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OBSERVATIONS OF THE MOLECULAR HYDROGEN EMISSION FROM THE ORION NEBULA

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ABSTRACT

Observations of the molecular hydrogen emission at 2 μm in Orion are presented. The data consist of maps at both 13″ and 5″ resolution in the $v = 1 \rightarrow 0$ $S(1)$ emission line; intensity measurements of the $v = 1 \rightarrow 0$ $S(0)$, $S(1)$, $S(2)$, and $Q(3)$ transitions and of the $v = 2 \rightarrow 1$ $S(1)$ transition are used to derive a vibrational temperature of 2000 ± 300 K and the associated column densities at the two peaks. The data presented here improve upon previous data of the Orion H_2 emission and support the suggestion that the hydrogen is excited in a thin sheet.

Subject headings: infrared: sources — interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

Near-infrared emission from molecular hydrogen has been detected in the direction of the infrared cluster in Orion by Gautier *et al.* (1976) and studied by Grasdalen and Joyce (1976). Molecular hydrogen emission has also been detected from NGC 7027 by Treffers *et al.* (1976) and from five planetary nebulae by Beckwith, Persson, and Gatley (1978).

In this paper new observations of the emission from molecular hydrogen in the Orion Nebula are presented. Maps at 13″ and 5″ resolution have been made which clarify the extent and structure of the emission. Accurate line ratio measurements have also been obtained; from these, temperatures and column densities are derived. The new data are used to discuss possible excitation mechanisms for the H_2 emission.

II. OBSERVATIONS

All the observations presented in this paper were made at the Cassegrain foci of the 2.5 m reflector at Mount Wilson and the 5 m Hale reflector at Palomar Mountain. A 0.5 m focal length Ebert-Fastie grating spectrometer was used for all the observations. The instrumentation, wavelength calibration, and standards to which the measurements are referred are described in the Appendix.

a) Mapping in the $v = 1 \rightarrow 0$ $S(1)$ Line

A map with 13″ resolution of the emission from the $v = 1 \rightarrow 0$ $S(1)$ transition of H_2 (2.1218 μm) was made in 1976 October using the 2.5 m reflector with the single-detector system (see Appendix). The result is shown in Figure 1. The entrance aperture was circular, the spectral resolution was 20 Å (4.4 cm^{-1}), and the incoming signal was chopped against an ambient temperature blackbody. The measurements were made by changing the grating angle every 40 s so that the detector saw first the wavelength of the line and then alternately wavelengths offset 36 Å (8 cm^{-1}) to each side of the line wavelength. The total integration time at each point on the sky was 160 s—80 s at the line wavelength and 40 s at each of the two continuum wavelengths.

The line strengths were measured on a grid of points spaced 10″ apart on the sky. The positions of the points were measured relative to that of the Becklin-Neugebauer (BN) source (see Wynn-Williams and

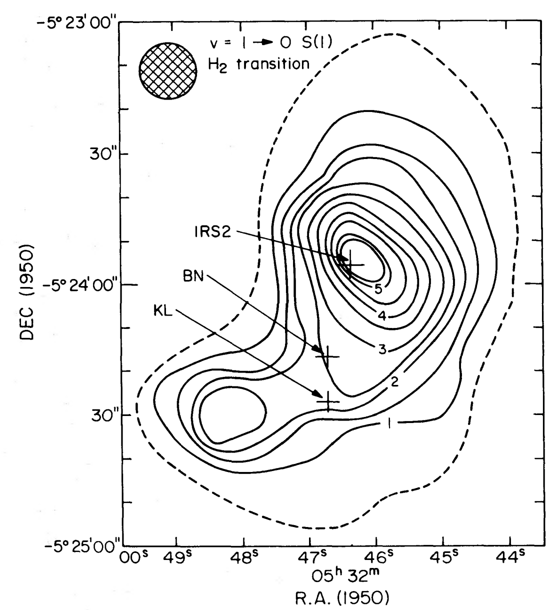

FIG. 1.—The Orion Molecular Cloud molecular hydrogen emission as seen in the $v = 1 \rightarrow 0$ $S(1)$ transition with 13″ spatial resolution. The crosses indicate the positions of the strong infrared continuum sources. Contour intervals are 6.1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}, so that the contour level labeled 1 is 1.22×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}. The limits of the map are given by the dashed contour, for which the signal-to-noise ratio was 5 to 1.

