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PAH emission in the diffuse ISM: ISO results

J. P. Bernard, J. L. Puget, A. Abergel, F. Boulanger, F. X. Désert, W. Reach, L. Verstraete

Institut d'Astrophysique Spatiale, Université Paris-Sud, Bât. 121, 91405 Orsay Cedex, France

Abstract.

A brief review of our pre-ISO knowledge about PAH (Polycyclic Aromatic Hydrocarbons) in the interstellar medium is given, based on the results of ground based and balloon-borne observations, as well as from the IRAS and DIRBE/COBE satellites. Particular emphasis is given to the AROME balloon-borne experiment which has allowed the first extensive mapping of the 3.3 and 6.2 μm PAH emission along the Galactic ridge. We also discuss the recent analysis of the DIRBE/COBE short wavelength emission, which has given the first evidence for the diffuse L(3.5 μm) and M(4.5 μm) band emission in faint, high latitude cirruses. The comparison between these two datasets indicates that, toward the Galactic plane, a large fraction of the DIRBE L band emission could be due to a continuum underlying the PAH 3.3 μm emission. This could easily be confirmed by IRTS/NIRS or ISO.

With the very successful first year of ISO observations, our understanding of the nature and physical conditions of PAH in the ISM is increasing dramatically. Detailed spatial and spectral information is now available, not only in bright regions of the sky such as HII region interfaces (like M17), or reflection nebula (like NGC7023) but also toward cirrus and molecular clouds. We show several examples of data obtained recently using the ISO-SWS, ISOCAM CVF and broad filters. These results confirm the ubiquity of PAH spectral signatures in regions spanning $\simeq$ 4 orders of magnitude in radiation field intensity. The existence of the IR features toward low radiation field regions confirms the interpretation of the IRAS band emission in terms of PAH and very small particles emitting stochastically. Destruction of the PAH in regions of very high radiation field (such as HII regions) which was proposed to explain IRAS color variations is fully confirmed by the ISO observations. These preliminary results show that the full analysis of the rapidely growing ISO database will allow a detailed understanding of the physical properties of PAH in space, including size distribution, ionization stage, dehydrogenation, destruction processes and their variations with physical conditions.

1. Introduction

The existence of Polycyclic Aromatic Hydrocarbons (PAH) in space has first been invoked (Léger and Puget 1984, Allamandola et al. 1985) to explain observations of the so-called Unidentified IR bands (UIRs) toward objects such as Planetary Nebulae, the interfaces between HII regions and molecular clouds and external galaxies. Léger and Puget proposed that most of the 12 and 25 μm emission evidenced by IRAS in the diffuse ISM should be due to very small dust particles such as PAH. In the next section, we review the status of our knowledge about UIR emission. Particular emphasis is given to the emission from the diffuse medium, since it is generally not affected by extinction or confusion along the line of sight and is therefore more easily interpreted. We then present and discuss a selected sample of preliminary ISO data in section 3.

2. Pre-ISO knowledge

PAH molecules efficiently absorb UV photons; their energy is rapidly converted to vibrationally excited levels of the molecule and is then slowly released through vibrational transitions : the observed IR bands at 3.3, 8.6 and 11.3 μm are due respectively to the stretching, in plane and out of plane bending modes of C-H bonds surrounding the PAH molecule, while the IR bands at 6.2 and 7.7 μm are caused by C-C stretching modes of the skeleton of the molecule. Since a single UV photon can raise the vibrational temperature of a PAH to high values (typically $\simeq$ 700 K), PAH molecules can emit efficiently in the NIR-IR region while cooling down and the UIBs are the main de-exitation channel.

