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A SEARCH FOR EMISSION FROM VIBRATIONALLY EXCITED H_2

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ABSTRACT

We have searched for the 8150 Å emission line of interstellar H_2 in Orion, in NGC 7027, and in the ρ Oph region, with negative results. In order that our results be consistent with the recently reported observations of H_2 emission lines near 2 μm in Orion, the visual extinction must be greater than 10 mag for a 2500 K thermal excitation model, or greater than 6–11 mag for a shock excitation model. Finally, a new ultraviolet excitation model is introduced.

Subject headings: interstellar: molecules — nebulae: general — nebulae: Orion Nebula — nebulae: planetary

I. INTRODUCTION

There is considerable observational evidence that molecular hydrogen in interstellar clouds is in some instances found in excited states which cannot be appreciably populated at mean gas temperatures below 100 K. In the ultraviolet, Spitzer and Cochran (1973) found H_2 rotational excitation temperatures between 315 K and 1110 K in the interstellar absorption spectra of several stars. Even higher excitation temperatures ($\sim$2500 K) have recently been determined from the 2 μm observations of emission lines from the $v = 1 \rightarrow 0$ vibrational band of H_2 (Gautier *et al.* 1976) in Orion and in the planetary nebula NGC 7072 (Treffers *et al.* 1976). The ultraviolet and infrared observations refer to different regions in the sky and may well also represent totally different excitation mechanisms.

The observations reported here were initiated with the objective of providing data with which to test the ultraviolet excitation model proposed by Black and Dalgarno (1976), according to which the vibrational states of H_2 will be highly populated in a nonthermal distribution and will yield emission lines in the 1–0, 2–0, 3–0, and higher bands. For this reason, we searched for 3–0 emission in regions thought to contain appreciable numbers of H_2 molecules which could be excited by a nearby strong ultraviolet source, such as an early-type star. In addition, the region should not be too highly obscured by interstellar extinction. We chose to look for the relatively strong $S(1)$ line (i.e., $J = 3 \rightarrow 1$) in the 3–0 (i.e., $v = 3 \rightarrow 0$) band, at a wavelength of 8150 Å, where low-noise photon-counting techniques can be employed. In the course of this work, we learned of the discovery by Gautier *et al.* of strong emission lines in the 1–0 band of H_2 in Orion; a subsequent mapping of this region by Grasdalen and Joyce (1977) prompted us to concentrate our efforts at the peak of this emission, which is displaced from the discovery location. Gautier *et al.* discussed their observations in terms of direct thermal excitation. Subsequently, these observations have been analyzed in terms of excitation in shock waves by Kwan (1977), Hollenbach and Shull (1977), and London, McCray, and Chu (1977), and in relation to radiative pumping in intense ultraviolet radiation fields by Shull (1978). For the case of Orion, in particular, the excitation mechanism is of great interest in that it may help to complete the current theoretical picture of star formation in this region (Elmegreen and Lada 1977). Our results are unfortunately not sufficiently sensitive to distinguish between these various models, but we have been able to set lower limits on the amount of extinction that is required for several of the theoretical models.

II. OBSERVATIONS

The observations reported here were made at various times between 1974 and 1977, using the PEPSIOS spectrometer located at the coudé focus of the 1.5 m telescope on Mount Hopkins near Tucson, Arizona. The spectrometer, which has been briefly described elsewhere (Hegyi, Traub, and Carleton 1972), basically consists of an isolating 12 Å wide interference filter, followed by three Fabry-Perot etalons with slightly different spacings, the largest of which is about 0.1 cm. The etalons are pressure tuned, using N_2 gas to bring the selected transmission peaks into coincidence, and the spectrometer is scanned by increasing the pressure equally in each chamber. The instrumental full width at half-maximum was about 2.7 ± 0.4 km s^{-1}, as determined from both the theoretically expected value and an experimentally estimated value based on scans of a laboratory neon line. The wavelength origin is determined from the position of the 8136.406 Å neon line. The H_2 3–0 $S(1)$ line position of 8150.67 Å is taken from our earlier observations of this line on Jupiter (Carleton and Traub 1974), and agrees within 0.04 Å with the wavelength predicted from energy levels determined from UV spectroscopy (i.e., 8150.71 Å). The signal detector is a dry-ice–cooled RCA GaAs photomultiplier with an average dark count rate which ranged from about 1.6 to 3.2 counts s^{-1}, depending upon the tube used; statistical fluctuations in this dark counting rate set the ultimate detection threshold. Photoelectron counts are integrated and recorded at intervals of 0.202 km s^{-1}, as determined by the fringe spacing in an auxiliary interferometer which is at the same pressure as one of the etalons.