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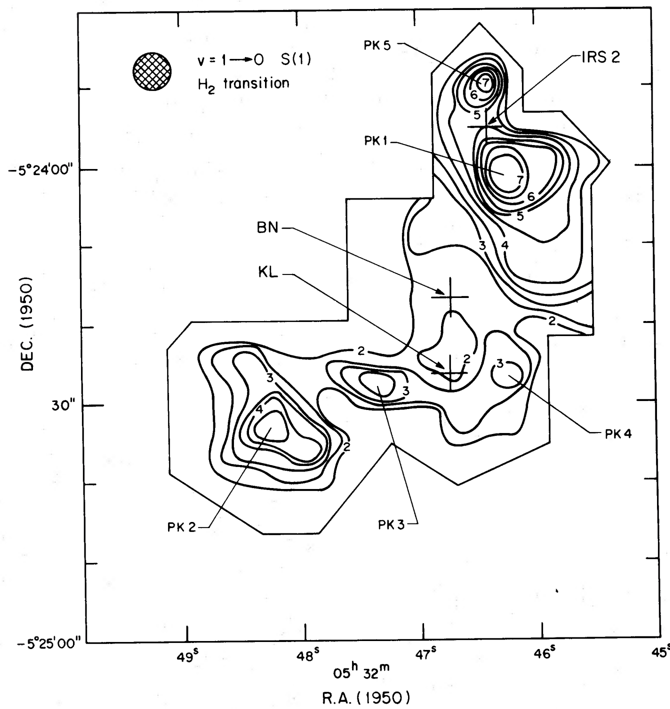

FIG. 2.—The molecular hydrogen emission in Orion as seen in the $v = 1 \rightarrow 0$ $S(1)$ transition with 5″ spatial resolution. Contour intervals are 6.1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}, so that the contour labeled 2 is 2.4×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}. The signal-to-noise ratio was 10 to 1 for this contour level. The extent of the area mapped is enclosed by the straight-line boundary.

Becklin 1974); the uncertainty in the absolute position of the map is $\pm 3''$ ($1\ \sigma$). On the basis of the known transmission of the Earth's atmosphere (Hall 1974), the air-mass correction at 2.12 μm was assumed to be negligible; no observations were made at an air mass greater than 2.

A map of the H_2 emission with 5″ resolution was made in the $v = 1 \rightarrow 0$ $S(1)$ transition in 1976 November, 1976 December, and 1977 February on the 5 m Hale reflector; it is shown in Figure 2. For all the mapping, a circular aperture was used and the signal was chopped against an ambient temperature blackbody. Most of the mapping was done with the single-detector system operated at a wavelength resolution of 17 Å (3.8 cm^{-1}). Approximately one-third of the map in Figure 2 was made with the double-detector system described in the Appendix. One-fourth of this mapping overlapped that done with the single-detector system; the results are in good agreement.

The map was made by measuring a grid of points spaced 2″.5 apart on the sky within the limits given by the boundary drawn in Figure 2. The telescope was pointed by offsetting from the position of the BN source; the resulting positional accuracy is probably better than $\pm 2''$. The total integration time per point varied somewhat in different portions of the map but was typically 160 s.

b) *Measurements of Line Ratios*

Table 1 gives the intensity measurements of molecular hydrogen lines measured in the Orion Nebula; Figure 3 shows four of the lines measured at Peak (Pk) 1. The $v = 1 \rightarrow 0$ $S(0)$, $S(1)$, $S(2)$, and $Q(3)$, and the $v = 2 \rightarrow 1$ $S(1)$ transitions of H_2 were measured on Pk 1 and Pk 2 in 1976 December using the 2.5 m reflector. For all the line intensity measurements, a 10″ aperture was used; for those measured on Pk 1 and Pk 2, sky subtraction was accomplished with a 1′ beam spacing. In the case of Pk 1, measurements of the $v = 1 \rightarrow 0$ $S(0)$ and $S(1)$, and $v = 2 \rightarrow 1$ $S(1)$ transitions were also made by chopping against an ambient temperature blackbody. From these measurements it was determined that no significant error resulted from sky subtraction.