Apart from the main IR bands, several substructures in the observed spectra have also lead to important conclusions regarding the nature of PAH molecules : In the 3.3 μm region, an emission plateau extending toward longer wavelengths is often observed as well as weaker bands at 3.4 and 3.46 μm. Although they could in principle be due to hot bands of the 3.3 μm transition, they are more likely to be vibrational transitions of alkyl groups ($-CH_3$) at the periphery of PAH molecules (Joblin et al. 1996). In the 11 μm region, the C-H out-of-plane bending mode is expected to split into 3 bands around 11.3 (solo), 12.0 (duo) and 13.0 μm (trio) depending on the number of neighbor H atoms on a single aromatic ring. Since observations of reflection nebulae showed strong 11.3 μm IR band emission, the PAH are believed to be partially dehydrogenated.

No single PAH molecule can explain the observed IR spectra so that one must invoke a family of such molecules in space with a broad size distribution. Non-compact PAH have a tendency to exhibit IR lines in regions where no strong features are observed in the astronomical spectra, indicating that the PAH family must be dominated by compact molecules which are also more stable. Note however that this does not exclude the existence of non-compact molecules as long as their modes do not accumulate to the point where they can be detected as an emission feature. In fact, vibrational modes with wavelengths varying from molecule to molecule could well sum up into an IR pseudo-continuum. We will see that several observations, including recent ISO results, seem to indicate the existence of such a continuum. Similarily, Moutou et al. (1996) have shown that such feature accumulations could be responsible for the emission plateau often observed below the IR bands. Finally, PAH in space are likely to be ionized and only partially hydrogenated, at least in regions with sufficient UV field strengths.

Most of the above conclusions were drawn from ground-based or airborne observations which have a limited sensitivity. They are therefore strongly biased toward bright objects where high density regions are located close to bright stars providing copious amounts of UV radiation (e.g. PN, PPN, HII region interfaces, ...) and therefore strong IR band emission. However, the existence of PAH in the diffuse ISM could not be shown directly by such observations and most conclusions about the general ISM were inferred from the IRAS data, without any spectroscopic information. In the following subsections, we review a series of evidences from balloon-borne and pre-ISO satellite observations which indicate that PAH are indeed present in the diffuse ISM.

2.1. IRAS data

The all-sky survey of the IRAS satellite brought the first indirect evidence for the existence of PAH in the diffuse ISM. The IRAS average energy distribution of high latitude clouds levels off in the IRAS 12 and 25 μm bands. This excess was predicted by Puget et al. (1985) as emission from PAH-like small particles emitting out of equilibrium. In their phenomenological model, Désert et al. (1990) showed that both the average extinction and the average IRAS emission can be reproduced assuming the existence of a mixture of transiently emitting 3-D very small grains and PAH molecules, in addition to the classical large grain population which remains in thermal equilibrium. In this model, the IRAS 12 μm emission is mainly due to PAH, namely the 11.3, 8.6 and part of the 7.7 μm emission bands.

Analysis of the IRAS images has shown that small dust properties are likely to change from place to place. The IRAS 12 μm/100 μm ratio decreases systematically toward hot stars and HII regions (Ryter et al. 1987). This is generally interpreted as the effect of PAH destruction in regions with high UV radiation. It has been confirmed by ground-based images of HII/MC interfaces such as the M17 and Orion regions obtained in narrow filters in the 3.3 μm feature by Giard et al. (1994). These images show that the PAH emission concentrates at the surface of individual molecular clumps in the interface region, but are absent or very weak in the HII region itself. However, similar images of dense HII regions at the center of C-rich planetary nebulae (NGC7027: Woodward et al. 1989, BD+30 3639: Bernard et al. 1994) have shown that a significant fraction of the PAH emission at 3.3 μm seems to originate from inside the HII region where the radiation field is orders of magnitude larger than in the Orion or M17 interfaces. It is therefore likely that recombination processes may slow down the destruction. This has lead Bernard et al. (1994) to argue that Coulomb destruction of PAH dications (proposed by Leach et al. 1989) might play a major role in PAH destruction in high UV field regions

As noticed by Boulanger et al. (1990), some molecular clouds exhibit sharp color transitions that must be due to rapid changes in the dust composition. Bernard et al. (1993) showed through a detailled analysis of specific regions that these color changes observed from the outside to the inside of several molecular clouds cannot be explained by radiative transfer effect, but must correspond to changes in the small dust composition. In particular, bright 12 μm haloes around some molecular clouds must have significantly enhanced PAH abundances relative to the average solar neighborhood value. These could be regions where PAH are formed or released from the surface of large grain surfaces and returned to the diffuse medium.

