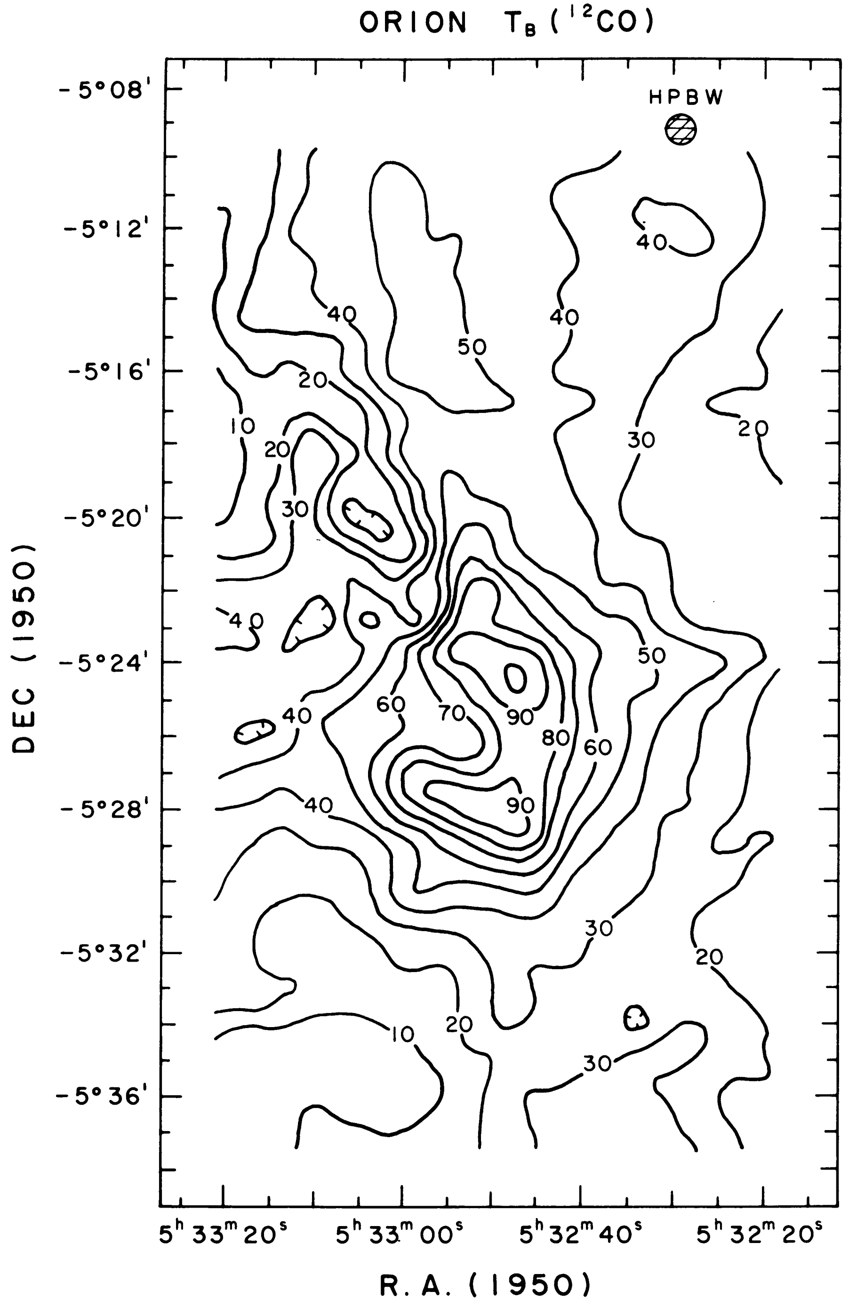

Figure 1. The CO (J = 1 → 0) brightness temperature distribution for the central 1/2° of the Orion nebula (Scoville, Schloerb, and Goldsmith 1980b). The map was densely sampled with the 45-foot University of Massachusetts antenna (HPBW = 45").

In Figure 1 a high resolution map of the CO brightness temperature is shown for the central $1/2^{o}$ surrounding M42 and the KL-BN cluster. The area shown in Figure 1 was fully sampled using the 45-foot mm-telescope (HPBW = 45") at the University of Massachusetts (Scoville, Schloerb, and Goldsmith 1980b). Dominant features of the emission on this scale are an obvious peaking in the line intensity near M42 and KL and the pronounced N-S elongation, especially to the north of the cloud core. The fine structure in the vicinity of KL and M42 closely follows some of the highest resolution far infrared data. In particular, a peak is seen corresponding to KL-BN and a ridge shows up for the first time at the southern ionization front in M42 similar to the FIR "bar" feature of Werner et al. (1976). It is significant that the CO brightness temperature and the 50/100 μm color temperatures agree within the calibration errors (~15%) for both the KL peak and the bar. In these regions, the CO transition is both optically thick and the levels are thermalized ($n_{H_2} \gg 3000$ cm^{-3}), so we may interpret the CO brightness temperature map as a map of gas kinetic temperature. Thermal equilibrium between the dust grains and H_2 gas is expected for $n_{H_2} > 5 \times 10^4$ cm^{-3} (Goldreich and Kwan 1974) which will probably hold here.

III. THE ORION CLOUD CORE

a) Radio Frequency Lines

The remarkable characteristic in the mm-lines, setting the central 1' of the core off from the remainder of the cloud, is the velocity dispersion of the emission seen there. Outside the core the full line widths are always $\lesssim 5$ km s^{-1} and the peak velocities vary only 5 km s^{-1} over the full 5^{o} length of the cloud. Yet within the core the emission of nearly half the observed molecules (e.g. CO, CS, SiO, SO, SO_2, and HCN) can be followed out 30 to 50 km s^{-1} with respect to the cloud rest frame at $V_{LSR} = 9$ km s^{-1}. Figure 2 shows the ^{12}CO and ^{13}CO spectra at the KL position. This high velocity gas component (the "plateau" source on account of the line shape) was first observed in J = 1 → 0 CO and analyzed by Zuckerman, Kuiper, and Kuiper (1976) and Kwan and Scoville (1976). The latter authors suggested that the gas was in a differentially expanding envelope, perhaps the result of an explosive event in the cloud core.

