DUST AND GAS EMISSION ACROSS THE BRIGHT SIDE OF THE ρ OPHIUCHI MAIN CLOUD

E. Habart[1], F. Boulanger[1], L. Verstraete[1], G. Pineau des Forets[2], E. Falgarone[3], and A. Abergel[1]

[1]Institut d'Astrophysique spatiale, Orsay, France
[2]Observatoire de Meudon, Meudon, France
[3]Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France

Abstract

We present imaging and spectroscopic observations of dust and gas emission, obtained with ISO, from the western edge of the ρ Ophiuchi molecular cloud illuminated by the B2 star HD147889 ($\chi \sim 400$). This photo-dissociation region (PDR) is one of the nearest PDRs from the Sun, has a low density ($n_H \leq 10^4$ cm^{-3}) and is viewed edge-on. It is therefore an ideal target to test our understanding of the physics of the H_2 photo-dissociation regions. The emission from dust heated by the external UV radiation, from collisionally excited and fluorescent H_2 are resolved and observed to coincide spatially. The spectroscopic data, obtained with ISO-SWS, allows to estimate the gas temperature to 350 $\pm$30 K in the H_2 emitting layer. The ratio of ortho-to-para H_2 ratio is about 1 significantly smaller than the equilibrium ratio of 3 expected in gas at that temperature. To interpret the excitation of H_2 we use a stationary physical model where the density profile is constrained by the dust emission data and where the gas chemical and thermal balances are solved at each position. A high H_2 formation rate, 3 10^{-16} cm^3 s^{-1} at 350 K, seems to be required to account for the observed emission.

Key words: ISM: clouds - ISM: dust, extinction - atomic processes - molecular processes - Missions: FIRST

1. Introduction

The edges of interstellar molecular clouds are excited and photodissociated by stellar radiation. The transition zone between the dense, cold molecular gas and the tenuous, warm, ionized gas closer to the star is called photodissociation region.

ISO observations of the dust emission and H_2 rotational lines are bringing a new perspective on the structure and physical conditions in PDRs. ISO enables us to detect pure rotational transition lines of H_2 that are not easily observable from the ground, which probes the temperature and density structure of the gas. ISO observations toward the PDRs in, e.g., S140, NGC 7023, or NGC 7023, provided evidence for gas temperatures in the 500-1000 K range in a portion of the PDR where H_2 fraction is appreciable (Bertoldi et al. 2000). These temperatures were higher than expected from current models of the heating and cooling processes in PDRs, and therefore require reconsideration of the physics of the gas and dust in PDRs. On the other hand, ISO camera provides mid-IR images of the dust emission at high angular resolution (3-6 arcsec) of illuminated edges of nearby molecular clouds, which give strong contraints on the penetration of UV radiations through these clouds and on their small scale density structure.

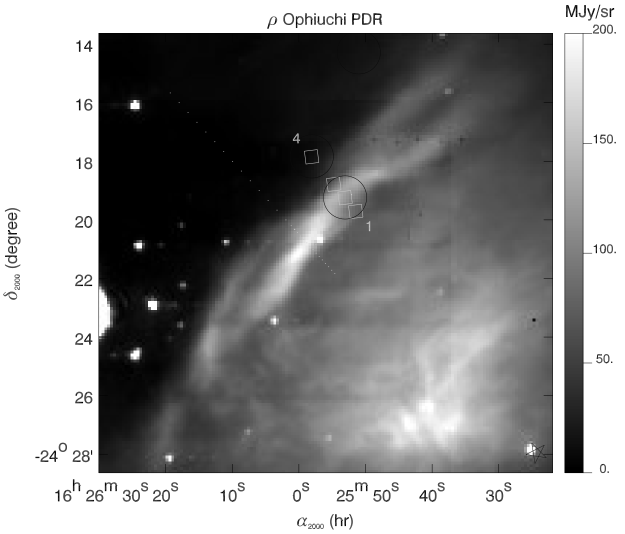

Figure 1. ISOCAM map, with the LW2 filter (5-8.5 μm), of the bright filament along the western edge of the ρ Ophiuchi main cloud. The filament is immersed in the radiation field of the star HD147889 (see the star sign). The four SWS positions (squares) and the LWS position (big circle) are marked. The symbol sizes represent the field of view of each of these observations. The infrared emission peak observed between the star and the filament might result from an face-on PDR.

