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AROMATIC EMISSION FROM THE IONISED MANE OF THE HORSEHEAD NEBULA

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Abstract. We study the evolution of the Aromatic Infrared Bands (AIBs) emitters across the illuminated edge of the Horsehead nebula and especially their properties in the HII region (IC434). A strong AIB at 11.3 μm is detected in the HII region, relative to the other AIBs at 6.2, 7.7 and 8.6 μm. The survival of AIB emitters (PAHs) in the HII region could be due to the moderate intensity of the radiation field ($G_0 \sim 100$) and the lack of photons above ∼25 eV. The enhancement of the intensity of the 11.3 μm band in the HII region, relative to the other AIBs can be explained by the presence of neutral PAHs. Our observations highlight a transition region between ionised and neutral PAHs observed with ideal conditions in our Galaxy. A scenario where PAHs can survive in HII regions and be preferantially neutral could explain the detection of a prominent 11.3 μm band in other Spitzer observations.

1 Introduction

Polycyclic Aromatic Hydrocarbons (PAHs) were proposed by Léger & Puget (1984) and Allamandola et al. (1985) to explain the infrared emission bands observed at 3.3, 6.2, 7.7, 8.6 and 11.3 μm. These aromatic infrared bands (AIBs) have already been observed in spectra attributed to HII regions (e. g. Peeters et al., 2002) but never with clear proof that their emitters are within the ionised gas rather than within an associated photodissociation region on the same line of sight. Moreover, several works report the destruction of these emitters in the HII regions of M17 and the Orion Bar. In these regions, the strong radiation field is thought to be the main cause of this destruction (e. g. Kassis et al. 2006, and references therein). Dust grains play an important role in the energetic balance of HII regions through photoelectric heating (Weingartner & Draine 2001 and references therein). Since these processes are dominated by small grains, the presence of PAHs in HII regions have a strong impact.

In front of the western illuminated edge of the molecular cloud L1630, the visible plates are dominated by extended red emission due to the Hα line emission emerging from the HII region IC434. In the visible, the Horsehead nebula, also known as B33, emerges from the edge of L1630 as a dark cloud in the near side of IC434 (Fig. 1). IC434 and the Horsehead nebula are excited by the σ Orionis star which is an O9.5V binary system (Warren & Hesser 1977) with an effective temperature of $\sim 34\,600$ K (Schaerer & Koter 1997). L1630 is located at distance of ~ 400 pc. Assuming that σ Orionis and the Horsehead are in the same plane perpendicular to the line of sight, the distance between them is ~ 3.5 pc ($\sim 0.5°$) which gives $G_0 \sim 100$ (in unit of Habing) for the radiation field which illuminates the Horsehead nebula.

In this paper, we study the AIBs of the Horsehead nebula observed with the Infrared Spectrograph (Houck et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004) and especially their evolution and properties in the IC434 HII region. More details are given in Compiègne et al. (2006).

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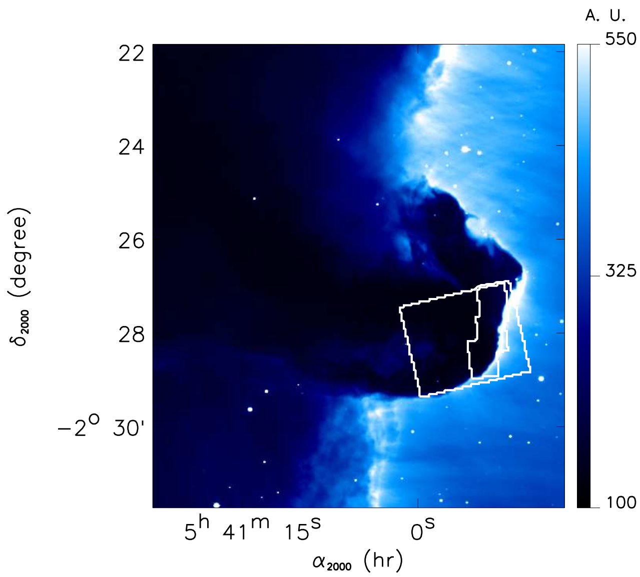

Fig. 1. Hα map, in arbitrary units, obtained with the 0.9 m Kitt Peak National Observatory (KPNO) telescope (Pound et al, 2003). The contours show the areas observed with both IRS-SL (small box) and IRS-LL (large box).