The product of overall system transmission (including the atmosphere, telescope, and spectrometer) and photomultiplier quantum efficiency was experimentally determined from observations of both Sirius and Vega; the expected flux from these stars was calculated from Breger's (1976) color catalog, giving 1730 and 439 photons cm^{-2} s^{-1} $Å^{-1}$, respectively, at 8150 Å. The overall efficiency ranged from $\tau \times QE = 0.0038$ to 0.0014 counts per photon, the latter occurring when an external coupling lens was utilized in a configuration that turned out to be unexpectedly inefficient. The measured average etalon transmission was about 73%.

Our observing technique is to make repeated scans of a given spectral region and record each scan separately. Subsequent data processing involves examining each scan for glitches, rejecting those few points which differ from the mean by more than 2.5 standard deviations, co-adding, binning into convenient intervals, and removing a very slight slope in the signal caused by a slowing down of the scan rate.

In the following subsections, we present our observed spectral scans in units of photoelectron counts per velocity bin width. If the signal is S(counts per bin), and the corresponding dwell time T(s per bin), we then have the following approximate expression for the intensity:

$$I(\text{ergs cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}) = \left(\frac{S}{T}\right)\cdot\left(\frac{\Delta V(\text{total})}{\Delta V(\text{inst.})}\right)\cdot\left(\frac{h\nu}{A\cdot\Omega\cdot\tau\cdot QE}\right)\cdot \quad (1)$$

The remaining constants are the observed (or estimated) total line width [ΔV(total)], the instrumental width [ΔV(inst.)], photon energy ($h\nu = 2.44 \times 10^{-12}$ ergs per photon), telescope area (A), effective solid angle (Ω), and overall efficiency ($\tau \times QE$). The above expression ignores detailed considerations of line shapes, but is sufficiently accurate for our present purposes.

a) *Orion*

We searched for the 8150 Å line at two positions in Orion: in 1975 February we used a 16″ diameter aperture centered on the KL nebula, which is the same position at which the 1–0 band was subsequently

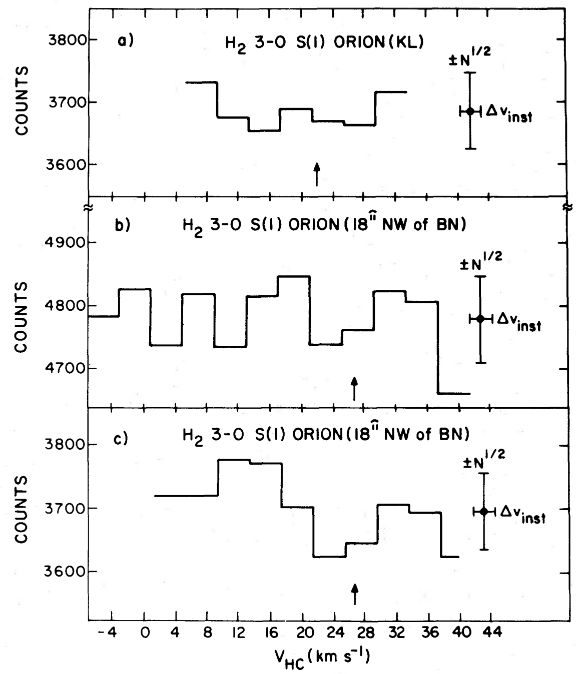

FIG. 1.—(*a*) Spectrum in the neighborhood of the H_2 3–0 $S(1)$ line at 8150.67 Å, toward the KL object in Orion. The expected emission line velocity is marked with an arrow. The total counts per 4.04 km s^{-1} bin are plotted, along with a horizontal bar indicating both the average level and the instrumental width; the vertical bar gives the expected rms fluctuations owing to counting statistics. The dark count level is 3280, or about 3.2 counts s^{-1}. There is no apparent emission line, within the indicated uncertainty. (*b*) Spectrum toward the region of peak H_2 1–0 emission in Orion, NW of the BN object. The dark count level is 4180, or about 1.6 counts s^{-1}. Otherwise the same as in (*a*) above. (*c*) Same as in (*b*) above, but from a later observing run.