The observations of line intensities were made using the single-detector system at seven wavelengths—four off the line wavelength to establish a continuum baseline, two at the half-power wavelengths of the instrumental profile to check centering, and one midway between the half-power wavelengths to measure the line strength. As this was done for each line, no significant error can accrue from velocity gradients in the source or from wavelength calibration shifts from point to point on the sky.

Air-mass corrections were taken to be zero for all the line transitions. For the $v = 1 \rightarrow 0$ $Q(3)$ line, the extinction depends strongly on the water vapor content of the atmosphere at the time of the measurements as well as on the relative velocity between the Earth and the source. Since neither of these quantities was well determined, the data on the $Q(3)$ line have been assigned a 30% uncertainty.

TABLE 1

INTENSITIES OF H_2 LINES IN THE ORION NEBULA

			Intensities (10^{-4} ergs s^{-1} cm^{-2} sr^{-1})*					
Location	α(1950)	δ(1950)	$v = 1 \rightarrow 0$ $S(0)$ 2.2233‡	$v = 1 \rightarrow 0$ $S(1)$ 2.1218‡	$v = 1 \rightarrow 0$ $S(2)$ 2.0338‡	$v = 1 \rightarrow 0$ $Q(3)$ 2.4237‡	$v = 2 \rightarrow 1$ $S(1)$ 2.2477‡	Column Density† N_{H_2}(10^{18} cm^{-2})
Pk 1.......	$5^h32^m46^s.2$	−5°24′02″	20	75	25	90 ± 30	7.2	22
Pk 2.......	5 32 48.3	−5 24 34	13	50	16	50 ± 20	5.2 ± 0.7	15
Pk 3.......	5 32 47.3	−5 24 26	...	33	...	25 ± 8	...	9.7
Pk 4.......	5 32 46.2	−5 24 27	9.4	32	...	...	...	9.4
Pk 5.......	5 32 46.4	−5 23 50	...	...	...	...	...	...
BN........	5 32 46.7	−5 24 17	7 ± 1.5	30	...	...	...	8.8

* Uncertainties in all intensity measurements are ±10% when not shown.

† Uncertainty in the column densities depends on the validity of the assumption that the populations are Boltzmann distributed, and there is no extinction. If this assumption is valid, the uncertainties are estimated to be ±20%.

‡ Vacuum wavelength in μm.

III. RESULTS

a) Mapping

Figure 1 shows the map of the $v = 1 \rightarrow 0$ $S(1)$ emission close to the near-infrared cluster in Orion. The peak surface brightness agrees well with that of Grasdalen and Joyce (1976), but the detailed shape and location of emission on the present map differs from theirs. In particular, the emission peak southeast of the BN source does not appear on their map. Since the boundary of the mapped area is given by the outermost contour where the surface brightness is about 1/10 that of Pk 2, the emission region is larger than that shown in Figure 1. In addition, the $v = 1 \rightarrow 0$ $S(1)$ line was detected with a line strength of (1.2 ± 0.3) × 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} in a 13″ aperture at a point 20″ west of θ^2 Ori A; this point lies on the ridge of near-infrared emission reported by Becklin *et al.* (1976).

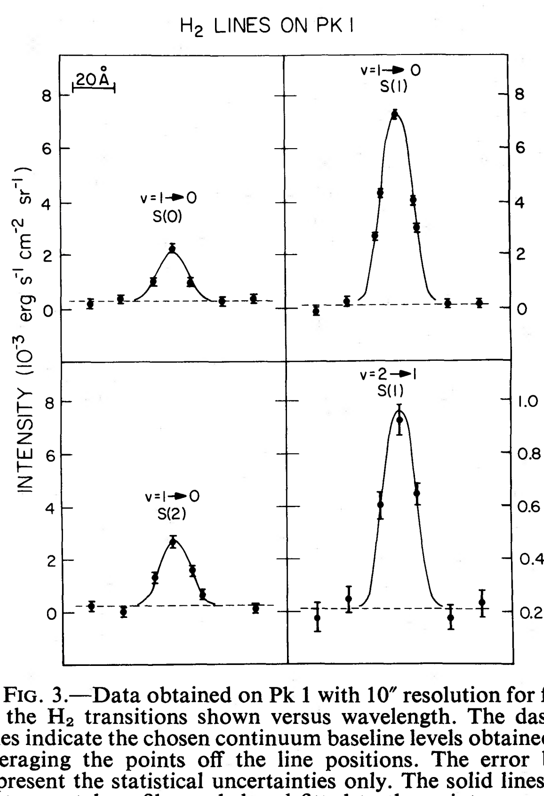

FIG. 3.—Data obtained on Pk 1 with 10″ resolution for four of the H_2 transitions shown versus wavelength. The dashed lines indicate the chosen continuum baseline levels obtained by averaging the points off the line positions. The error bars represent the statistical uncertainties only. The solid lines are instrumental profiles scaled and fitted to the points as an aid to the eye.

