HIGHLY EXCITED MOLECULAR HYDROGEN IN ORION

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INTRODUCTION

Observations of H_2 lines in the IR have been mostly restricted to those with upper levels of low energy, which can be excited either collisionally in shocks or radiatively by UV starlight. In order to discriminate between the two excitation mechanisms we have measured in 1 μm range lines of the v=2-0 band arising from high rotational levels J$\leq$13. Their intensities, together with those of the IR lines, allow an estimate of the line of sight effective extinction and a determination of the rotational temperature measuring their joint degree of excitation. The latter parameter provides information about the energy state of the molecules at their formation and ejection from grain surfaces and thus constrains the hypothetical models for H_2 molecule formation.

M 42

With a Fabry-Perot interferometer using an instrumental resolution of 11 km s^{-1} we scanned the lines (2,0)S(10)λ10516, S(11)λ10523, S(7)λ10639 and S(5)λ10848 at various positions in M42. Towards the BN-object the S(5) and S(7) lines show distinct blue wings similar to that observed in the infrared (1,0)S(1) line, explained by a shock of ~20 km s^{-1} that excites the H_2 gas and leads to an expansion of the BN gas bubble. The relative line intensities of the blue wings determine the foreground extinction to be A_V ~4.5 (Münch et al., 1984).

In the S(10) and S(11) lines the wings are not seen, since the contribution from shock excitation is much too small to be detectable at these high energy transitions. The observed lines, therefore, must arise from regions excited by resonance absorption of UV starlight and subsequent radiative cascade (Hippelein and Münch, 1989).

The intensity distribution in M42 for the highest excited line S(11), based on 33 line scans through diaphragms between 40" and 80" over an area of ~8 arcmin, appears rather flat with a maximum at the Trapezium and nearly centrisymmetric to it. The intensity map shows no enhancement at the cluster of IR-sources and does not reflect any of the dominant structures of the HII region, except the dark bay in the East produced by foreground extinction.

The radial velocities over the whole nebula have an rms deviation of only $\pm$2 km s^{-1} around the mean, without any systematic trend with position in the nebula. After coaddition of the single scans we derived a mean S(11) profile which can be fitted by a Gaussian with a dispersion of σ=7.1 km s^{-1}. This leads, after instrumental profile deconvolution to a velocity dispersion along the line of sight of σ_V=4.7 km s^{-1}, somewhat larger than the widths of other molecular lines emitted from OMC.

Towards the Orion Bright Bar where Hayashi et al. (1985) have measured for the probably partly shock excited (2,1)S(1) line an intensity of

$I(1) = 40\ 10^{-6}$ erg s^{-1} cm^{-2} sr^{-1}, we derived intensities for the high J transitions in the v=2-0 band of

I(5) = 13.5 10^{-6},

I(7) = 8 10^{-6},

I(10) = 4 10^{-6} and

I(11) = 8 10^{-6} in the same units. From these numbers, under assumption of a foreground axtinction of A_V =3.2 mag, we can directly determine the column densities N(J') for the upper transition levels.

In Fig. 1a the excitation parameters ln[N(J')/(2J'+1)g] for the various J' using an para/ortho ratio of 1/2.2 (corresponding to an H_2 formation on grains with a temperature of 50 K) are plotted versus their relative energy in excitation temperature units. From the slope of the curves, we find for the levels lower than J'=7 a rotational temperature of ~2200 K, whereas for J'>7 the temperature is as high as ~11000 K.