2.2. Arome and DIRBE data

Balloon borne observations brought the first direct evidence for the existence of PAH molecules in diffuse ISM in our own Galaxy. Giard et al. (1989) and Ristorcelli et al. (1994) have presented maps of the 3.3 and 6.2 μm emission of the inner Galaxy obtained using the AROME experiment. These observations, although they were limited to $|b| < 6$ degree showed that PAH emission features are ubiquitous along the Galactic ridge and comes, not only from individual HII regions along the plane, but mainly from the diffuse medium. This result has been fully confirmed by the more sensitive IRTS measurements (Onaka et al. 1996). In the meantime, analysis of the DIRBE/COBE full sky maps has allowed the extension of these results to high latitude regions in wide NIR filters. After proper subtraction of the zodiacal and stellar light emission from the annual average DIRBE maps, one can produce a residual full sky diffuse emission in the L(3.5 μm) and M(4.9 μm) bands (see Bernard et al. 1994, Bernard et al. 1995 for the full sky maps analysis). The residual emission shows a clear correlation with the thermal emission distribution which implies a dust origin. The average spectrum of high latitude dust emission shows significant emission in the M band and an increase toward the L band which follows well the predictions of the PAH model : the increase in the L band can therefore be interpreted as the contribution of the 3.3 μm feature to the DIRBE L band emission. The comparison with the AROME data at low $|b|$ shows that the AROME 3.3 μm feature emission contributes only 30% of the DIRBE L band emission. The remaining 70% is most likely due to the continuum emission also seen in the M band. Within this interpretation, this NIR continuum would have a spectral shape similar to the one observed by Sellgren et al. (1983) toward reflection nebulae. Extended cirrus therefore contributes to a hot NIR continuum which must originate from some kind of small dust grains, maybe PAH themselves. Recent ISO results toward external galaxies (Helou et al. 1996, this volume) seem to confirm that hypothesis.

3. First ISO results

Given the richness and large amount of ISO data already available, describing in detail the present status of ISO data reduction is definitely beyond the scope of this paper. Instead, we wish to present a few specific observations which illustrate the capabilities of ISO instruments and already lead to a few firm conclusions relative to PAH emission in the diffuse ISM. We will mainly concentrate on large scale mapping of molecular clouds with ISOCAM, CVF spectra of selected regions and finally show the preliminary results of the detailled spectroscopic study of the M17 interface with SWS. Most of the material presented here has been taken from letters recently published in a special issue of A&A (1996, vol 315) dedicated to the first ISO results. A detailled description of the ISO