The luminosity in the $v = 1 \rightarrow 0$ $S(1)$ line of the region mapped in Figure 1 is 2.5 $L_\odot$ if no correction is made for interstellar extinction. If all the molecules are assumed to be at a temperature of 2000 K (see below), the contribution of other lines to the total molecular hydrogen luminosity can be calculated to be ~50 $L_\odot$ if extinction is neglected.

Both regions of line emission maxima, as determined from Figure 1, are close to infrared continuum sources. The southernmost region coincides with the continuum source found at 10 μm by Gehrz, Hackwell, and Smith (1975), and the northern region is near the unresolved near-infrared source IRS 2 found by Hilgeman (1970) at 2.2 μm and shown on the map of Wynn-Williams and Becklin (1974). There is no enhancement of molecular hydrogen emission in the immediate vicinity of the BN and Kleinmann-Low (KL) sources. The centroid of the H_2 emission lies within ~10″ of the centroid of the high-velocity $J = 3 \rightarrow 2$ CO emission found by Phillips *et al.* (1977), but the distribution of H_2 emission as given in Figure 1 is not reproduced by their data. The general shape and extent of the emission are not correlated with those in the high-spatial-resolution radio continuum map at 5 GHz of Gull and Martin (1975).

With the higher-resolution data of Figure 2 it can be seen that there is substantial structure in the line emission, as evidenced by five emission peaks identified on the map. The positions of these peaks and the measured surface brightness are given in Table 1. It is seen that the ratios of the various H_2 line intensities are the same on Pk 1 and Pk 2 within the uncertainties and furthermore, where measured, are independent of position on the map. This is one of the basic observational results of this work.

TABLE 2

COLUMN DENSITIES $N(v, J)$ OF VIBRATIONALLY EXCITED UPPER LEVELS OF H_2

Upper Level	Transition Used	Pk 1 (cm^{-2})	Pk 2 (cm^{-2})
$v = 1, J = 2$........	$v = 1 \rightarrow 0$ $S(0)$	1.1×10^{17}	7.4×10^{16}
$v = 1, J = 3$........	$v = 1 \rightarrow 0$ $S(1)$	2.8×10^{17}	1.8×10^{17}
$v = 1, J = 4$........	$v = 1 \rightarrow 0$ $S(2)$	7.2×10^{16}	4.6×10^{16}
$v = 2, J = 3$........	$v = 2 \rightarrow 1$ $S(1)$	2.1×10^{16}	1.5×10^{16}

NOTE.—Uncertainties in the column densities of the upper levels depend mainly on the extinction uncertainty. The relative column densities are subject to a smaller uncertainty than are the overall densities.

It is of interest that the northernmost source seen in Figure 1 splits up into two components, neither of which is coincident with the continuum source IRS 2. Comparison of the 5″ resolution map with data on various compact radio, infrared, and optical sources shows that no detailed spatial correlation exists between the H_2 surface brightness and the various sources. In particular, the H_2O maser positions of Genzel and Downes (1977), the infrared source positions given by Wynn-Williams and Becklin (1974) and by Gehrz, Hackwell, and Smith (1975), and the photograph in the [O I] λ6300 line of Münch and Taylor (1974) do not show overall detailed correlations with the surface brightness of H_2 emission. A 1 μm photograph of the region shows no features coincident with any of the peaks of H_2 emission. Maps of other molecular lines have too low a spatial resolution to be compared with the data presented here.