New measurements of the high velocity 2.6-mm CO emission at the best available spatial resolution, 45" using the 45-foot University of Massachusetts antenna, find the center at $\Delta\alpha = 0 \pm 4''$, $\Delta\delta = 0 \pm 5''$ relative to BN (Solomon et al. 1980). Within the errors IRC-2 could be located within the centroid but KL which is 12" south of BN appears ruled out. The diameter of the emission region is 36" when corrected for the telescope HPBW, giving a radius of $r_{CO} = 1.3 \times 10^{17}$ cm.

From comparison of the ^{12}CO and ^{13}CO profiles in Figure 2, one sees that the opacity of the ^{12}CO high velocity wings is $\lesssim 3$ in the J = 1→0 line if $[^{12}CO/^{13}CO] \lesssim 89$. The low opacity of the 2.6-mm line wings

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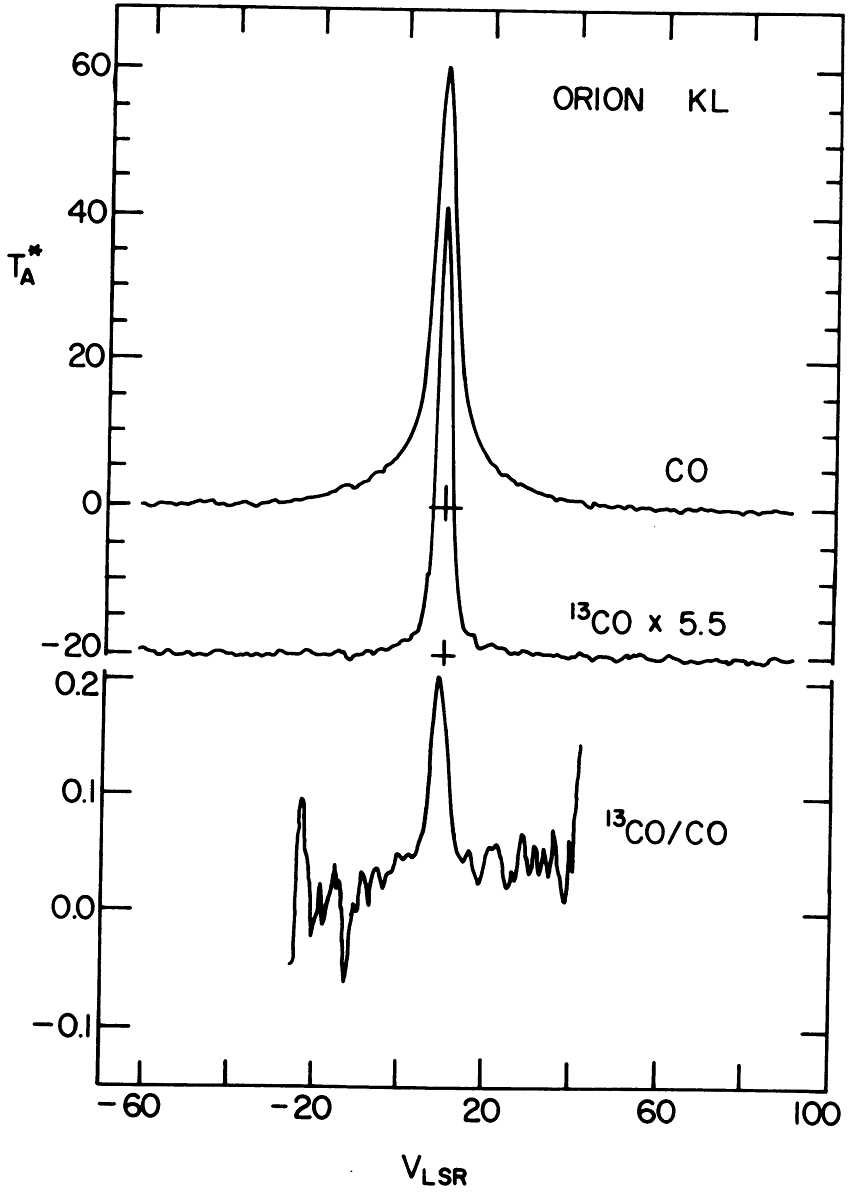

Figure 2. Spectra of CO and ^{13}CO corrected antenna temperature ($T_A{}^*$) at the position of KL. Note that the high velocity emission, prominent in ^{12}CO, is hardly visible in ^{13}CO due to the low opacity of this kinematic component compared to the 9 km s^{-1} component from OMC-1.

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allows one to directly use the integrated flux in the line wings to estimate the CO column density and hence the total mass of high velocity gas. For a rotational temperature of 200 K, as indicated by the higher CO lines (Phillips et al. 1977), and assuming 10% of the C is bound in CO, this mass is $M_{H_2} = 5\ M_\odot$. The total kinetic energy involved in the high velocity motions at present is therefore ~1-2 x 10^{47} ergs and the momentum is ~200 $M_\odot$ km s^{-1}.

It should be noted that the center of the high velocity emission and its size appear different in several other molecules. Using the new mm-interferometer at Hat Creek, Baud et al. (1980) locate the ground state SiO emission (v = 0, J = 2 → 1) at IRC-2 with a size of only 12" and from data obtained on the 100-m Effelsberg antenna, Zuckerman, Palmer, and Morris (1980) identify a "hot" NH_3 component with IRC-4 near the center of KL. Phillips et al. (1977) find the J = 3 → 2 CO emission centered midway between BN and KL, only 4" from IRC-2. And from VLBI data, Genzel et al. (1979) deduce that the SiO maser emission from v = 1 and v = 2 is from IRC-2; however, the relationship of this emission to the other high velocity emission is unclear since the line shape and velocity extent (v = -10 to +21 km s^{-1}) appear rather similar to those in late-type giant stars. An outstanding question at present is which, if any, of the molecular line maps one should adopt for the most meaningful picture of the high velocity gas distribution. My own preference is for the 2.6-mm CO line: its opacity can be demonstrated to be low ($\tau < 3$); its excitation is likely to be saturated at the gas kinetic temperature and therefore the brightness translates directly into column density (rather than an emission measure $\alpha\ n^2L$), and lastly the abundance of CO in the gas is likely to be relatively stable against perturbations resulting from passage of shock fronts. In contrast, the higher CO lines will have at least 4 times greater opacity, while SiO, SO, SO_2, and HCN probably suffer all the above difficulties to some extent.