2 Observations: HII region and inner region spectra

IRS (Houck et al. 2004) is a slit spectrograph which can be used in spectral-mapping mode. The Horsehead Nebula has been observed, as part of the "SPECPDR" program (Joblin et al. 2005), using this mode with the four IRS modules. We developped our own reduction pipeline in order to build spectral cubes (two spatial dimensions and one spectral dimension). Figure 1 shows regions observed with the Short-Low (SL, 5.2-14.5 μm, $\lambda/\Delta\lambda$=64-128) and Long-Low (LL, 14-38 μm, $\lambda/\Delta\lambda$=64-128) modules. The common area contains both a HII region (IC434) (bright in Hα, Fig. 1 and Fig. 2, left panel) and a photodissociation region (PDR) (bright at 11-11.5 μm, Fig. 2, middle panel). In this paper, we only present the SL spectra which allow us to study AIBs. We focus our study on the mean spectra of the HII region and of the inner region (i.e. the PDR). The HII region (to the west of the IR emission peak) is defined as pixels where $I_{H\alpha} > 450$ in arbitrary units (AU) and $I(H_2\text{-}12.3\,\mu m) < 6\,10^{-9}\,W\,m^{-2}\,sr^{-1}$ (in order to avoid PDR emission due to projection effects). We define the inner region where $I_{H\alpha} < 135$ AU and $I_{11-11.5\mu m} < 15$ MJy sr^{-1} in order to avoid the bright infrared filament. The reason to avoid the emission peak in the later case is to define a typical PDR spectrum which does not contain a strong continuum since our work is focussed on the AIBs. Countours in the two maps of Fig. 2 show these two regions. Spectra seen in the right panel of the Fig. 2 are the mean spectra of the inner region and the HII region. The zodiacal emission is subtracted from these spectra using the SSC background estimator[1] which is based on the COBE/DIRBE model (Kelsall et al., 1998). The inner region spectrum which is typical of a PDR, contains H_2 rotational lines and AIBs. [NeII] and [ArII] lines are also present in this spectrum due to surrounding emission of ionised gas in which the Horsehead is embedded. The HII region spectra contains [NeII] and [ArII] and, suprisingly, a strong 11.3μm AIB. We show in Compiègne et al. (2006) that a significant fraction of the 11.3μm AIB emitters could be located in the ionised gas.

The relative intensity of the AIBs presents striking differences between the HII region and inner region spectra (Fig. 2). While the intensity of the 11.3 μm band is comparable, the 6.2, 7.7 and 8.6 μm bands present a spectacular decrease in the HII region (more than a factor 2-3). In the following section, we study the different

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[1] see http://ssc.spitzer.caltech.edu/documents/background/

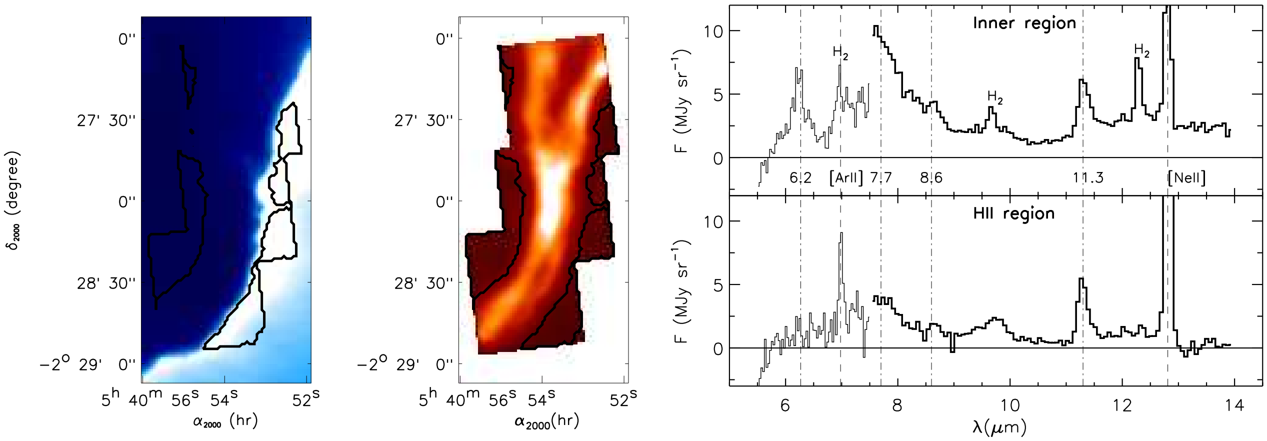

Fig. 2. Left panel: Hα map (see Fig.1). **Middle panel:** Map of the mean emission at 11-11.5 μm (SL). On the two maps, contours show the area used to define the mean emission spectrum of the HII region (west of the IR peak) and of the inner region (east of the IR peak) shown on the **right panel**. The [NeII] line at 12.8 μm is truncated for clarity. In the HII region spectrum, the broad feature at $\sim 10\,\mu$m is an artefact systematically detected at a fixed offset in the slit. The zodiacal emission has been removed from these spectra.

processes which could explain such spectral variation of the 6-9 μm / 11.3 μm ratio.