In this paper, we present imaging and spectroscopic observations of dust and gas emission across a fainter PDR on the western edge of the ρ Ophiuchi molecular cloud heated by the star HD147889. This is a nearby PDR ($d = 135 \pm 15$ pc from the star parallax) with an edge-on geometry where the observations allow to spatially resolve the layer of UV light penetration and of H_2 photo-dissociation. A detailed comparison between ISO

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

observations of dust and gas with theoretical model calculations allows us to discuss important issues such as: penetration of ultraviolet light, H_2 formation rate or non-stationary effects. Observations presented in Section 2 are used in Section 3, in relation to a physical model of PDRs, to discuss the formation of H_2 in warm gas.

2. The ρ Ophiuchi photo-dissociation region

In the mid-IR image made with the ISO camera (Abergel et al. 1996 and see Fig. 1), the western edge of the nearby star forming cloud ρ Ophiuchi is delineated by a long filament located at the edge of the dense molecular as traced by its $^{13}CO(1-0)$ emission (Loren 1989). Spectral observations carried out with the Circular Variable Filter (CVF) of the ISO camera show that the mid infrared emission from the cloud is dominated by the dust features considered to be characteristic of aromatic hydrocarbons (Boulanger et al. 1998). The interstellar particles at the origin of this emission are hereafter referred as PAHs. This is a generic term which encompasses large molecules and small dust grains with up to a few 1000 atoms.

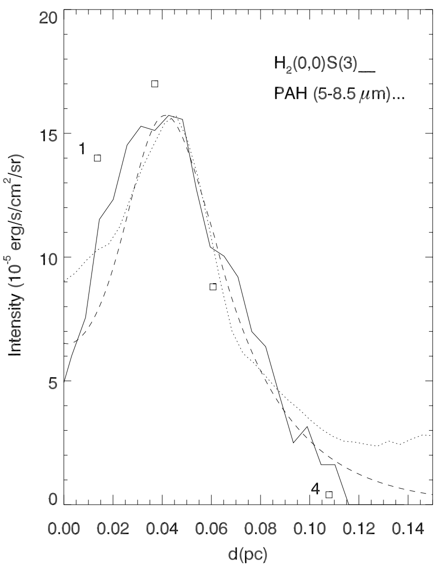

Figure 2. Brightness cut of the v=0-0 S(3) H_2 line (solid line) compare with PAH emission in a 5-8.5 μm filter (dotted line). The cut goes through the SWS pointings: squares represent the intensity of the v=0-0 S(3) H_2 line measured by SWS. The dashed line shows the PAH emission as predicted (see text). The star HD147889 lies at the left end of the cut.

The CVF observations also provided a map of the emission in the v=0-0 S(3) line of H_2 at 9.66μm. A profile of the PAH emission across the filament is presented and compared with the S(3) line emission in Fig. 2. We have obtained from the ground an image of the near-IR 1-0 S(1) line of H_2 over a small section of the filament. The 1-0 S(1) H_2 emission (ESO Observations, not displayed here) show a surprisingly smooth and well resolved filament coinciding spatially with the dust emission.

Assuming a constant abundance of PAHs across the interface, the mid-IR emission traces the cloud skin ($\tau_{UV} \sim 1$) over which UV light from the exciting star HD 147889 is absorbed by dust. The filament marks the edge of an extended halo of bright mid-IR emission seen all around HD 147889 in the direction of the dense ρ Ophiuchi molecular cloud. We believe that the stellar radiation emitted towards the dense cloud is absorbed within the filament which thus represents the illuminated surface of the cloud seen edge-on. For an edge-on geometry, the exponential decrease of the PAH emission on the inner side of the filament can be explained by the attenuation of the radiation field. Assuming an homogeneous medium and a dust mean UV extinction per H of $1.5\,10^{-21}\,\mathrm{cm}^2\,\mathrm{H}^{-1}$, we get a density $n_H = 8\,10^3\,\mathrm{cm}^{-3}$ at distances > 0.05 pc (Fig. 2).

3. H_2 infrared line emission

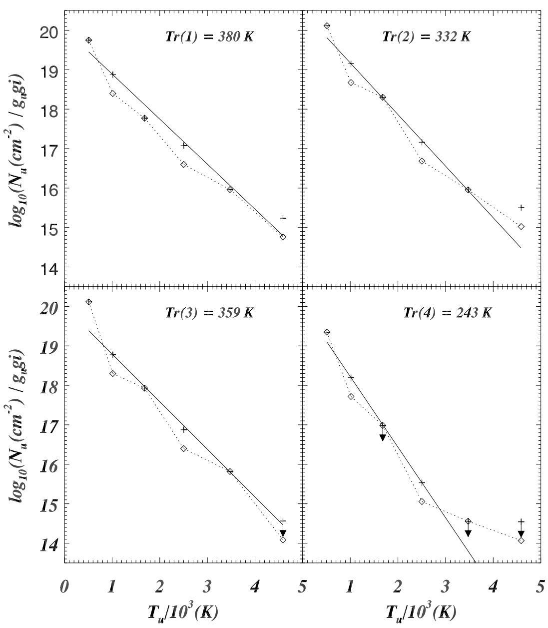

Figure 3. The excitation diagrams of H_2 at each SWS position: N_u is the column density of the transition upper level, g_u is the degeneracy of the upper level, g_I the nuclear spin degeneracy and T_u is the upper level energy in Kelvin. The crosses indicate the values for R_{op}=1, while the diamond show the case of R_{op}=3. The arrows show upper limits. The rotational temperature have been estimated with R_{op}=1.