IV. DISCUSSION

In this section the new data are used to make simple estimates of the temperatures of the emission region and the power requirements for the source or sources of energy that excite H_2 molecules.

a) *Physical Parameters*

The column densities $N(v, J)$ of the molecules in the level (v, J) can be derived for the upper levels of the observed transitions independent of the excitation mechanism. For optically thin emission, the intensity of a particular transition is given by

$$I = Ah\nu N(v, J)/4\pi ,$$

where A is the Einstein A-value of the transition and $h\nu$ is the photon energy. Table 2 lists the derived column densities for Pk 1 and Pk 2 using the values of A and $h\nu$ given by Gautier *et al.* (1976) for the $v = 1 \rightarrow 0$ transitions. The assumed A-value for the $v = 2 \rightarrow 1$ $S(1)$ transition is $5.0 \times 10^{-7}\ s^{-1}$ (Turner, Kirby-Docken, and Dalgarno 1977), and the corresponding frequency is computed using the spectroscopic constants given by Fink, Wiggins, and Rank (1965). For an optical depth of unity in these transitions, column densities of $\sim 10^{26}\ cm^{-2}$ are required. The derived column densities are $\sim 10^8$ times smaller; therefore, the emission is optically thin.

If the level populations are in a Boltzmann distribution and the molecules are excited by collisions,

$$\ln [N(v, J)/g_J] = -E/kT + \text{const.} ,$$

where g_J is the statistical weight for the (v, J) level and E is the energy of the level above the ground state. The additive constant is independent of E. Figure 4 shows a plot of log $[N(v, J)/g_J]$ versus E for the $v = 1 \rightarrow 0$ $S(0)$, $S(1)$, and $S(2)$, and the $v = 2 \rightarrow 1$ $S(1)$ transitions on Pk 1 and Pk 2. The data from the $v = 1 \rightarrow 0$ $Q(3)$ transition have not been incorporated in the plot because of the large measurement uncertainty.

Both vibrational and rotational temperatures can be derived from the data; Gautier *et al.* (1976) derived a rotational temperature of 2500 K (+1500 K, −700 K) in the direction of the BN source. The slopes of the lines drawn in Figure 4 yield a vibrational temperature of $\sim 2200 \pm 220$ K. A rotational temperature of 1100 ± 150 K is derived from the $v = 1$ levels alone.

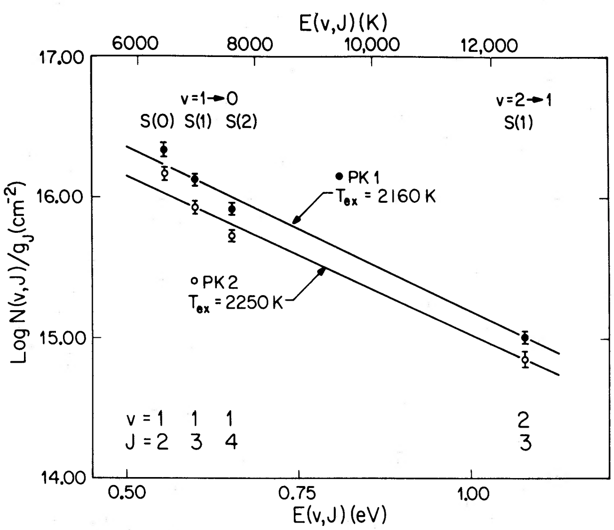

FIG. 4.—The plot of log $N(v, J)/g_J$ versus E used in deriving the excitation temperatures on Pk 1 and Pk 2 (see § IV*a*). The uncertainties in log $N(v, J)/g_J$ are calibration and statistical uncertainties; uncertainties in the A-values and extinction have not been included. The solid lines are drawn through the $v = 1$ and 2, $J = 3$ levels. As discussed in the text, the slopes of these lines are inversely proportional to the vibrational excitation temperature.

The data plotted in Figure 4 display only the calibration and statistical uncertainties; if uncertainties in the A-values are taken into account, the uncertainty in the vibrational temperature becomes ± 300 K.

Only the $J = 3$ level for the two different vibrational levels has been used to derive the vibrational temperature. This temperature must be corrected for reddening as discussed below, since the $v = 2 \rightarrow 1$ $S(1)$ and $v = 1 \rightarrow 0$ $S(1)$ lines are at different wavelengths and since differential extinction will change the observed line ratio. If, instead, the $v = 1 \rightarrow 0$ $S(0)$ line is used with the $v = 2 \rightarrow 1$ $S(1)$ line, the effects of reddening are negligible, since these two lines occur at almost the same wavelength. The derived vibrational temperature is then 2000 K. This method assumes that the rotational and vibrational temperatures are equal and that the ortho to para hydrogen ratio is 3 to 1.