detected by Gautier *et al.* (1976); in 1977 January and March we used a 19″ (and 23″) aperture centered about 18″ NW of the BN object, corresponding to the local peak intensity in H_2(1–0, $S1$) as mapped by Grasdalen and Joyce (1977). The results of these searches are shown in Figure 1, where we plot the integrated number of photoelectron counts in bins of 4.04 km s^{-1}. This bin width approximately matches the combined profile due to the instrument and an assumed nebular line width of about 3.0 km s^{-1}. In Figures 1*a* and 1*b* the dark count level is about 3280 and 4180 counts per bin, respectively, corresponding to rates of 3.2 and 1.6 s^{-1}. The remainder of the continuum results from stray light in the observing room, night-sky light, and nebular continuum, in undetermined proportions. Thus the expected rms fluctuation in the continuum should be attributable to statistical ($N^{1/2}$) fluctuations, as shown by the 1 σ uncertainty bars in Figure 1. We note that the actual rms fluctuations in Figure 1 are somewhat less than the expected $N^{1/2}$ value; this is most likely due to the fact that a few large but otherwise genuine fluctuations in the Poisson tail of our original single scans were clipped during the glitch-removing procedure described above.

According to the 1–0 observations of Gautier *et al.* (1976), the expected heliocentric velocity of the H_2 lines is about 22 ± 8 km s^{-1} at KL, and 10 ± 8 km s^{-1} at BN; another estimate can be derived from Balick, Gammon, and Hjellming (1974), where a range from 14 to 26 km s^{-1} is found for high and low excitation lines, respectively. A very recent measurement of the 1–0 $S(1)$ line at the position of maximum brightness (i.e., 18″ NW of BN) gives an LSR velocity of 9.5 ± 3.0 km s^{-1}, or 26.5 km s^{-1} heliocentric (Joyce *et al.* 1977). Inspection of the spectra in Figure 1 fails to reveal any significant feature either at or near the suggested velocities; we therefore find a 1 σ upper limit to the emission of 61 counts at KL, and 69 counts at the position NW of BN. The corresponding limits on the intensities are calculated from equation (1) and shown in Table 1.

A similar search for the 8150 Å H_2 line was carried out by Gull and Harwit (1971), using a 72″ beam and 19 km s^{-1} resolution. Gull and Harwit's relatively large aperture included the entire BN–KL complex, as well as the 1–0 peak emission region NW of BN. If we assume that the 1–0 and 3–0 emission contours are similar, then Gull and Harwit's large aperture upper limit of 1.4×10^{-6} ergs cm^{-2} s^{-1} sr^{-1} implies a flux about 5 times larger from the 1–0 peak region. By comparison, our upper limit for this same area is a factor of about 20 more sensitive than Gull and Harwit's result.

b) *NGC 7027*

In 1975 May we searched for the 8150 Å line in the planetary nebula NGC 7027, using the same 2.7 km s^{-1} resolution as described above. The 18″ spectrometer aperture is more than adequate to encompass the entire visible disk; for the purpose of estimating intensities, we have adopted a diameter of 7″, as determined from inspection of the 10 μm map by Becklin, Neugebauer, and Wynn-Williams (1973) and the Hβ map by Coleman, Reay, and Worswick (1975). The heliocentric radial velocity is given by Perek and Kohoutek (1967) as 13 km s^{-1}, and by Chaisson and Malkan (1976) as 10 km s^{-1}; our scan is approximately centered on these values. The line width is expected to be significantly larger than our instrumental width, assuming that the H_2 emission originates in the same region as the visible spectrum and radio spectrum; averaging the results of Osterbrock's (1974) Hα and Hβ observations with Chaisson and Malkan's H76α observations we expect a line width of 45 ± 5 km s^{-1}. If the H_2 line is as broad as this, we can expect to be able to see most, but not all, of the profile, since our total scan length is only about 40 km s^{-1}.