In addition to the relatively continuous (in velocity) emission seen in the millimeter lines, the Orion cloud core shows H_2O maser emission with over 50 discrete velocity components between v = $\pm$ 50 km s^{-1}. Position measurements obtained in VLBI experiments over the last three years have been recently analyzed by Genzel et al. (1980) to yield the first proper motion detections in Orion. Noticing that the proper motion vectors appear to radiate out of a common center, they attempted to fit the kinematic data with an expanding envelope and identify the center of expansion as IRC-2. A subset of this data for which proper motions could be determined in both RA and DEC is shown in Figure 3.

b) Infrared Lines of H_2 and CO

Probably the greatest surprise in the spectroscopic studies of Orion has been the discovery in 1976 by Gautier et al. of the 2 μm H_2 emission lines. Their detection was totally unanticipated since the v = 1 states from which the emission arises are at an energy E/k ≃ 6800 K above ground and the emission was found to be spatially extended.

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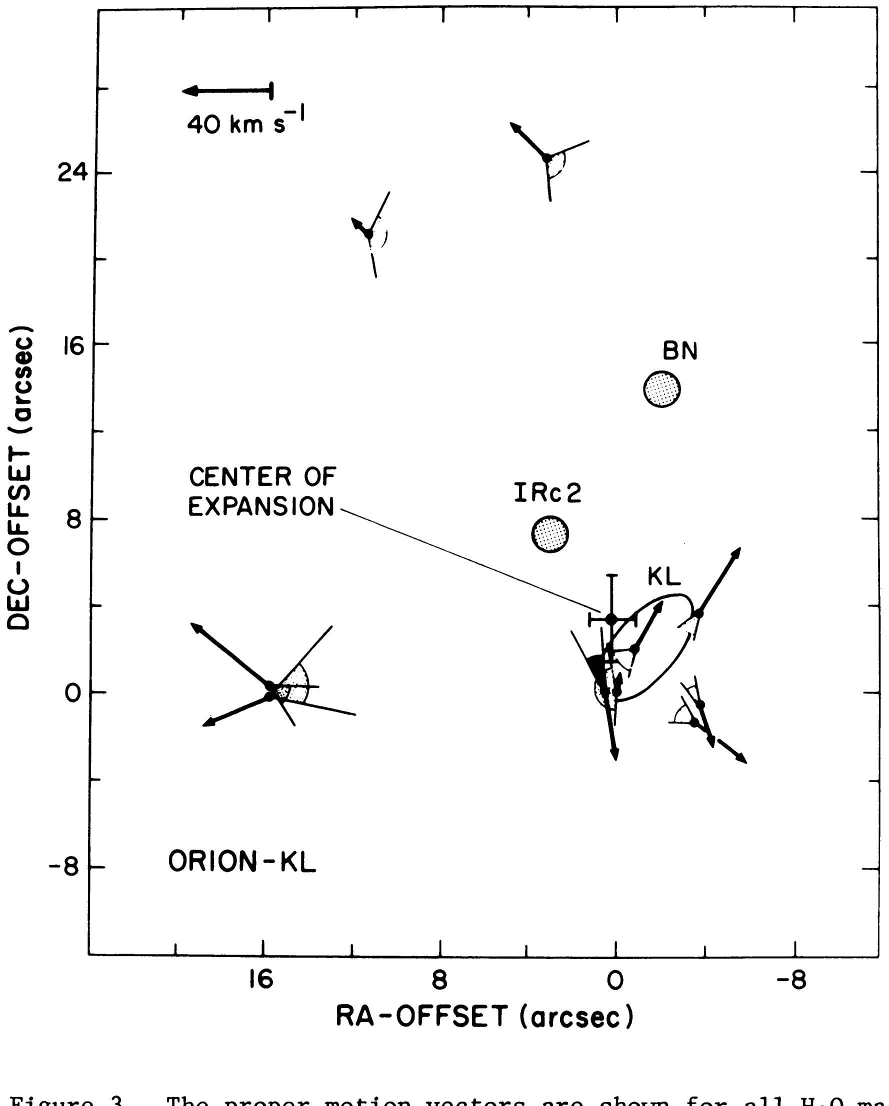

Figure 3. The proper motion vectors are shown for all H_2O masers in Orion for which motions could be measured in both RA and DEC (Genzel et al. 1980). All velocity vectors are relative to the center of expansion, that is, they have been corrected for the motion of the reference maser feature based upon the model parameters.

The initial interpretation that the H_2 emission was collisionally excited in shock heated gas has been borne out by subsequent observations and theoretical models.