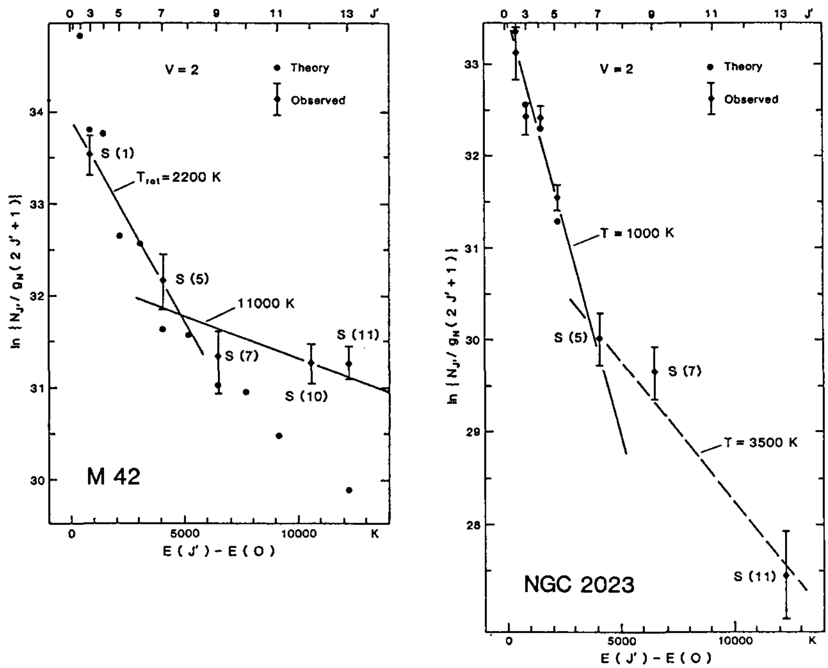

Fig 1a and b. Fit of a Boltzmann distribution to the populations of the various rotational levels in the (2,0) band for lines measured in M 42 (left) and in NGC 2023 (right).

COMPARISON WITH THEORY

From extensive theoretical model calculations done by Black and van Dishoeck (1987) it became obvious, that a significant population of the high J levels can not be realized by fluorescent excitation alone, but only in combination with the process of H_2 formation on grains. Three different formation processes were included in these models: In the first one, 1/3 of the 4.5 eV binding energy is distributed among the (v,J) states according to a Boltzmann law (Black and Dalgarno, 1976); in the two others, the nascent H_2 molecules escape from the grains at high v leves but J<2. It was found, that the total line emission is rather sensitive to paramaters such as the intensity of the radiation field of the exciting source, the gas density and the properties of the grains, whilst the relative line intensities change only slightly with these parameters. The intensities for the high rotational transitions, however, vary by orders of magnitude from one formation model to the other.

In order to compare the predicted and observed populations of the various rotational levels in v=2, we have entered in Fig. 1 the excitation parameters corresponding to the line intensities as determined by Black and v. Dishoeck for their model Nr. 14, normalized to the total line flux of model Nr. 69, which they suggest to be as representative for the Orion Bright Bar we are considering. The theoretical curve matches quite well the population of the levels up to J=7, for the higher rotational states, however, it is too low by a factor up to ~4. As the model was already calculated for the H_2 formation model providing the highest populations for the high J levels the other two formation models can be ruled out completely.

A possible explanation for the discrepancy at high J' could be the increasing importance of collisions at densities in the order of 10^5 cm^{-3} reached in M42, interchanging the energy between vibrational and rotational modes. Elastic collisions may also induce a dipole in the highly excited molecules, increasing their transition probabilities and thus simulating a higher excitation temperature. Finally, the formation model used may be unrealistic. Hunter and Watson (1978) for example proposed a formation model, where the molecules escape from the grains in a mean rotational state of J~10.

NGC 2023

We observed high rotational transitions also in M17, NGC 2023, NGC 7023 and NGC 7027, where infrared line emission has been reported. Here, we will discuss only the results for the reflection nebula NGC 2023, where we recently succeeded to observe S(11) at a very low count rate.

In Fig. 1b the excitation parameters determined for the various J' levels using a ratio 1/2 for the g values and corrected for a foreground extinction of A_V =1.6, are entered against the excitation energies for NGC 2023. The data for J'<6 are taken from Hasegawa et al. (1987) who have measured the intensities for a number of infrared H_2 lines in the brightest region 80" south from the central star. The dots stand for the predictions of the model H of Black and van Dishoeck (1987), for fluorescent excitation deriving from the star HD 37903. The predicted rotational temperature (1000 K), considerably lower than that in M 42, fits well the intensities of lines with $J\leq7$. For lines with $J\geq7$ a rotational temperature near 3500 K is indicated, again considerably lower than that in Orion. Model calculations for such high level lines are unfortunately not available. It is thus not possible to find out whether the discrapancy between theory and observations for the high level lines, found in M 42, is also present in NGC 2023.

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Discussion:

PECKER: How well does one know the transition probabilities and the collisional cross sections? And are not the higher levels likely to be "safer" than the low levels used in the theoretical interpretation you mention?

DALGARNO (to Pecker): I computed these quantities, they are good, and as good for low levels as they are for high levels.

HASEGAWA (Comment): As can be seen in the classic case of the Orion Bright Bar, the excitation of H_2 emission (e.g. vibrational temperature) changes over the nebula (Hayashi et al. 1985, MNRAS, 215, 31P). This can explain the bimodal excitation apparent in your population diagram.

DALGARNO: It may be possible to explain the high J population by fluorescence pumping into high V, low J levels followed by collisional transfer into low V high, J levels. Collisions of this kind in which the energy transfer is small should be rapid.