We have observed a set of H_2 emission lines (0-0 S(0) through to S(5)) with the ISO Short Wavelength Spectrometer (SWS) at positions marked on Figure 1. The H_2 excitation diagram toward the filament is shown in Figure

3. The H_2 rotational level populations provide a thermal probe, showing the presence of a gas with a temperature $T_{gas} = 350 \pm 50\ K$ in which the ratio of ortho-to-para H_2 is only ~1 significantly smaller than the equilibrium ratio of 3 expected in gas at that temperature.

A physical model is necessary to interpret the H_2 excitation which results both from collisions and fluorescence. The model calculations presented in Figs. 4 and 5 are based on an updated version of the stationary model of Le Bourlot et al. (1993). In this model a PDR is represented by a semi-infinite plane-parallel slab with an isotropic radiation field incident on the interface. The inputs parameters are (i) χ, the scaling factor for the radiation field, and (ii) the density profile. With these inputs the model solves the chemical and thermal balance starting from the slab edge. We use recent gas phase elemental abundances measured in the diffuse interstellar medium: He/H = 0.1, C/H = 1.4 10^{-4} (Cardelli et al. 1996), and O/H = 3.19 10^{-4} (Meyer et al. 1998). For the photoelectric effect on small dust grains, we adopt the formalism of (Bakes et al. 1994) with a dust-to-gas mass ratio of the small grain populations (PAHs and VSGs) equal to 8.6 10^{-4}.

In the model calculations, the density profile has been chosen so as to fit the PAH emission profile. The far-UV radiation field intensity, G=400 in units of the mean Solar Neighborhhod radiation (1.6×10^{-3} erg cm^{-2} s^{-1}), has been estimated from the spectral type of HD 147889 and the projected distance between the star and the interface. We show the model outputs in Fig. 4. For these physical parameters, the gas heating is mainly provided by the photoelectric effect on small dust particles and the temperature profile across the interface is little dependent on the H_2 formation rate.

Our Model and the data are compared in the Fig. 5, which corresponds to the peak of the H_2 emission. The model results show that within the emission layer, the excitation of the first few H_2 rotational lines is dominated by collisions and can be used to determine the gas kinetic temperature. Outside this region the contribution of UV pumping followed by fluorescent cascade becomes important even for the lowest energy levels. Qualitatively, the contribution of collisional excitation relative to UV pumping decreases inwards because the gas becomes too cold and outwards because the gas density drops. For the J=6 and 7 levels the density is below the critical density and UV pumping happens to compensate the drop in collisional excitation. The model results presented in Fig. 5, in which we use an ortho to para ratio of 1, show the effect of the H_2 formation rate on the gas temperature over the line emitting region. A high formation rate, $3\,10^{-16}$ cm^{3}s^{-1} at 330 K , appears necessary to account for the H_2 temperature of the emitting gas. For the lower formation rate considered in the Fig. 5, the warm gas is fully photo-dissociated, the H I/H_2 transition is moved inwards where the gas is colder due to the radiation attenuation.

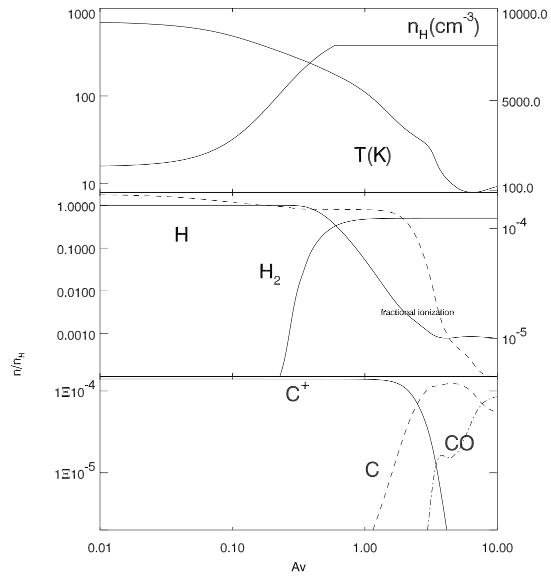

Figure 4. Variation of the gas temperature, gas density and the fractional ionization $x = n_e/n_H$ for PDR model with $\chi = 400$ and with the density profile constrained by the dust emission. We also shown the H/H_2 and $C^+/C^0/CO$ transitions for the same model.