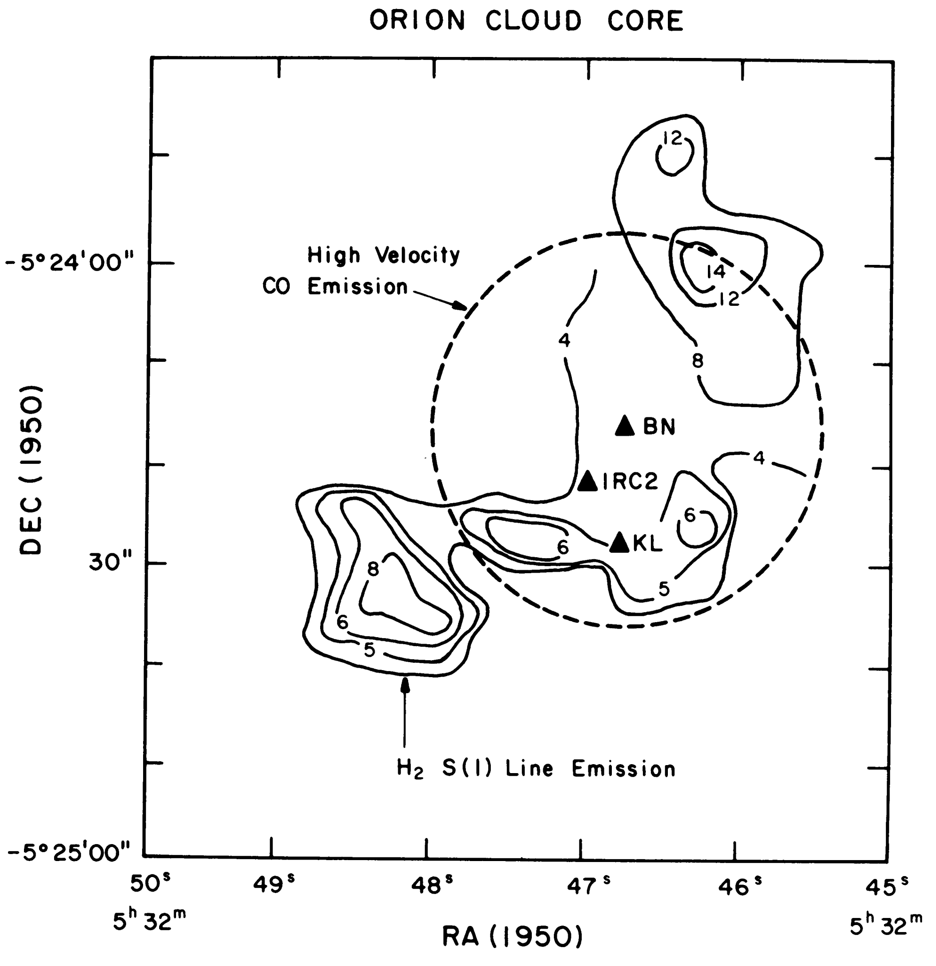

Figure 4. The H_2 S(1) line emission from the Orion nebula observed with 5" aperture (Beckwith et al. 1978). The size and position of the high velocity CO (J = 1 → 0) emission is also shown (Solomon, Huguenin, and Scoville 1980). The intensity contour units are 6.1 x 10^{-4} ergs s^{-1} cm^{-2} sr^{-1}. Peak 1 (highest contour 14) is 18" NW of BN; Peak 3 (highest contour 6) is 8" E of KL; and Peak 5 (highest contour 12) is the most northern source.

The spatial distribution of the H_2 emission appears extremely nonuniform and clumpy on the scale of 5-10", but low level emission does appear over at least 40". A high resolution map (5") in the S(1) line (v = 1 → 0, J = 3 → 1) made by Beckwith et al. (1978) is shown in Figure 4. In the map at least five distinct H_2 peaks may be seen--none of which show correlation with previously identified continuum sources.

Using the fact that several of the observed H_2 lines originate from a common upper state, for example S(1)(v = 1 → 0, J = 3 → 1) and Q(3) (v = 1 → 0, J = 3 → 3), Beckwith, Persson, and Neugebauer (1979) and Simon et al. (1979) have estimated the differential extinction in front of a couple of the H_2 peaks. Both investigations measure the 2 μm reddening and infer $A_v \simeq 40 \pm 10$ mag (or $N_{H+2H_2} \simeq 6 \times 10^{22}$ cm^{-2} for a standard gas-to-dust ratio). Since the extinction estimated for three locations was similar within the errors, it appears likely that most of the spatial structure seen in Figure 4 is actually in the H_2 source and cannot be attributed solely to a clumpy foreground extinction. When the observed S(1) line luminosity of 2.5 $L_\odot$ from the entire Orion source is corrected for the measured extinction ($A_{2\mu m} = 4 \pm 1$ mag) and the contributions of the other H_2 lines are included (a factor of 10 for T_{vib} = 2000 K), the total implied H_2 luminosity is 1000 $L_\odot$ (Beckwith et al. 1979).

Theoretical analyses for the emission have favored collisional excitation of the H_2 in gas which has been shock heated to several thousand degrees (Hollenbach and Shull 1977, Kwan 1977). The high extinction deduced to the H_2 suggests that these shocks cannot merely be at the interface of M42 and OMC-1. Indeed the similarity of the estimated extinction for the H_2 and that found for the HII region associated with BN (see below) implies that both regions are at an equivalent distance inside the cloud. Both the large spatial extent of the H_2 emission within a dense cloud and the relatively weak v = 2 → 1 emission, compared to v = 1 → 0, argue against the UV fluorescense excitation for H_2. The shock models in which the H_2 vibrational states are collisionally excited can give the proper luminosity (1000 $L_\odot$) and correct line ratios ($\bar{T}_{ex}$ = 2000 K) with an ambient density $n_{H_2} \gtrsim 10^6$ cm^{-3} and shock velocities in the range 10-25 km s^{-1} (Kwan 1977). In this picture the emitting layer of <u>hot</u> H_2 is extremely thin (~10^{13} cm along the line-of-sight) since the observed column densities are only ~10^{20} cm^{-2}. The overall extent of the H_2 emission <u>is</u> similar to that of the high velocity CO as can be seen in Figure 4 where an outline of the CO volume is superposed. This suggests that the H_2 is excited in shock fronts where the expanding envelope seen in the mm-lines collides with the ambient cloud (Kwan and Scoville 1976, Kwan 1977).

The most extensive data at high spectral resolution to measure the H_2 velocities and map the shock front kinematics have been taken by Nadeau and Geballe (1979) using a Fabry-Perot interferometer with 10" aperture and by Scoville et al. (1980a) using the KPNO-FTS with 3".75 aperture. An extremely large velocity range ~100 km s^{-1} for the H_2 emission was first reported by Nadeau and Geballe (1979). Figure 5 shows the FTS spectra taken on three of the H_2 peaks in Figure 4 with the seven visible H_2 lines spliced together. An enlarged view of the S(1) line from Peak 1 (shown in Figure 6) demonstrates that significant emission can be seen over at least 150 km s^{-1}. Although the emission profiles for the three positions appear quite different, they do <u>all</u> exhibit a very large velocity range, 100-150 km s^{-1} for the emission. One of the most puzzling aspects of the H_2 emission is how the molecules