The observations are shown in Figure 2, averaged over 4.04 km s^{-1} intervals. By looking away from the nebula at the end of each scan, we determined that the background constitutes about 88% of the recorded counts. The remaining 12% of the spectrum appears to be flat, within the uncertainties of the counting statistics.

Several approaches are available to help determine the possible contribution of an 8150 Å emission line to the continuum-like spectrum shown in Figure 2. First, we can compare our measured count rates from Vega and NGC 7027 with independent observations. Using data given by Breger (1976) for Vega, and Danziger and Goad (1973) for the continuum from NGC 7027, we find a ratio 2.1×10^{-4}. Using our measured values of 1970 and 0.24 counts s^{-1} for these same objects, we find a ratio of 1.2×10^{-4}, which indicates that (*a*) our spectrometer is less efficient for extended sources than point sources, or (*b*) the continuum level of NGC 7027 at 8150 Å is actually about 2 times smaller than the value given by Danziger and Goad (1973), or (*c*) the optical nebula is somewhat larger than 18″. In any case, it appears from this that the observed flux can easily be explained by the nebular continuum alone, without any emission line. Second, the ratio of reference to signal count rates was found to be 70 ± 10 on α Lyr and 89 ± 19 on NGC 7027, which again formally indicates no emission line to within about ± 0.5 of the measured level. Third, if we try to fit a 45 km s^{-1} wide Gaussian profile to the data in Figure 2, assuming the line to be approximately centered in our scan, the maximum allowable amplitude is about 0.05 of the nebular continuum. In summary, the maximum allowable line intensity in Figure 2 is about 360 counts per bin width (4.04 km s^{-1}). The corresponding upper limit on the line flux listed in Table 1 is not nearly as stringent as the limits for Orion and ρ Oph, largely because the intrinsic line width is much broader than the instrumental width.

c) *ρ Ophiuchi Region*

We searched for the 8150 Å line in the ρ Oph cloud on three nights in 1975 May (Fig. 3*a*) and on five nights in 1976 June (Fig. 3*b*). Assuming the B2 V star HD 147889 to be a possible source of excitation for H_2, we centered our beam about 40″ SW of this star. Chaisson (1974) gives the C 158α radial velocity as 3 km s^{-1} (LSR), which is about -7 km s^{-1} (heliocentric); Chaisson's data also yield a line width of about 3 km s^{-1} (FWHM), so we expect a recorded line width at 8150 Å of about 4 km s^{-1}. In order to increase our field of view, we utilized an external reimaging lens; unfortunately, part of the expanded beam was lost owing to a somewhat undersized photomultiplier lens, and the overall gain was less than expected. Our 1975 spectrum (Fig. 3*a*) showed an almost statistically significant feature in the two bins near the expected radial velocity; in 1976 (Fig. 3*b*) we again examined this same region, but this time found no evidence of any emission line in the entire range from about -18 to 6 km s^{-1}. The corresponding upper limits on the flux as listed in Table 1 are based on the rms fluctuation in the spectrum for Figure 3*a*, and on the counting statistics in Figure 3*b*. The upper limit on the line intensity in Figure 3*a* is taken to be the rms fluctuation with respect to the continuum, since this was about 1.5 times greater than $N^{1/2}$ here; in Figure 3*b*, the rms and $N^{1/2}$ are nearly identical, in

TABLE 1

H_2(3–0, *S*1) 8150 Å SEARCH

Object	α, δ (1950)	Heliocentric Radial Velocity (km s^{-1})	Effective Source Diameter (arcsec)	Signal per Bin Width, 1 σ Limit *S* (counts)	Observing Time per Bin Width *T* (s)	Total Line Width ΔV_{total} (km s^{-1})	Efficiency $\lvert \tau \times QE \rvert$ (counts/photon)	Line Intensity *I*(ergs cm^{-2} s^{-1} sr^{-1})
Orion (KL)	$5^h32^m46^s.7$, $-5°24'28''$	+5 to +34	16	< 61	1020	4	0.0038	$< 6.9 \times 10^{-7}$
Orion (18″ NW of BN)	$5^h32^m46^s.1$, $-5°24'03''$	−7 to +42; +1 to +39	19; 23	< 69; < 61	2560; 1580	4; 4	0.0032; 0.0022	$< 2.6 \times 10^{-7}$; $< 3.7 \times 10^{-7}$
NGC 7027	$21^h05^m09^s.6$, $42°02'03''$	−12 to +29	7	< 360	3000	45	0.0038	$< 8.1 \times 10^{-6}$
ρ Oph Region (40″ SW of HD 147889)	$16^h22^m21^s$, $-24°20'38''$	−18 to +6	39; 23	< 146; < 137	4730; 8300	4; 4	0.0014; 0.0024	$< 1.6 \times 10^{-7}$; $< 1.5 \times 10^{-7}$