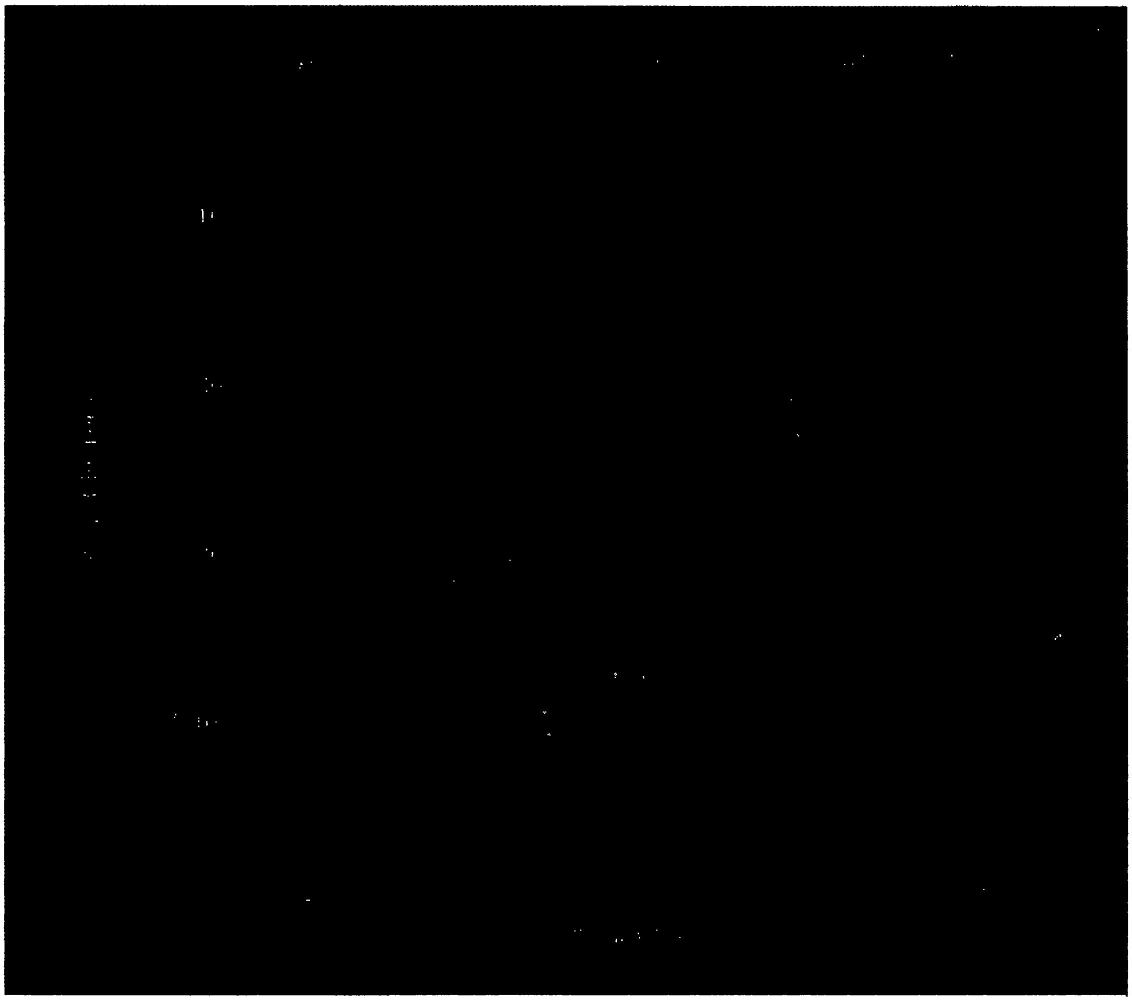

Figure 1. ISOCAM map of the ρ-Ophiuchi molecular cloud. Emission at 6.75 (LW2) and 15 μm (LW3) are coded in blue and red respectively.