The largest uncertainty in determining the temperature arises from the lack of knowledge of the extinction to the H_2 emission. If the extinction at 2 μm is as large as 3 mag, the corrected rotational temperature is 2000 K at Pk 1. The corrected vibrational temperature for this amount of extinction at Pk 1 is 1960 K. This amount of extinction is reasonable for sources in the Orion Molecular Cloud, as given by Thaddeus *et al.* (1971); Becklin, Neugebauer, and Wynn-Williams (1973); and Grasdalen and Joyce (1976). Because uncertainties in the extinction to the H_2 create substantially larger uncertainties in the rotational temperature than in the vibrational temperature, we will take the vibrational temperature to be representative of the actual temperature of the H_2.

Column densities of all the H_2 molecules can be derived from the line intensity measurements and the calculated temperature. In a Boltzmann distribution, the level populations are given by

$$N(v, J) = N_{H_2} g_J e^{-E/kT} / Q(T) ,$$

where $Q(T)$ is the partition function and N_{H_2} is the total H_2 column density. This formula has been used to compute the values of N_{H_2} listed in Table 1 by assuming the temperature at all the peaks to be 2000 K. The column densities at the peaks are all of order 10^{19} cm^2.

It is of interest to see whether the conditions necessary for the molecules to be in a Boltzmann distribution obtain for the region under consideration. A necessary condition is that the time between collisions be shorter than the radiative lifetime of any level. The collision rate per molecule is given by

$$R_c \approx n_{H_2} \sigma_c v_{th} \approx 5 \times 10^{-14} n_{H_2} \sqrt{T}\, s^{-1} ,$$

where n_{H_2} is the volume density of H_2 molecules (cm^{-3}), σ_c is the H_2–H_2 collision cross section, v_{th} is the molecular thermal velocity, and the temperature T is measured in K. The radiative rates for the relevant levels are $\sim 10^{-6}$ s^{-1}, and σ_c is of the order of 10^{-18} cm^2 for collisions which change the vibrational quantum number. If T is taken to be 2000 K, the relation above indicates that collisions are dominant for $n_{H_2} \gtrsim 10^6$ cm^{-3}. This is consistent with lower limits to the volume density of $\sim 10^5$ cm^{-3} derived from measurements of other molecules in the same direction (Kutner *et al.* 1971; Liszt *et al.* 1974), and thus conditions for the molecules to exist in a Boltzmann distribution can be satisfied. Note that the cross sections for collisions which change the rotational quantum number of the molecules will in general be larger than those which change the vibrational quantum number, and thus a Boltzmann distribution should be established among levels with the same vibrational quantum number at lower densities and temperatures than are necessary to establish this distribution among all the levels. We have used the cross sections necessary for thermalization of the observed vibrational levels.

If the surface brightness of the H_2 is roughly uniform over the resolution element of the observations, then the thickness of the emitting region is less than $\sim 10^{13}$ cm (3×10^{-6} pc) for a column density of $\sim 10^{19}$ cm^{-2} and a volume density greater than $\sim 10^6$ cm^{-3}. This is 10^{-5} times the projected size of the emission on the sky of ~ 0.3 pc. Even if the volume density is only $\sim 10^3$ cm^{-3}, the thickness of the emitting region is very small in comparison with the size of the region. We conclude that the H_2 exists in a thin, hot sheet. This conclusion was also reached by Grasdalen (1976).

b) *Energy Sources*

Shock excitation of the H_2 has been suggested by Gautier *et al.* (1976) and Kwan and Scoville (1976) to explain the H_2 emission. Since then, several detailed calculations have been made which support this possibility (Hollenbach and Shull 1977; London, McCray, and Chu 1977; Kwan 1977). The model calculations give limits to the shock velocity and volume densities of molecular hydrogen in the preshocked material required to produce the observed line intensities. Kwan (1977) derives a lower limit of ~ 10 km s^{-1} for the shock velocity required to produce the observed temperature of 2000 K. From the observed intensity of the $v = 1 \rightarrow 0$ $S(1)$ line, the minimum average H_2 volume density $n_{H_2} \approx 10^5$ cm^{-3} if shock excitation obtains (see, e.g., Kwan 1977). Any correction to the $v = 1 \rightarrow 0$ $S(1)$ line intensity to account for extinction at 2.1 μm will raise n_{H_2} proportionally.