The high H_2 formation rate proposed here is incompatible with H_2 formation from physisorbed H atoms on grain surfaces which is effective only at low temperatures (Pirronello 2000). It suggests that H_2 formation, at least in PDRs, comes from chemically attached H atoms. One possibility which still needs to be experimentally and/or theoretically validated is the reaction of free H atoms with H atoms attached on the periphery/surface of PAHs.

The ortho to para ratio suggested by the excitation diagram is much lower than the equilibrium value computed in the model (~ 3 at 330 K). This discrepancy may be a signature of advection of molecular hydrogen from colder layers of gas. For the physical conditions in the H_2 emitting layer, the dominant conversion process between ortho and para H_2 is the proton exchange with H atoms with a time scale $1.9\,10^4$yr at 330 K (Schofield 1967). Note that this is also about the life time of the H_2 molecule before photo-dissociation within the approximations of the stationary model. Based on the 0.02 pc thickness of the H_2 emitting layer in the model, we find that the advection speed has to be of the order of 1 km s^{-1} or larger for the ortho to para ratio to deviate from the local equilibrium value. This is a reasonable value which could be accounted for by turbulent motions and/or a progression of the dissociation front into the cloud. It is presently not easy for us to quantify the effect of this interpretation of the ortho to para ratio on the estimate of the H_2 formation rate based on the statinary model.

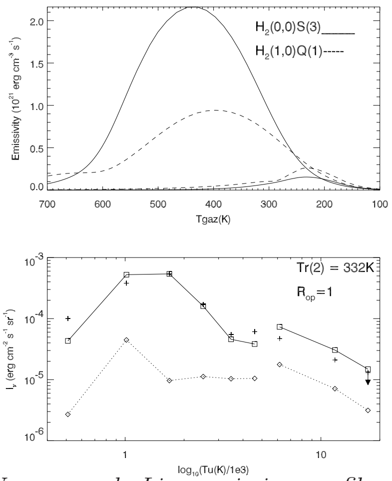

Figure 5. Upper panel: Line emission profiles as a function of gas temperature for two H_2 formation rates 6 $10^{-17} \times T_g^{0.5} \times S(T_g)$ *cm*^{3} *s*$^{-1}$ *(set of curves to the left) and 4.3* $10^{-18} \times T_g^{0.5} \times S(T_g)$ *cm*^{3} *s*$^{-1}$ *(set of curves to the right) as a function of the gas temperature. The lower rate gives the reference value inferred from Copernicus data: 3* 10^{-17} *cm*^{3} *s*$^{-1}$ *at 70 K. Lower panel: The lines intensity of H_2 as observed (crosses) and predicted for the tow H_2 formation rates (solid and dotted lines for the highest and lowest rate respectively), as a function of the upper level energy in Kelvin, at the peak of the H_2 emission (SWS position 2).*

FIRST will give a new perspective on the advection motion: HIFI measurements at high spectral resolution (0.03-300 km/s) of the [C^+] 158μm line will constrain the velocity fields of the turbulence or/and dissociation front propagation. Also, FIRST with PACS will provide Big Grains (BGs) emission maps at high angular resolution (6"). Their comparison to small dust grains emission maps obtained with ISOCAM will constrain the small dust grains abundance variations, crucial for the photoelectric heating and consequently for the thermal balance in low excited PDRs. Finally, note that the complete spectral coverage of FIRST over a wide wavelength range, coupled to the good angular and spectral resolution of FIRST, will give information on the total cooling lines and contraints on the physical parameters (n_H, T_{gas}) from the observed excitation of atoms and molecules.

References

Abergel, A. et al., 1996, A&A 315, 329

Bakes, E. L. O and Tielens, A. G. G. M., 1994, ApJ 427, 822

Bertoldi, F. et al., 2000, IAU Symposium, Vol. 197

Boulanger F., Boissel P., Cesarsky D. and Ryter C., 1998, A&A 339, 194

Le Bourlot, J. et al., 1993, A& A 267, 233

Cardelli, J. A, Meyer, D. M, Jura, M. and Savage, B. D., 1996, ApJ, 467, 334

Meyer, D. M., Jura, M, and Cardelli, J. A., 1998, ApJ 493, 222

Loren, R.B., 1989, ApJ, 338, 902

Pirronello, V., 2000, In H_2 in space, Paris 2000

Schofield, K., 1967, Pl. & Spa. Sc., 15, 643