MID-INFRARED PAH AND H$_2$ EMISSION AS A PROBE OF PHYSICAL CONDITIONS IN EXTREME PDRS

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ABSTRACT

Mid-infrared (IR) observations of polycyclic aromatic hydrocarbons (PAHs) and molecular hydrogen emission are a potentially powerful tool to derive physical properties of dense environments irradiated by intense UV fields. We present new, spatially resolved, Spitzer mid-IR spectroscopy of the high UV-field and dense photodissociaction region (PDR) around Monoceros R2, the closest ultracompact H II region, revealing the spatial structure of ionized gas, PAHs and H$_2$ emissions. Using a PDR model and PAH emission feature fitting algorithm, we build a comprehensive picture of the physical conditions prevailing in the region. We show that the combination of the measurement of PAH ionization fraction and of the ratio between the H$_2$ 0-0 S(3) and S(2) line intensities, respectively at 9.7 and 12.3 µm, allows to derive the fundamental parameters driving the PDR: temperature, density and UV radiation field when they fall in the ranges $T = 250 - 1500$ K, $n_H = 10^4 - 10^6$ cm$^{-3}$, $G_0 = 10^3 - 10^5$ respectively. These mid-IR spectral tracers thus provide a tool to probe the similar but unresolved UV-illuminated surface of protoplanetary disks or the nuclei of starburst galaxies.

1. INTRODUCTION

Dense (> 10$^4$ cm$^{-3}$) and high UV field (> 10$^4$ times the standard interstellar radiation field in units of the Habing field, written $G_0$ hereafter) photodissociation regions rule the energy balance, and thus evolution, of some of the most fundamental astrophysical objects such as protoplanetary disks, planetary nebulae and starburst galaxies. One of the best tools to probe this UV illuminated matter is spectroscopy in the mid-infrared (5-15 µm, hereafter mid-IR), because it provides information on both the gas and small dust grain properties (polycyclic aromatic hydrocarbons and very small grains, hereafter PAHs and VSGs). Ideally, one would like to spatially resolve the emission of these components in order to study their variations as the UV field is attenuated. Unfortunately, such observations are very hard to achieve (for the moment) on one hand because large ground-based telescopes, providing arcsecond angular resolution, are restrained in wavelength coverage, while on the other hand, space borne telescopes have diameters that are usually too small to resolve the sources. Because it is the closest ultra compact H II region at a distance of 850 pc, Monoceros R2 (Mon R2, see Wood & Churchwell 1989 and Howard et al. 1994) constitutes one of the rare exceptions where one can resolve the PDR between the H II region and molecular cloud. In this Letter, we present and analyze the mid-IR PAH and molecular hydrogen emissions in Mon R2 based on spatially resolved Spitzer spectral mapping.

2. OBSERVATIONS

Mon R2 was observed using the Infrared Spectrograph (IRS) onboard Spitzer, in the low resolution mode ($\Delta \lambda = 60 - 127$) as part of the “SPECHII” program (PI C. Joblin). The data were obtained in the spectral mapping mode. The full spectral cubes of the SL1 and SL2 modules were built using the CUBISM software (Smith et al. 2007) from the basic calibrated files retrieved from the Spitzer archive (version S19 pipeline). The two cubes were then assembled to provide the full SL cube of 26x26x36 positions in space and ~ 170 points in wavelength, ranging from 5 to 14.5 µm.