From the values of density and velocity, the minimum pressure necessary to sustain the shock is $\sim 3 \times 10^{-7}$ dynes cm^{-2}. There is no observed source in the region that can drive such a shock continuously by exerting pressure on the molecular cloud (see, e.g., Hollenbach and Shull 1977; or Kwan 1977). In particular, the H II region cannot provide enough pressure—nor can any luminosity source or combination of luminosity sources in the Orion Molecular Cloud. If the H_2 is shock excited, the shock was probably the result of an energetic explosion such as that from a supernova, as suggested by Kwan and Scoville (1976).

An immediate conclusion that can be drawn from the data presented above is that the level populations are not determined by pure radiative excitation and cascades, as calculated by Black and Dalgarno (1976). In particular, Black and Dalgarno predict a ratio of $[v = 1 \rightarrow 0\ S(1)]/[v = 2 \rightarrow 1\ S(1)] = 1.8$ whereas the measured value is 10. Gautier *et al.* (1976) have reached a similar conclusion based on their upper limit for the $v = 2 \rightarrow 1\ S(1)$ line. It may be possible for radiative excitation to provide the energy input to the molecules, but in this case collisions or some other process must redistribute the level populations so as to give the observed line ratios. No detailed mechanism has been proposed which can easily redistribute the level populations, except for that of resonant H_2–H_2 collisions as discussed by Shull (1978). The effectiveness of this mechanism is not known. The most likely candidate to provide the radiation energy would be θ^1 Ori C. This star has just enough luminosity to provide the necessary energy input only if all of the energy can be put into the $v = 1$ level with close to unit efficiency. If the visual extinction were even as high as 3 mag, then θ^1 Ori C could not provide the necessary energy and radiative excitation would be extremely unlikely.

We have not considered the possibility that the H_2 is powered by the release of energy during gravitational collapse of the cloud material. It is very unlikely that a temperature of 2000 K could be generated in a sheet during a collapse of the entire cloud. If, instead, the emission arises from the collapse of many small regions, we might expect each peak in the H_2 emission to be associated with an infrared continuum source or protostar. Our data do not show a detailed correlation to exist between H_2 emission and infrared continuum emission at 2 μm, although the continuum data are not particularly sensitive and sources may be masked by extinction.

V. SUMMARY AND CONCLUSIONS

From the observations presented in this paper, the basic properties of the molecular hydrogen emission in the Orion Nebula are the following:

1. As shown in Figures 1 and 2, the spatial extent of the emission is of the order of $2' \times 2'$, with several localized emission peaks. The highest surface brightness of emission in the $v = 1 \rightarrow 0\ S(1)$ transition is 8.5×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}. The total luminosity of the Orion source is 2.5 $L_\odot$ in this transition alone. The centroid of the emission corresponds approximately to the positions of the BN/KL infrared cluster. The detailed structure of the H_2 emission does not correlate with the position of other types of emission from this region.

2. The excitation temperature, as determined from the ratio of the intensities of the $v = 2 \rightarrow 1\ S(1)$ and $v = 1 \rightarrow 0\ S(1)$ transitions, is 2000 ± 300 K. The same temperature is observed on the two brightest emission peaks shown in Figure 1. None of the line ratios measured at any place in the emission region show evidence for deviations from this temperature.

3. If the H_2 level populations are in a Boltzmann distribution, the average H_2 column density is $\sim 10^{19}$ cm^{-2}.

Based on these results, several conclusions regarding the molecular hydrogen emission can be drawn.

1. The hydrogen probably exists in a sheet less than $\sim 10^{13}$ cm thick.

2. Pure radiative excitation and subsequent fluorescence as discussed by Black and Dalgarno (1976) are not responsible for the emission, since the observed line ratios are substantially different from those predicted by this mechanism.

3. There is not enough energy density either in the H II region or in the observed luminosity sources in the region to provide for shock excitation of the H_2. Thus, if the H_2 is shock heated, the shock must have resulted from a cataclysmic event such as a supernova explosion.