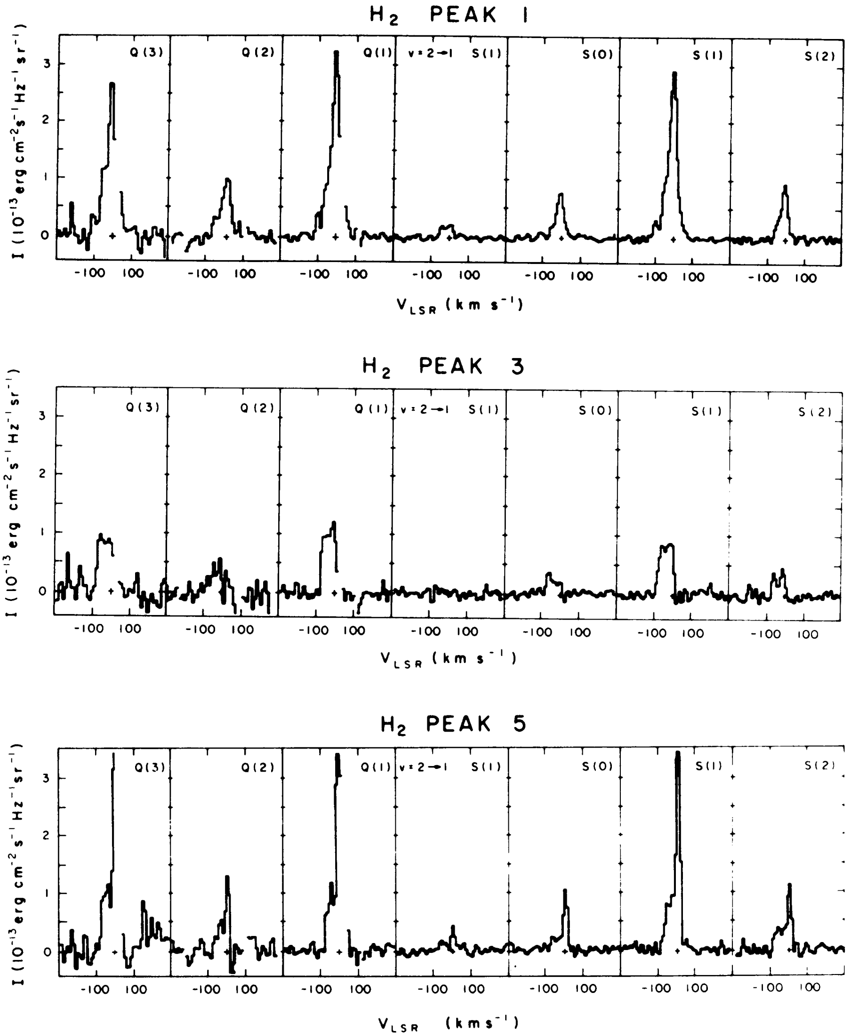

Figure 5. Seven H_2 transitions in v = 1 → 0 and 2 → 1 bands are shown for three H_2 peaks shown in Figure 4. (The positions of these peaks are given in the Figure 4 caption.) The spectra were taken with the KPNO-FTS on the 4-m telescope using a 3".75 aperture (Scoville et al. 1980a).

can survive acceleration to such high velocities. Theoretical models predict collisional dissociation of all the preshock H_2 for shock velocities exceeding 25 km s^{-1} if the density is above 10^5 cm^{-3} as it should be here (Kwan 1977; Dalgarno and Roberge 1979). Thus most of the

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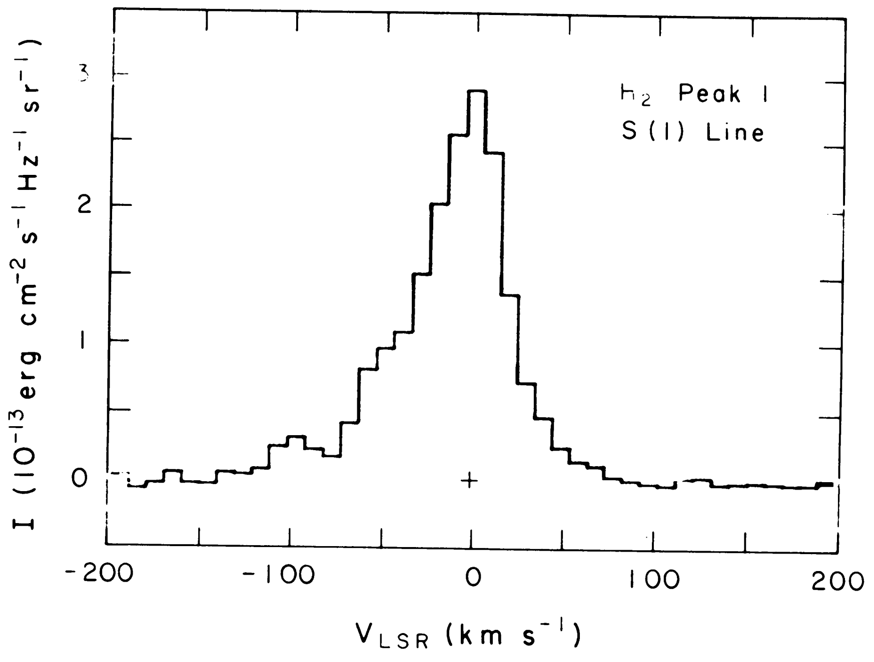

Figure 6. An expanded spectrum of the v = 1 → 0 S(1) H_2 line on Peak 1 showing emission over more than 150 km s^{-1} (Scoville et al. 1980a).

very high velocity H_2 may have been reformed downstream from the shock after the dissociated gas cools below about 4000 K. Alternatively if the original H_2 were contained largely in clumps, the gas in the center of these clumps could conceivably be accelerated without dissociation.