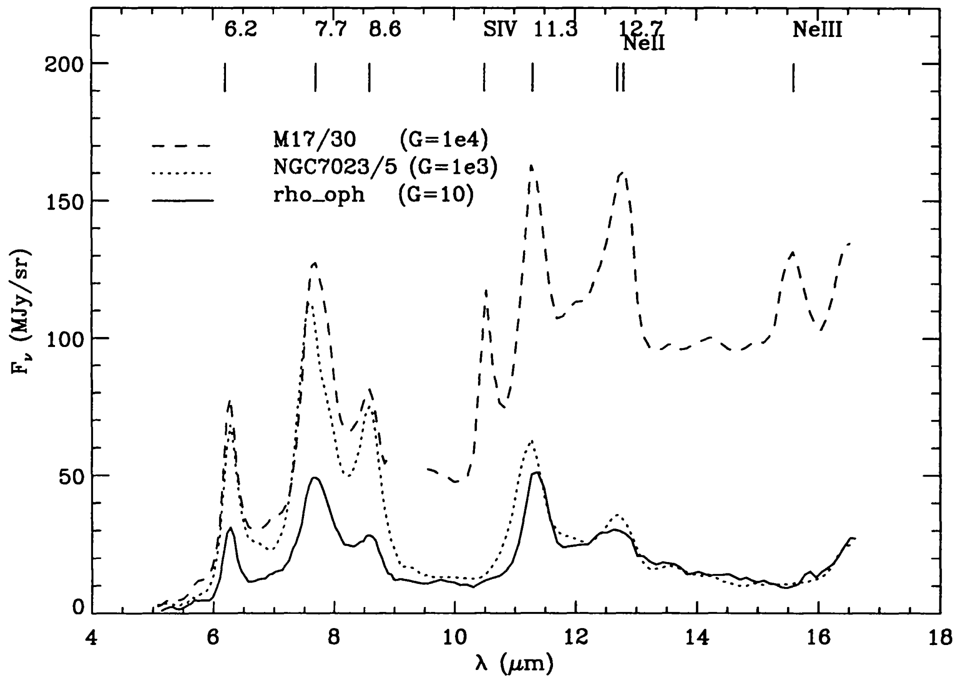

Figure 2. CVF spectra of several Galactic regions with various radiation field intensities. The data is from Cesarsky et al. (1996b,c) for M17 and NGC7023, Boulanger et al. (1996) for ρ-Ophiuchi.

satellite and instruments capabilities is given in Kessler et al. (1996), Cesarsky et al. (1996a), Clegg et al. (1996), deGraauw et al. (1996).

Figure 1 shows the ISOCAM LW2(6.75 μm) mosaic image of the ρ-ophiuchi molecular cloud presented by Abergel et al. (1996). A similar image was obtained in the LW3(12 – 18 μm) filter. Both images show a similar structure with a bright extended region on the West corresponding to the heating of the cloud by the nearby hot star HD147889 which lies just outside the covered area. The two brightest spots correspond to known YSOs which strongly interact with their surrounding (bow shocks can be seen). The dark patches extending NW-SE across the image correspond to extinction associated to the known $C^{18}O$ ridge in ρ-ophiuchi. Of particular interest is the deep absorption feature close to the center. It corresponds to the ρ-Oph B1-B2 clumps which were detected in DCO^+ (Loren and Wootten 1986) and was also well detected by the SPM-PRONAOS balloon experiment in the Sub-mm dust continuum as cold dust (see Ristorcelli et al. 1996, this issue). The analysis of the two bands (LW2 and LW3) images revealed that important color variations are present at small scale in this cloud. The new ISO data show that the IRAS 12 μm halo detected around this cloud has an LW2/LW3 emission ratio higher than the inner cloud region by a factor of 2. This could be due to extinction raising abruptly in the cloud or to changes in the PAH distribution. Firm conclusions must await further analysis.

Figure 2 shows a series of CVF spectra obtained with ISOCAM, toward regions spanning 3 orders of magnitude in the UV radiation field intensity. Similar spectra have been obtained toward the Galactic plane by Mattila et al. (1996). Recently a CVF spectrum (as yet unpublished) was obtained toward the even