3. OBSERVATIONAL RESULTS

An overview of our observations is presented in Fig. 1. The ionized gas in the H II region, traced by the [Ne II] line at 12.8 µm, appears confined in a spherical region, as seen by radio continuum observations (Wood & Churchwell 1989) and in higher angular and spectral resolution [Ne II] ground based observations (Takahashi et al. 2004; Jaffe et al. 2003). The cometary shape of the H II region is well seen in our [Ne II] map and peaks at about 0.12 erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in the surroundings of the B1 star IRS1. The fact that [Ne II] maxima contours do not include the exact position of IRS1 is due to the saturation of the IRS detectors at this position, implying that the intensity could not be measured, though likely peaking there as shown by Takahashi et al. (2000) and Jaffe et al. (2003). PAH emission is present everywhere in the region, but for clarity in Fig. 1 we only present the region where it is the brightest in the 11.3 µm band (1 to 4 × 10$^{-2}$ erg s$^{-1}$ cm$^{-2}$sr$^{-1}$) forming a filamentary/shell structure that surrounds the H II region. The H$_2$ 0-0 S(3) rotational line at 9.7 µm peaks in a filament which lies between the H II region and the cold and dense molecular gas traced by the [Ne II] 0-0 S(3) rotational line at 9.7 µm. The H$_2$ 0-0 S(2) line at 12.3 µm follows a similar spatial distribution. As in the Orion bar (Tielens et al. 1993), the spatial distribution of these H$_2$ lines is not correlated with the PAH emission contrary to what is seen in lower UV field PDRs like the Horsehead nebula (Habart et al. 2003; Compiègne et al. 2007) or the ρ-Ophiuchus filament (Habart et al. 2005). In the following we investigate the origin of these structures from a physical point of view, using PAH emission and modeling the H$_2$ excitation in the PDR. To simplify the task we select three different
zones named PDR1, PDR2, and PDR3 as displayed in Fig[1]. PDR1 was chosen to be representative of the region where the maximum of $H_2$ emission is found (PAH emission is weaker but present). PDR2 is the transition from the $H_\alpha$ region to the molecular gas. At these two positions it is well seen that $H_2$ gas is found further from the star than the PAH emission (see cut in Fig[1]). Finally, we positioned PDR3 in a region situated further from IRS1 which is a smoother transition from ionized to neutral and molecular gas. For comparison, we also consider the mid-IR spectrum obtained integrating the whole IRS cube over the area imaged.

4. PROBING THE PHYSICAL CONDITIONS OF A HIGH UV FIELD, HIGH DENSITY PDR

4.1. $H_2$ emission as a probe of gas density and temperature

In dense and high-UV PDRs like Mon R2, the excitation of the $H_2$ pure rotational lines is dominated by inelastic collisions (Le Bourlot et al. 1999). To quantitatively probe the role of density $n_H$ and radiation field $G_0$ on the excitation of the lowest energy rotational levels of $H_2$, we use the revised Meudon PDR code (Le Petit et al. 2006; Goicoechea & Le Bourlot 2007), for a large grid of radiation fields and densities above $10^3$ cm$^{-3}$. Since the critical density of the $S(3)$ line is $\sim 5 \times 10^4$ cm$^{-3}$ (Le Bourlot et al. 1999), the lowest energy rotational levels are thermalized when $n_H \geq 5 \times 10^4$ cm$^{-3}$. As a consequence the $S(3)/S(2)$ line ratio scales with the gas temperature and $T_{rot} \approx T$, where $T_{rot}$ is the rotational temperature of the associated rotational transition. In high UV high density PDRs, the main mechanism heating the gas is the photo-electric heating by electrons ejected from very small dust grains and PAHs. Thus, the photoelectric heating efficiency will depend on the ability to eject electrons from the grain surface (less efficient as grains become positively charged) and on the density of electrons in the gas with which charged grains recombine and neutralize. In PDRs, low energy electrons are provided by the ionization of carbon atoms, and as essentially all the carbon is ionized, the electron density depends on gas density and carbon abundance. Overall, as the elemental abundance [C]/[H] is constant, an increase of the gas density (thus of electron density) reduces the grains charge and increases the photoelectric heating efficiency (i.e., the gas temperature). This explains the dependence of the $S(3)/S(2)$ ratio with density seen in Fig[2].