The H_2 kinematic data along a strip running between Peak 1 in the northwest and Peak 2 in the southeast is shown in Figure 7. The lines broaden towards the center of the region, but there is no evidence of the line splitting one expects in a symmetric, expanding shell. The absence of splitting could be due merely to inhomogeneities in the ambient medium--something which was already evident from the clumpiness of the spatial maps. It is also noteworthy that the emission profiles of S(1) and Q(3) appear similar in shape (Figure 5). Thus the different velocities seen in a given direction are not located behind grossly dissimilar columns of dust. We can rule out an expanding shell model in which the interior volume is filled with dust to the extent that one velocity component suffers twice as much extinction as the other. It does appear that the H_2 emission in the direction of IRC-2 suffers about twice as much extinction as in the other positions. Figure 7

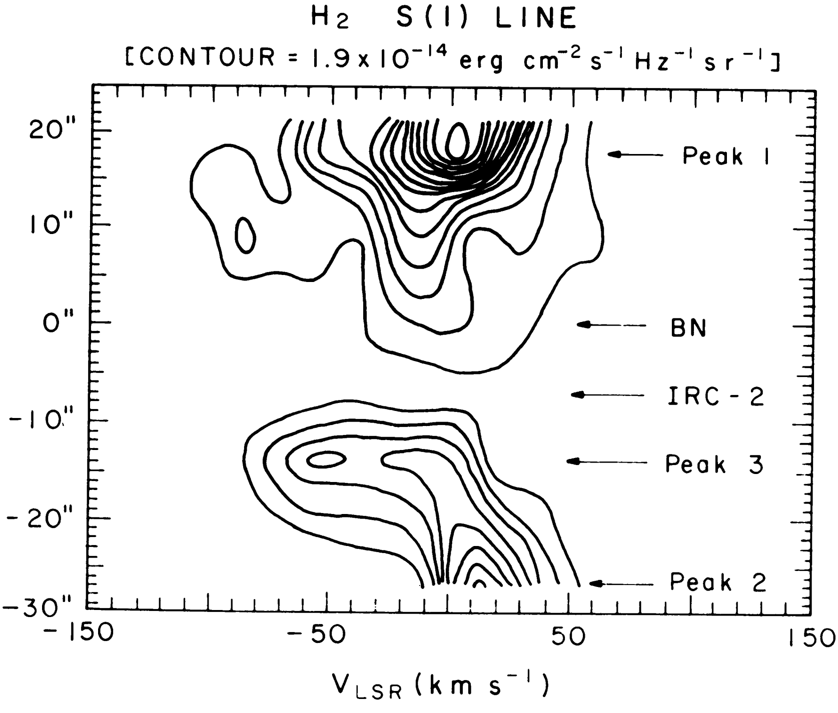

Figure 7. Spatial-velocity contour map from the FTS data at the S(1) line along a strip crossing the Orion cloud core (northwest to southeast).

shows little or no S(1) emission at IRC-2, yet we quite easily detect the Q(3) line there. The 10 μm silicate feature also is particularly deep in IRC-2 (Aitken et al. 1980).

A dynamic timescale of 1300 yrs is found for the H_2 shock front when one divides the radius of the emission region (2 x 10^{17}cm) by the measured half-width of 50 km s^{-1}. Assuming that the H_2 luminosity is constant over this time, we estimate that a total of 1.5 x 10^{47} ergs has been radiated in the vibrational lines. The equivalence of this integrated cooling rate to the kinetic energy (1 - 2 x 10^{47} ergs) estimated earlier for the high velocity CO envelope supports the earlier suggestion that the CO envelope feeds kinetic energy to the H_2 shocks where the expanding gas hits the stationary cloud, OMC-1.

IV. SPECTROSCOPY OF BN

Despite the fact that most of the high resolution spectroscopy of

BN has been in two narrow bands at λ = 2.1 - 2.4 μm and 4.5 - 4.8 μm, the initial observations already demonstrate real advantages over photometric techniques for study of bright, embedded sources. For BN the NIR photometric data indicate a color temperature $T_c \simeq 500$ K and a NIR luminosity $L_{\lambda \lesssim 20\ \mu m} \gtrsim 2 \times 10^3\ L_\odot$ (Becklin, Neugebauer, and Wynn-Williams 1973). The radius at which the observed continuum arises must therefore be greater than $r_{BB} = 4 \times 10^{14}$ cm. On the other hand, the spectroscopic data now reveal emission from CO (at λ = 2.3 μm) for which the analysis indicates a radius of 10^{13} cm and mass of just $10^{-7}\ M_\odot$. Thus, in addition to probing the physical conditions and dynamics of varied excitation regimes in both neutral and ionized gas, the spectroscopy is also capable of penetrating closer to the ultimate source of energy and detecting the small quantities of matter one expects in a primitive solar nebula.

The spectroscopic data in BN reveal at least three distinct regimes: an HII region from which Br α and Br γ are observed; a hot, dense molecular region giving rise to CO emission at 2.3 μm; and cooler molecular gas producing CO absorption at 4.6 and 2.3 μm. The first two regions are probably at a radius of a few AU; the latter is probably much further out, possibly in the high velocity mm-line envelope.

The Br α emission in BN was first detected and mapped by Grasdalen (1976) and Joyce, Simon, and Simon (1978) using a grating spectrometer. The measured flux indicated an exciting star with a Lyman continuum emission rate $7 \times 10^{46}\ s^{-1}$ (equivalent to a B0 main sequence star with $L \simeq 10^4\ L_\odot$) assuming the HII was optically thin and photoionized. Hall et al. (1978) measured a velocity of V_{LSR} = + 21 km s^{-1} for both Br α and γ and detected broad symmetric wings on the Br α line. Recent FTS data in the vicinity of Br γ is shown in Figure 8. The line here shows two components: a narrow one with ΔV_{FWHM} = 30 km s^{-1} and a high velocity one with emission out to $\pm$ 200 km s^{-1}. Based upon these kinematic properties, i.e. the 11 km s^{-1} redshift of the HII center velocity from the cloud center of mass and the large linewidth, it appears more reasonable to attribute the emission to circumstellar gas rather than a more extended HII region ($r \gtrsim 10^{15}$ cm) formed in the cloud by BN. Comparison of the Br α/Br γ flux ratio with that from optically thin, photoionized HII gives a Br α/Br γ color excess of 1.6 $\pm$ 0.1 mag. or $A_V \simeq 30$ mag. to the region (Hall et al. 1978). Figure 8 also shows the $^2S - {^2P^o}$ transition of NaI with a kinematic width similar to the broad HII component. This doublet was previously detected in the F8 supergiant IRC + 10420 where the analysis indicated the emission could be pumped by absorption of UV at 3000 Å out of the ground state (Thompson and Boroson 1977).

From the upper limits to the radio free-free flux in BN, the size of the HII region must be less than 5×10^{15} cm (Grasdalen 1976). This size combined with the measured emission measure imply that $M_{HII} < 10^{-4}\ M_\odot$. It is thus clear that the present kinetic energy and momentum in the HII region are insufficient (by two orders of magnitude) to drive the flow in the high velocity CO envelope.