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APPENDIX

I. INSTRUMENTATION

All measurements presented in this paper were made with the Ebert-Fastie spectrometer of 0.5 m focal length described by McCammon, Münch, and Neugebauer (1967). A 600 groove mm^{-1} grating is used at ambient temperature and gives a dispersion of 33 Å mm^{-1} in first order at 2.1 μm. An important modification to the system beyond that described by McCammon *et al.* is that a barium fluoride lens is used to convert the incoming f/16 beam from the telescope to f/5 for the spectrometer. This allows for entrance apertures less than 0.5 mm in diameter to be used in the spectrometer without requiring extremely high spatial resolution on the sky. Thus spectral resolution is preserved, and a large gain in signal for extended sources is achieved. The f/5 beam out of the spectrometer is converted back to f/16 and enters an InSb detector system. Narrow-band ($\Delta\lambda \approx 0.08\ \mu$m) interference filters are used to reduce the background radiation from the spectrometer.

A focal-plane chopper is used to chop the incoming beam between two different parts of the sky for sky subtraction or between the sky and a reference blackbody at the ambient temperature. The chopping mirror reflects light not entering the spectrometer during each half-cycle into a broad-band (2.0–2.4 μm) detection system. This system is used for peaking up on 2 μm continuum sources which serve as positional reference points for the maps.

For the map with 5″ resolution, two separate detector systems were used for different parts of the map. One detector system uses a single detector which senses light from a single portion of the spectrum and whose wavelength resolution is determined by the entrance and exit apertures of the spectrometer. Subsequently, a two-detector system was put into operation. One detector senses light from a single portion of the spectrum as in the initial system, and the other senses light from portions of the spectrum directly adjacent to and at both longer and shorter wavelengths than those of the first detector. In a typical observation, the grating angle is set to center the line wavelength in the "line" channel of the two-detector system and to center the continuum on either side of the line in the continuum channel. The centers of the line and continuum channels are 17 Å apart. Wavelength resolution of the "signal" channel is 20 Å, and resolution in the adjacent wavelengths is approximately 15 Å. The detector outputs are always adjusted so that the response to a strong continuum source is the same for each. The signals from the two detector channels are then subtracted to give a direct measurement of the line strength. In this way, mapping around a strong continuum source such as BN can be accomplished without incurring errors in the line strength due to fluctuations in seeing conditions and to guiding.

The flux was calibrated by observing α Leo and β Aur with 20 Å resolution at 2.1218 μm. The fluxes of these stars as determined from measurements relative to α Lyr were 150 and 120 Jy at 2.1218 μm; the flux of α Lyr at 2.2 μm is taken as 260 Jy, and its spectrum is assumed to be Rayleigh-Jeans. The uncertainty in the overall flux calibration at each wavelength is estimated to be 10% for the $v = 1 \rightarrow 0$ $S(0)$, $S(1)$, and $S(2)$ and the $v = 2 \rightarrow 1$ $S(1)$ transitions, and 30% for the $v = 1 \rightarrow 0$ $Q(3)$ transition.

II. WAVELENGTH CALIBRATION

The spectrometer wavelength scale was calibrated at the telescope by observing the argon lines at 2.0616, 2.0986, 2.1534, and 2.2077 μm from a laboratory argon lamp. Identifications of the H_2 lines were then made using the wavelengths given in Fink, Wiggins, and Rank (1965). For the $v = 2 \rightarrow 1$ $S(1)$ transition, the wavelength was calculated using the empirical constants of Fink, Wiggins, and Rank. The calculated wavelength for this transition is 2.2477 μm (4449.0 cm^{-1}).

The precise grating angle corresponding to the wavelength of the $v = 1 \rightarrow 0$ $S(1)$ transition was determined relative to the four lines of argon by measuring the instrumental response versus grating angle on the line at the position of greatest line brightness in Orion. The line wavelength could then be set by measuring the four argon lines and offsetting the grating angle relative to them. This was done before, during, and after mapping each night; the wavelength calibration was found to be constant to within 2 Å (0.4 cm^{-1}) or 30 km s^{-1} at the source. From the instrumental profile, it is estimated that a wavelength shift of $\sim$2.5 Å or 38 km s^{-1} at the source is required to produce a 10% change in the measured line intensity.

For the measurements of the different H_2 lines, the grating angles were calculated from the spectrometer wavelength calibration and the known grating angle for the $v = 1 \rightarrow 0$ $S(1)$ transition.

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