4.2. PAHs as a probe of radiation field

In order to analyse the full Spitzer mid-IR cube we use a model adapted from Joblin et al. (2008) and Berné et al. (2009). This emission model includes the four major dust
components, introduced in these previous works: VSGs (small carbonaceous dust grains), free neutral PAHs, positively ionized PAHs (PAH$^+$), and finally PAH$^+$ that are large (with $N_C > 100$ carbon atoms) charged PAHs. We decompose the observed mid-IR emission using the 4 template spectra presented in Berné et al. (2008). In addition, we consider continuum emission that is simply modelled with two slopes. Furthermore, we include the effect of extinction by multiplying the mid-IR spectrum by $(1 - e^{-\tau_T})/\tau_T$ where $\tau_T = C_{ext}(\lambda) \cdot N_T$, $C_{ext}(\lambda)$ being the extinction cross section per nucleon, taken from Weigartner & Draine (2001) with $R_V = 5.5$ and $N_T$, the column density on material on the line of sight is left as a free parameter in the fit. The values $A_V$ of visual extinction corresponding to the derived $N_T$ (related by $N_T = 1.8 \times 10^{23} A_V$) for each PDR, and used to correct the measured H$_2$ lines intensities as a function of their wavelength, are given in Table 1. We fit all the spectra of the cube using this technique, thus providing the spatial distributions of the emission of each component. An example of these fits is provided in Fig. 1 and spatial distributions of PAH$^+$ and PAH$^0$ populations are presented in Fig. 2.

4.2.2. Estimating $G_0$ using PAH ionization ratio

As shown by models (Tielens 2005) and observations (e.g. Bregman & Temi 2003; Flagey et al. 2006; Galliano et al. 2008), the PAH ionization ratio ($[PAH^+] / [PAH^0]$) depends on the parameter $G_0 \sqrt{T/n_e}$ where $T$ is the gas temperature and $n_e$ the electron density. Ionization of PAHs will influence the emission cross section of these molecules, so that the ratio between the 6.2 to 11.3 $\mu$m bands ($I_{6.2}/I_{11.3}$) will increase with increasing $G_0 \sqrt{T/n_e}$. Assuming that most electrons are provided by the ionization of carbon, we can write that

$$n_e = x(C^+) n_H \approx [C]/[H] n_H$$

with $[C]/[H]$ the elemental abundance of carbon assumed to be $1.6 \times 10^{-4}$ (Sofia et al. 2004). Finally, using the empirical law of Galliano et al. (2008), we can relate the $I_{6.2}/I_{11.3}$ to $G_0 \sqrt{T/n_H}$ by:

$$G_0 (T/n_H)^{1/2} = (1.990 [C]/[H]) \times I_{6.2}/I_{11.3} - 0.26$$

Using the ratio between the 6.2 and 11.3 $\mu$m bands for neutral and ionized PAHs found in Table 1 in Rapacioli et al. (2009) we relate $I_{6.2}/I_{11.3}$ to the ionized to neutral PAH density ratio $[PAH^+] / [PAH^0]$, using Eq. (2) in Joblin et al. (1996):

$$I_{6.2}/I_{11.3} = 1.12 \times \frac{[PAH^+] / [PAH^0]}{1 + [PAH^+] / [PAH^0]} \times 0.85 \times 2.09$$