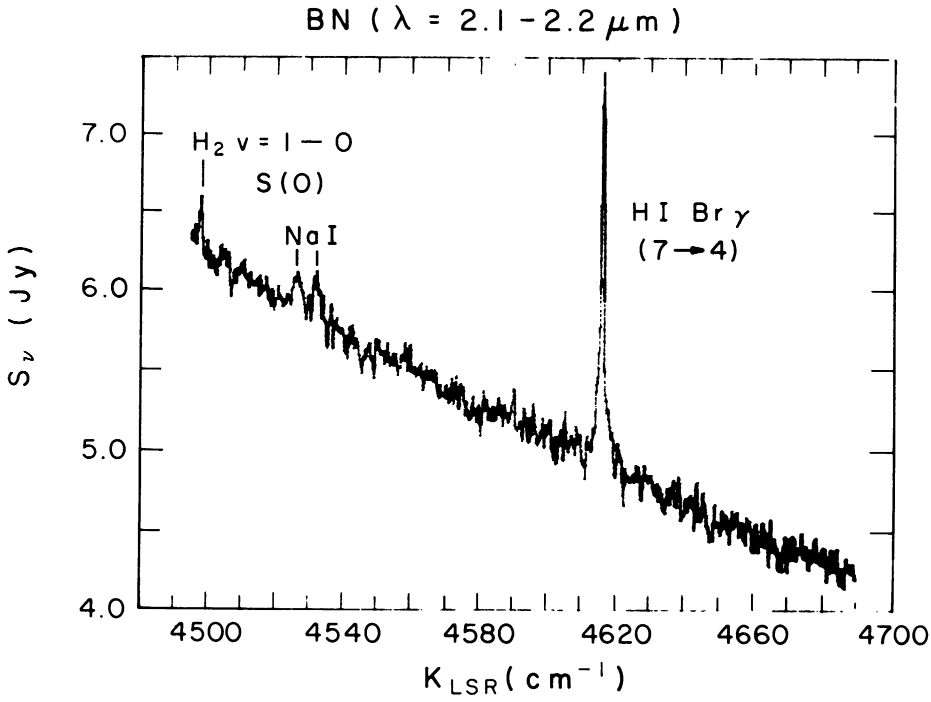

Figure 8. FTS spectrum of BN in the vicinity of the Br γ and Na I lines (Scoville et al. 1980a).

Molecular gas in BN was first observed as CO absorption in the 4.6 μm fundamental band from gas along the line of sight (Hall et al. 1978). At high resolution they found two doppler components: one at V_{LSR} = 9 km s^{-1} arising from the foreground part of OMC-1 and the other at $V_{LSR} \simeq -16$ km s^{-1}. The second system must arise from gas expanding toward us relative to BN; conceivably it is the foreground part of the "plateau" source. [Later data at 4.6 μm has revealed still a third system in emission at $V_{LSR} \simeq +20$ km s^{-1} (Scoville et al. 1980a).]

Emission from high excitation molecular gas much closer to BN is seen at λ = 2.3 μm. Figure 9 shows the CO overtone bandhead features (v = 2→0, 3→1, and 4→2) first detected by Scoville et al. (1979). The highest states from which the emission arises (v = 4, J ≃ 50) are at an equivalent energy E/k ≃ 19000 K and their radiative decay time is only 5 ms. Collisional excitation of the states requires $n_{H+H_2} > 10^{10}$ cm^{-3} and $T_K \gtrsim 3000$ K. From lower limits to the optical depth of the bandheads and the observed fluxes, we find that the emitting region must be only ~10^{13} cm in size. The center velocity and width of the individual lines are $V_{LSR} \simeq 25 \pm 10$ km s^{-1} and

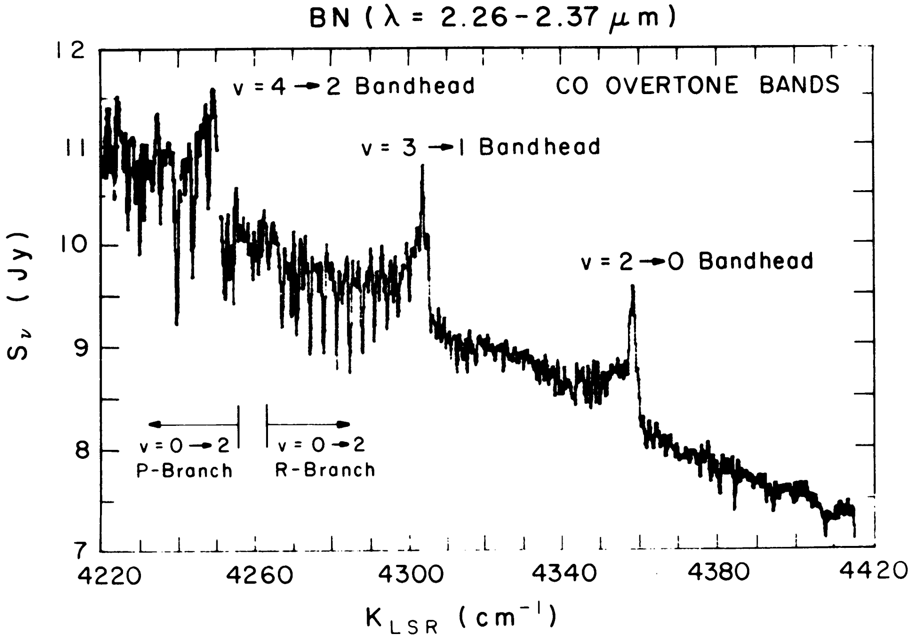

Figure 9. FTS spectrum of BN at λ = 2.3 μm showing CO absorption in the low J lines of the v = 0 → 2 overtone band and emission in the v = 2 → 0, 3 → 1, and 4 → 2 overtone bandheads (J = 50). Data was taken on the KPNO 4-m telescope with a 3ʺ.75 aperture and 0.3 cm^{-1} (20 km s^{-1}) spectral resolution (Scoville et al. 1980a).