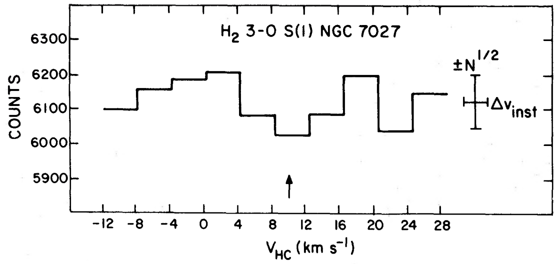

FIG. 2.—Spectrum toward NGC 7027. The dark count level is 5400, or about 1.8 counts s^{-1}. Otherwise as in Fig. 1.

part owing to our use, in this case only, of a 3.0 σ rejection criterion. The derived upper limits on the line intensity are given in Table 1.

III. ANALYSIS

A number of excitation mechanisms have been suggested to account for the observed H_2 transitions in the ultraviolet Lyman bands and also in the infrared (1–0) vibrational band. It is of interest to see whether the present results can be used to help distinguish between the suggested models.

a) *Orion*

For the Orion region, we utilize the results of Gautier *et al.* (1976), who measured rotational line intensities in the 1–0 band and found the data to be best fitted by temperatures on the order of 1400 (+1700, −600) K at KL, and 2500 (+1500, −700) K at BN; we also have the map by Grasdalen and Joyce which places the 1–0 $S(1)$ peak about 18″ NW of BN (coincident with our second observing position in Orion), with an intensity of about 6.3×10^{-3} ergs $cm^{-2}\ s^{-1}\ sr^{-1}$, averaged over our aperture. Assuming then that the H_2 is thermally excited to about 2500 K, we would expect to see a 3–0 intensity about 83 times greater than was in fact observed at the peak position; in fact, the observed upper limit suggests a vibrational temperature less than 1200 K, which is still in rough agreement with the rotational temperatures found by Gautier *et al.* However, it is quite likely that interstellar dust plays a significant role here, and it is equally possible to interpret our results in terms of a 2500 K temperature, but with $\Delta m \gtrsim 4.8$ mag at 8150 Å, or $A_v \gtrsim 10$. (We are using van de Hulst's curve no. 15 where $A_v{:}A_{3-0}{:}A_{2-0}{:}A_{1-0} \approx 3.05{:}1.68{:}0.83{:}0.27$). The only independent estimate of extinction is the intensity ratio of the 1–0 $Q(3)$ to $S(1)$ lines, which we estimate to be 1.15 ± 0.28 from the graphs of Gautier *et al.*; this can be converted to a visible extinction $A_v \approx 9 \pm 15$, which agrees with the above estimate, but is by no means much of an improvement.

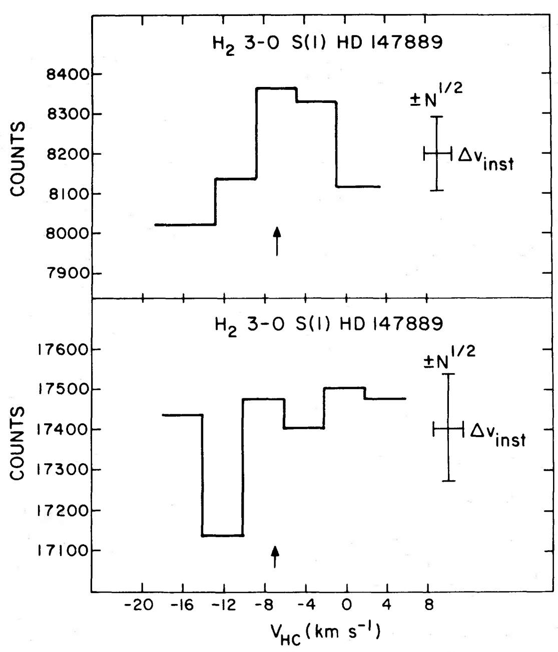

FIG. 3.—(*a*) Spectrum toward a region SW of HD 147889, in the ρ Oph molecular cloud. The dark level is 8200, or about 1.7 counts s^{-1}. Otherwise as in Fig. 1. (*b*) Same as in (*a*) above, for a later observing run. Here the dark level is 14,200, or about 1.7 counts s^{-1}.