3 Interpretation of the spectral properties

Hydrogenation state of PAHs can be traced by relative intensities of the 11.3, 12, 12.7 and 13.6 μm bands (e. g. Schutte et al. 1993) which are C-H out-of-plane bending modes with one, two, three and four H atoms on the same aromatic ring, respectively (e. g. Léger & Puget 1984). Both inner region and HII region spectra (Fig. 2) present a 11.3 μm band and an emission plateau between 11.3 and 13 μm above the continuum, which can be attributed to hydrogenated PAHs. Moreover the intensity of the 11.3 μm band compared to the plateau does not present any strong variation between the two spectra, which indicates that the hydrogenation states are comparable. We conclude that hydrogenation effects are likely not the main process which could explain the difference in the 6-9 μm / 11.3 μm ratio between the two spectra.
Variations of the size distribution of PAHs could also affect the 6-9 μm / 11.3 μm ratio but with a lower amplitude than those seen between the two spectra (e. g. Verstraete et al. 2001).
On the other hand, theoretical (e. g. Bakes et al. 2001) and experimental (e. g. Szczepanski & Vala 1993) works show that the charge state of PAHs has a strong impact on the 6-9 μm / 11.3 μm ratio. Neutral PAHs emit significantly less at 6-9 μm than charged ones (both anions and cations). The inner region spectrum which comes from neutral gas presents a high value of the 6-9 μm / 11.3 μm ratio, which can be explained by ionised PAHs (anions or cations). On the contrary, the low value of the 6-9 μm / 11.3 μm ratio in the HII region spectrum can be explained by the presence of neutral PAHs. The spectra extracted from ISOCAM observations (4-16 μm) of NGC7023 present comparable spectral variations attributed to charge effects (Rapacioli et al., 2005). Our spectra from the HII region and the inner region (Fig. 2) are comparable to their extracted spectra attributed to PAH^0 and PAH^+, respectively.
The charge state of PAHs is mainly determined by the balance between photoionisation and recombination rates of electrons (Weingartner & Draine 2001; Bakes et al. 1994) which is generally described by the ratio of the UV intensity to the electronic density, G_0/n_e. The presence of positively ionised PAHs in the inner region can be explained by (1) the presence of UV photons which efficiently ionised the PAHs and (2) a lack of free electrons for the recombination ($n_e/n_H \sim [C]/[H] \sim 10^{-4}$, C^+ being the main provider of electrons in the PDR).
For the HII region, we use CLOUDY (v05.07) (Ferland et al. 1998) in order to derive a quantitative estimate of the charge state of PAHs (vanHoof et al. 2004; Weingartner & Draine 2001) in a fully ($n_e \sim n_H$) ionised medium.
We perform a simple model with an incident radiation field defined for an O9.5V star of the Costar catalogue (Schaerer & de Koter 1997) and located at 3.5 pc. The gas is taken to be at $T = 7500$ K (Ferland 2003) and with

$n_e \sim 100$-$350\,cm^{-3}$ (from the [SIII]19μm/[SIII]33μm intensity ratio, for which we have the IRS-LL observations of this region). For PAHs with radius from 4.5 to 10.5 Å and distributed in size as $n(a) \propto a^{-3.5}$ (Bakes et al. 1994), we obtain a mean charge of 0.55 - 0.75 electron per PAH, corresponding to a fraction of neutral PAHs in the HII region of 25 - 45%. Moreover, the 6-9 μm / 11.3 μm ratio of the HII region spectrum is in agreement with those predicted by the emission model of (Bakes et al. 2001) for such a charge distribution. We conclude that the HII region spectrum can be explained by a mixture of neutral and anionic PAHs.

4 Summary and conclusion

Our main observational result is the detection of a strong 11.3 μm emission band in the HII region facing the Horsehead nebula. The 11.3 μm emitters appear to survive to incident UV photons which have an energy below ~ 25 eV as suggested by the detected ionised species ([SIII], IP=23.34 eV). The survival of PAHs in the HII region could be due to the moderate intensity of the radiation field ($G_0 \sim 100$) and the lack of photons above ~ 25 eV ([ArIII]8.99μm, IP=27.63 eV, is not detected), compared to high excited HII regions (in terms of intensity and hardness), where PAHs can be destroyed on time scales lower than 1000 years (Kassis et al. 2006). The enhancement of the intensity of the 11.3 μm band in the HII region, relative to the other AIBs, can be explained by the presence of neutral PAHs. Our modelling of the charge state of PAHs with CLOUDY confirms that the HII region should contain a significant amount of neutral PAHs. On the contrary, PAHs from the inner region must be positively charged.
The presence of neutral PAHs has been suggested by Kaneda et al. (2005) to explain the prominent emission feature at 11.3 μm compared to the 6.2, 7.7 and 8.6 μm features observed with Spitzer in several elliptical galaxies (the 12.7 μm band is also mentioned, but it cannot be distangled from the [NeII] line at 12.8 μm). Preliminary results by Gordon et al. (2006) from spectroscopic observations of several HII regions in the spiral (Sc) galaxy M101 also indicate a decrease of the 6-9 μm / 11.3 μm ratio which seems correlated with the hardness of the radiation field. The IRS observations of the Horsehead nebula provide a textbook example in our Galaxy of the transition region between ionised and neutral PAHs.

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