$\Delta V \simeq 100$ km s^{-1}. Thus the CO emission probably arises from a high density, circumstellar shell--perhaps just adjacent to the HII region. Since both the HII and CO velocities are V_{LSR} = 20-25 km s^{-1} and these lines probably originate at very small radii from BN, we conclude that BN is probably moving along the line of sight at 10-15 km s^{-1} relative to OMC-1. This could represent the orbital velocity of BN within the young star cluster.

V. CONCLUSIONS

As a result of close coordination between the radio and infrared spectroscopic investigations and theoretical modeling we might now claim at least partial understanding of the physical conditions and energetics in the high velocity gas and associated shock fronts of Orion. Despite the reasonably good specification we now have for the present state of the active gas, the most intriguing issues such as the driving mechanism for the flow and the source of activity are still very open. A radiatively driving wind was originally discounted by Kwan and Scoville (1976) on account of the shape of the millimeter lines which can be fit well by a differential (non-constant velocity) flow and the insufficient momentum in the radiation field of KL ($P_{rad} = L_{KLN}\ \tau_{exp}/c$). On the other hand a single explosive event to drive the flow can be criticized since the short time over which its effects are detectable ($\lesssim 10^4$yrs) would appear to conflict with recent data reporting high velocity mm-lines and H_2 emission in several other cloud core regions. A conceivable solution to the radiative momentum problem could occur if the IR photons in the central source were trapped and reused ~50-100 times (Phillips and Beckman 1980; Solomon, Huguenin and Scoville 1980). Alternatively the objection to an explosive event could be overcome if the energy is released in many minor events--perhaps some phase of stellar instability.

The best candidates for the origin of the activity appear to be BN and IRC-2. Future IR spectroscopy of IRC-2, similar to what has been described for BN, will be extremely helpful in defining its characteristics. Measurement of the physical conditions and gas dynamics so immediate to young stars and protostars is a unique capability of infrared astronomy.

Though most of the discussion here has relied upon the NIR spectroscopy it is clear that much will be gained in the future by a shift toward longer wavelengths to pick up the pure rotational transitions of hydrides and fine structure transitions. In Orion there have already been detections of the S(2) transition of H_2 at 12.3 μm (Beck, Lacy and Geballe 1979) and the CO J = 21 → 20 and J = 22 → 21 transitions at 120 μm (Watson et al. 1980). These longer wavelength lines furnish the missing probe of the excitation regimes between those sampled in the millimeter lines and in the vibrational transitions of the NIR.

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DISCUSSION FOLLOWING PAPERS ON THE ORION MOLECULAR CLOUD

ZUCKERMAN (TO GRASDALEN): It has been suggested by some astronomers studying the VLBI maps of H_2O emission that IRc4 is simply a hot spot in a cloud rather than a bona fide star or protostar like BN or IRc2. Could you comment on that?

GRASDALEN: I deliberately used the word condensation to describe the peaks in the KL nebula, because I do not believe we yet have enough information to determine the fundamental problem of the source of energy.

THOMPSON (TO SCOVILLE): What do you think the total luminosity of BN is and does it power KL?

SCOVILLE: This is basically an infrared photometric problem which I do not feel qualified to answer. You need small aperture far infrared measurements to look for symmetry around BN, when integrated over all wavelengths. There are other sources in the complex and I see no reason to suggest that BN is the only powerful source. The luminosity of BN would have to be a little greater than 10^4 $L_\odot$ if one accounts for the Brα and γ emission with photoionization by a main sequence star (B0-B1).

RIEKE: Unpublished maps at 34 μm show that the Orion region is basically double, centered on BN and IRc4. This implies IRc4 is a luminosity source in its own right.

AITKEN: IRc4 shows a silicate extinction significantly different from that to most heavily obscured sources. The minimum is shifted to shorter wavelengths which can be explained by strong temperature gradients within the beam. This implies that a source of luminosity is present within IRc4.

GENZEL: Using the IRTF, Downes, Becklin, Wynn-Williams, and I have shown that IRc2 has a deeper silicate absorption feature than any of the other peaks, and, consequently, that it is a substantial source of luminosity for the BNKL region. Its position coincides within 1.5 σ with the proper motion expansion center of the H_2O masers in Orion (Genzel, Reid, Moran, and Downes, preprint). IRc2 is already known to coincide with the SiO maser in Orion, and we now propose that large-scale (10^{-4} or 10^{-3} $M_\odot$ yr^{-1}) outflow from IRc2 is the cause of both the maser features and the "plateau" source in Orion.

ROWAN-ROBINSON: IRc2 sounds very like one of those extreme M6 supergiants like VY CMa or NML Cyg. Is this a possibility?

GENZEL: The mass loss rate needed for IRc2 is a factor of 100 higher than that attributed to M supergiants.

GRASDALEN: The error bars for the center of H_2O expansion embrace IRc4, but are outside of IRc2. Why do you reject your error bars and pick IRc2 as the center of expansion, particularly in view of Aitken's result that the silicate extinction is stronger in IRc4 than IRc2?

GENZEL: Firstly the positional discrepancy is only 1.5 σ. Secondly, the H_2O masers have features which are identical to the SiO maser features, and we know that the SiO maser is well identified with IRc2. A 5 km s^{-1} proper motion of IRc2 could also account for the discrepancy. Our data with a 3.8 arcsec beam and narrow band filters show IRc2 to have a much deeper silicate feature than IRc4.

AITKEN: 10-μm spectroscopy with the AAT and a 3.4 arcsec beam indicate deeper absorption in IRc2 than IRc4. However, when you take into account radiative transfer effects in order to fit the shift of minimum wavelength in IRc4 you come up with a much larger silicate optical depth to IRc4 than to IRc2. We find roughly similar luminosities of around 5000 $L_\odot$ for BN, IRc2, and IRc4.

BECKLIN: Since the discovery by Hall et al. that the BN object has many of the properties of a B star, there has been the nagging question as to why it and other infrared sources in regions of star formation are so bright at near infrared wavelengths (λ < 10 μm). The answer could come from the recent work by Genzel and others that at least one such object shows evidence for large mass loss. If this mass loss is a general property of all such objects, then the infrared emission could result from dust formed out of the material lost from the stars. Such processes would be similar to those seen in many novae.