Ultraviolet excitation and fluorescence followed by a cascade through rotation-vibration levels has been proposed by Black and Dalgarno (1976) to account for the nonthermal excitation of the higher rotational levels observed in ultraviolet absorption line studies. The models described by Black and Dalgarno (1976) are appropriate for diffuse clouds of moderate density immersed in a radiation field due to typical background starlight. The conditions needed to produce 1–0 lines of the observed strength in Orion must be vastly different. Shull (1978) has discussed the ultraviolet pumping mechanism in the presence of extremely intense radiation. A radiation field roughly 10^6 times the intensity of the normal galactic background would be required to pump the 1–0 lines in Orion, while the limit on the 3–0 line would be consistent with a radiation field only 10^3 times the background. Such a radiation field would exist at the boundary of a molecular cloud located very close (less than 0.5 pc) to an O star like θ^1 Ori C. High densities would also be required to maintain the requisite abundance of H_2 against rapid photodissociation. Another effect, however, would likely dominate the ultraviolet pumping in this kind of model. The intense radiation just longward of 912 Å is also available to heat the gas, so that even in the presence of efficient coolants, a temperature near 2000 K might be maintained over a substantial column density of H_2. In this view, the 1–0 line emission would be thermal but would result from the presence of an intense radiation field; one need only suppose that a part of the dense Orion molecular cloud is within 0.3 pc of θ^1 Ori C. Such a model for the Orion H_2 emission, based upon a "warm" molecular cloud near a hot star, will be described in detail elsewhere (Black 1978).

Shock waves at cloud boundaries can also be invoked to account for elevated temperatures and high densities. Shock waves have been applied to the interpretation of the Orion H_2 observations by Hollenbach and

Shull (1977), by Kwan (1977), and by London, McCray, and Chu (1977). These three studies, while differing in details, all require shock velocities in the range 10 to 20 km s^{-1} and preshock densities in the range 10^5 to 10^6 cm^{-3}. The model of London, McCray, and Chu (1977) suggests an intensity in the 3–0 $S(1)$ line (averaged over our aperture size and in the region of the peak 1–0 emission) in the range 0.4 to 2.6×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}. This is 15–100 times larger than our observed upper limit, implying a minimum foreground visual extinction of 6–11 mag.

As a general comment, models of any kind seem to require rather high densities in the region of line emission: shock models need high densities to account for the 1–0 line intensities and photoexcitation models must have high densities to support adequate molecule abundances in the face of rapid photodissociation. Thermal models require high densities merely for thermalization of the $v = 1$ upper state. In simplest terms, the upper levels of transitions of interest are thermalized when the rate of collisional de-excitation exceeds the total spontaneous transition probability out of the level. Minimum densities required for thermalization of $v = 1$ populations with respect to $v = 0$ populations will be of order $n(H_2) = 3 \times 10^8$ cm^{-3} or $n(H) = 10^6$ cm^{-3} at a temperature of 2000 K. Densities higher by factors of at least 3 are needed to thermalize $v = 3$ due to shorter radiative lifetimes and possibly smaller collisional rates. The absence of detectable 3–0 lines may be partly attributable to insufficient density for thermalization, even in regions where the 1–0 emission is thermal. These constraints arise because vibrational transitions in H_2 take place in only a small fraction of gas kinetic collisions. De-excitation from $v = 1$ in H_2–H_2 collisions has a rate coefficient ranging from 3.5×10^{-17} cm^3 s^{-1} at 300 K to 2×10^{-13} cm^3 s^{-1} at 10,000 K, according to recent theoretical work (Ramaswamy and Rabitz 1977) which supports previous experimental determinations (DeMartini and Ducuing 1966; Hopkins and Chen 1972). Vibrational relaxation upon electron impact (Ehrhardt *et al.* 1968; Crompton, Gibson, and McIntosh 1969) has a larger cross section, but electrons will most likely not be abundant in the region of astrophysical interest. H–H_2 collisions are much more efficient than H_2–H_2 collisions in deactivating H_2 ($v = 1$), owing to a dominant contribution from reactive scattering (Heidner and Kasper 1972); a rate coefficient of 3×10^{-13} cm^3 s^{-1} is indicated at 300 K. Although the relative strengths of rotation-vibration lines might be consistent with minimum densities as low as 10^4 cm^{-3} (in order for rotational minimum levels to be thermalized among themselves within a given vibrational state), the absolute intensities of the lines in Orion indicate either very high densities or a surprisingly large volume of "hot" molecules.