5. APPLICATION TO MON R2 PDRS

The high value of $I_{5(3)}$ we observe require both $G_0 > 1 \times 10^4$ and $n_H > 1 \times 10^4$ cm$^{-3}$ (Fig. 2 and Burton et al. 1992; Kaufman et al. 2006). This implies that the observed $I_{5(3)}/I_{5(2)}$ ratio, after correction for extinction (Table 1), allows to derive the approximate densities of PDR 1,2,3 in Fig. 2. In addition, since these lines are thermalized, the gas temperature, $T$, is coincident with the rotational temperature, $T_{rot}$, and we can infer $T$ for the different PDRs (Table 2). To calculate the rotational temperature we have assumed an ortho-to-para ratio of 3, that is the equilibrium value for temperatures larger than 100 K. Finally, using the value of $G_0 (T/n_H)^{1/2}$ estimated with the PAH ionization fraction (or $I_{6.2}/I_{11.3}$), and the above derived $T$ and $n_H$ we can derive the intensity of the radiation field that illuminates the three PDRs and position precisely PDRs 1,2 and 3 in Fig. 2. The found values for $n_H$, $T$, $G_0$ (Table 2) are consistent with Mon R2 being a dense and highly UV irradiated PDR as estimated from other molecular lines (Choi et al. 2003; Rizzo et al. 2003; 2005). The found values for density are lower than in these previous works, because the present tracers (PAHs and H$_2$) probe the outermost cloud regions directly exposed to the UV radiation field that are usually warmer ($> 500$ K) and less dense than regions situated deeper into the molecular cloud (see cut in Fig. 1). Finally, the estimated parameters using this technique, for the entire Mon R2 region (see Table 2), are more consistent with the ones derived for spatially resolved PDRs 2 and 3.

6. CONCLUSIONS

The main results we have presented in this Letter are: (i) Mon R2 is a unique template of high-UV/high-density PDRs that is spatially resolved, similar to the Orion bar (where the UV field is slightly lower), (ii) our observations are consistent with PDR models which predict that in high-UV and dense PDRs, the excitation of pure rotational H$_2$ lines is collisional and depends on gas temperature, (iii) for this reason, the spatial distributions of PAHs and warm H$_2$ are different, contrary to what is seen in cool PDRs, (iv) however, because PAH emission is present in the extended region illuminated by the radiation, their ionization fraction can be used to probe the intensity of the UV radiation field, even where H$_2$ emission peaks. Thus, the mid-IR spectrum of dense and
highly irradiated PDRs appears as an efficient probe of the physical conditions in these environments. The ratio between the molecular H$_2$ 0–0 S(3)/S(2) line intensities allows to directly compute the density and temperature of the gas, while the measurement of the ionization fraction of PAHs allows to derive the intensity of the radiation field. We show that the derived parameters for the entire Mon R2 region are consistent with those found for the spatially resolved PDRs 2 and 3. This is likely because the dense PDR1 occupies only a small part of the whole region, and therefore dilution effects imply that the spatially averaged spectrum is dominated by emission from lower density PDRs. Thus, we suggest that this spectral methodology could be useful to derive the dominant physical conditions in PDRs that are not spatially resolved in the mid-IR. In particular, the PDRs at the surface of protoplanetary disks around Herbig Ae/Be stars (Berné et al. 2009) or in the inner rim of T-Tauri disks (Agúndez et al. 2008) are expected to be the targets where such an analysis can be applied. The mid-IR spectrum of starburst galaxies is probably dominated by the emission of PDRs having similar conditions as those described in this paper (see Fuente et al. 2008 for the case of M82). Thus, the present methodology could be a useful tool to derive global properties of galaxies, in connection with massive star formation activity, using forthcoming James Webb and SPICA space telescopes that will observe these emission features at low and high redshifts.

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REFERENCES

Kaufman, Michael J.; Wolfire, Mark. G.; Hollenbach, David J., 2006, ApJ, 644, 283
Le Bourlot, J., Pineau des Forêts, G., & Flower, D. R. 1999, MNRAS, 305, 802
Le Petit, F., Nehmé, C., Le Bourlot, J., & Roueff, E. 2006, ApJS, 164, 506
Rapacioli, M.; Joblin, C.; Bossel, P., 2005, A&A, 429, 193
Rizzo, J. R., Fuente, A., & García-Burillo, S. 2005, ApJ, 634, 1133
Rizzo, J. R., Fuente, A., & Rodríguez-Franco, A., & García-Burillo, S., 2003, ApJ, 597, L153
Smith, J. D.; Armus, L.; Dale, D. A.; Rouselle, H.; Sheth, K.; Buckalew, B. A.; Jarrett, T. H.; Helou, G.; Kennicutt, R. C., Jr. 2007, PASP, 119, 1133
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