In summary, then, the present observations of Orion are not able to discriminate among the various excitation mechanisms proposed for H_2, unless it becomes possible to determine independently the line-of-sight extinction to the source. On the basis of 3–0 to 1–0 intensity ratios only, our data require the following minimum extinctions: 1200 K thermal (0 mag), 2500 K thermal ($A_v \gtrsim 10$ mag), and shock ($A_v \gtrsim 6$–11 mag).

b) *NGC 7027*

For NGC 7027 Treffers *et al.* (1976) have obtained a 1–0 spectrum similar to that seen in Orion, but about a factor of 2 weaker (Fink 1976), i.e., $I[1–0, S(1)] \approx 1.6 \times 10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1}. The extinction toward this nebula was shown by Osterbrock (1974) to be almost entirely foreground, with $A_v \approx (2.7 \pm 0.4)$ mag, derived from his adopted Hβ extinction. This in turn gives $A_{3-0} \approx 1.5 \pm 0.2$ and $A_{1-0} \approx 0.24 \pm 0.04$, in agreement with the value $A_{1-0} = 0.29$ determined by Treffers *et al.* (1976). With these extinctions and the measured fluxes, we find the unreddened $S(1)$ intensities to be in the ratio $I(3–0)/I(1–0) \leq 0.16$. Unfortunately, this is not stringent enough to be of much use: in a thermal model this leads to $T <$ 21,000 K, which is hotter than the H II region itself (see above references) and certainly hotter than the H_2 component; in Black and Dalgarno's (1976) ultraviolet excitation model $I(3–0)/I(1–0) \approx 0.05$, which certainly satisfies the observations; and finally in the shock model, a ratio of about 0.0006 to 0.004 is expected, if we simply carry over from Orion the results of London, McCray, and Chu (1977).

It would be of great interest to improve the 3–0 sensitivity by a factor of $\sim 10^2$, thereby allowing a clear-cut comparison with theory. This nebula is the only region for which the extinction is well known.

c) *ρ Ophiuchi Region*

Our most stringent upper limits on the 3–0 flux are for the ρ Oph region, although there are not yet any corresponding observations of the 1–0 band. We searched in an area about 40″ SW of the B2 V star HD 147889, with the expectation that the ultraviolet excitation mechanism might be operating there. The star itself is expected to be at a distance of about 200 pc with $A_v \approx 3.3$, as estimated from its color ($B - V = 0.85$) and the theoretical colors given by Morton and Adams (1968). This location does not coincide with any of the known infrared stars, dust emission peaks, or radio molecular line peaks, since we expected that all the 3–0 line emission from these regions would be heavily obscured by dust. We do expect, however, that HD 147889 is embedded in the ρ Oph cloud, so it should be a good place to search for evidence of ultraviolet excitation in particular.

Our flux measurements suggest a de-reddened intensity $I(3–0) < 8.0 \times 10^{-7}$ ergs cm^{-2} s^{-1} sr^{-1}, which can be compared with Black and Dalgarno's predicted intensity of 0.4×10^{-7}; clearly, if the model is a fair representation of the region near HD 147889, we have not achieved sufficient sensitivity to detect an ultraviolet excited line. On the other hand, we are able to rule out a shock wave near HD 147889 similar to that postulated for Orion by London, McCray, and Chu (1977), since the de-reddened 3–0 upper limit is a factor of about 5–32 times smaller than would be expected; however, by reducing the preshock H_2 density from its Orion range (10^5–10^6 cm^{-3}) to the appropriate ρ Oph cloud range (10^3–10^4 cm^{-3}; see Fazio *et al.* 1976), the theoretical 3–0 intensity will also drop by a factor of $\sim 10^2$, putting it below our detection threshold. In summary, our observations are not sufficiently sensitive to reject either an ultraviolet or a low-density shock wave excitation model for the region near HD 147889.

REFERENCES

Balick, B., Gammon, R. H., and Hjellming, R. M. 1974, *Pub. A.S.P.*, **86**, 616.

Becklin, E. E., Neugebauer, G., and Wynn-Williams, C. G. 1973, *Ap. Letters*, **15**, 87.

Black, J. H. 1978, in preparation.

Black, J. H., and Dalgarno, A. 1976, *Ap. J.*, **203**, 132.

Breger, M. 1976, *Ap. J. Suppl.*, **32**, 7.

Carleton, N. P., and Traub, W. A. 1974, in *IAU Symposium No. 65, Exploration of the Planetary System*, ed. A. Woszczyk and C. Iwaniszewska (Dordrecht: Reidel), p. 345.

Chaisson, E. J. 1974, *Ap. J.* (*Letters*), **197**, L65.

Chaisson, E. J., and Malkan, M. A. 1976, *Ap. J.*, **210**, 108.

Coleman, C. I., Reay, N. K., and Worswick, S. P. 1975, *M.N.R.A.S.*, **171**, 415.

Crompton, R. W., Gibson, D. K., and McIntosh, A. I. 1969, *Australian J. Phys.*, **22**, 715.

Danziger, I. J., and Goad, L. E. 1973, *Mém. Soc. Roy. Sci. Liège*, Ser. 6, **5**, p. 153.

DeMartini, F., and Ducuing, J. 1966, *Phys. Rev. Letters*, **17**, 117.

Ehrhardt, H., Langhans, L., Linder, F., and Taylor, H. S. 1968, *Phys. Rev.*, **173**, 222.

Elmegreen, B. G., and Lada, C. J. 1977, *Ap. J.*, **214**, 725.

Fazio, G. G., Wright, E. L., Zeilik, M., and Low, F. J. 1976, *Ap. J.* (*Letters*), **206**, L165.

Fink, U. 1976, private communication.

Gautier, T. N., III, Fink, U., Treffers, R. R., and Larson, H. P. 1976, *Ap. J.* (*Letters*), **207**, L129.

Grasdalen, G. L., and Joyce, R. R. 1977, private communication.

Gull, T. R., and Harwit, M. O. 1971, *Ap. J.*, **168**, 15.

Hegyi, D. J., Traub, W. A., and Carleton, N. P. 1972, *Phys. Rev. Letters*, **28**, 1541.

Heidner, R. F., and Kasper, J. V. V. 1972, *Chem. Phys. Letters*, **15**, 179.

Hollenbach, D. J., and Shull, J. M. 1977, *Ap. J.*, **216**, 419.

Hopkins, B. M., and Chen, H.-L. 1972, *J. Chem. Phys.*, **57**, 3161.

Joyce, R. R., Gazari, D. Y., Scoville, N. Z., and Furenlid, I. 1977, preprint.

Kwan, J. 1977, *Ap. J.*, **216**, 713.

London, R., McCray, R., and Chu, S.-I. 1977, *Ap. J.*, **217**, 442.

Morton, D. C., and Adams, T. F. 1968, *Ap. J.*, **151**, 611.

Osterbrock, D. E. 1974, *Pub. A.S.P.*, **86**, 609.

Perek, L., and Kohoutek, L. 1967, *Catalogue of Galactic Planetary Nebulae* (Prague: Acad. Pub. House).

Ramaswamy, R., and Rabitz, H. 1977, *J. Chem. Phys.*, **66**, 152.

Shull, J. M. 1978, *Ap. J.*, **219**, 877.

Spitzer, L., and Cochran, W. D. 1973, *Ap. J.* (*Letters*), **186**, L23.

Treffers, R. R., Fink, U., Larson, H. P., and Gautier, T. N., III. 1976, *Ap. J.*, **209**, 793.

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