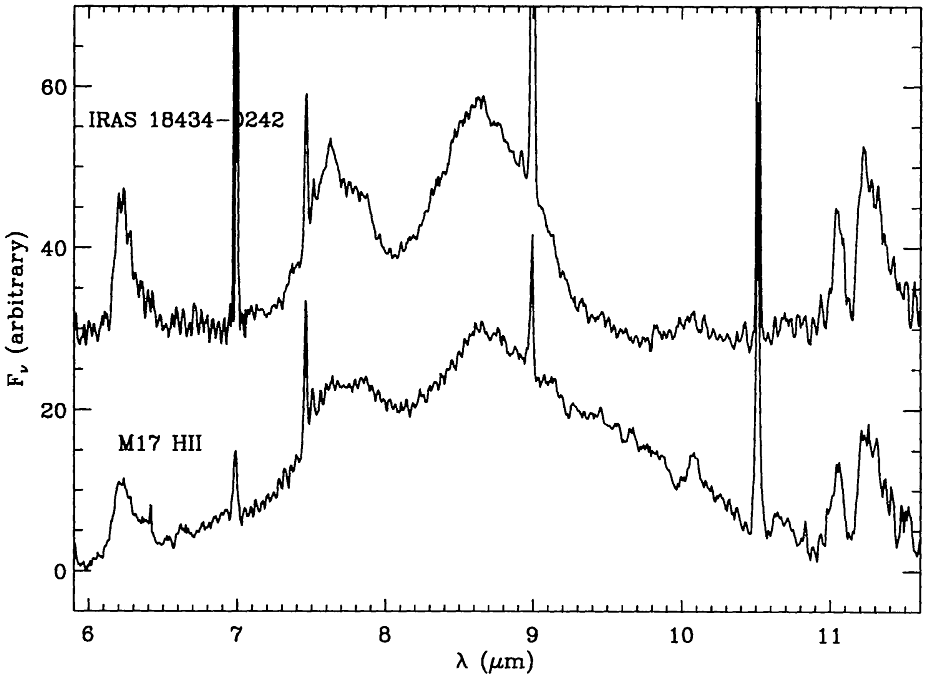

Figure 3. SWS spectra toward the M17 HII region (Verstraete et al. 1996) and toward the compact HII region IRAS18434-0242 (Roelfsema et al. 1996). Note the similarity between these two spectra and the difference with those of figure 2.

fainter cirrus cloud Chamaeleon (G≃ 1). All spectra clearly show the PAH features signatures, which demonstrates the existence of PAH down to faint regions with as little as one local ISRF. This requires transiently excited very small grains (or large molecules) as the carrier of the features and definitely rules out models invoking larger grains at equilibrium with unusual optical properties. Except for the shape of the continuum (which varies due to the presence of hot dust in bright regions) or the appearance of ion lines toward HII regions, the PAH spectrum is fairly similar over 4 order of magnitude in G. The Chamaeleon CVF spectrum also seems to confirm that bright IRAS 12 μm haloes around molecular clouds are indeed PAH over-abundant.

Finally, we would like to emphasize the importance of higher spectral resolution data that can be obtained using the SWS spectroscopy of bright regions. Verstraete et al. (1996) have shown the first full SWS spectra toward five positions across the molecular cloud / HII interface of M17. These data extend our knowledge to longer wavelengths and reveal the spectroscopic details of the PAH bands. They have already allowed the detection of weaker features that might be due to PAH as well, such as the 5.25 and 5.65 μm features - currently assigned to combination modes of PAH proper mode features (Allamandolla et al. 1989, Roche et al. 1996) - and a new feature at 4.65 μm. This type of observations will help understand in more details the nature of the physical changes undergone by PAH molecules across such bright interface regions. From the band intensity ratio variations expected from PAH dehydrogenation and ionization (Pauzat et al. 1995, Langhoff 1996), Verstraete et al. (1996) have shown that the trends observed along the M17 cut indicate a decrease of the PAH ionization and an increase of the Hydrogen coverage inside the molecular cloud as compared to the interface or the HII region. These data also indicate that the spectrum toward the HII region exhibits very broad spectral features instead (or in addition to) the well defined PAH features observed toward the interface. This is confirmed by the SWS data obtained by Roelfsema et al. (1996) toward compact galactic HII regions (see fig 3). The origin of this unusual spectral behaviour is still to be understood. It could be a consequence of the changes in the physical properties of small dust particles or PAH surviving inside HII regions. It could also reveal the existence of another dust population in highly irradiated regions such as coals, which in laboratory spectra (Papoular et al. 1996) present some similarity with the spectra of figure 3.

4. Conclusion

The recent ISO results have definitely demonstrated the existence of the IR feature emission toward very diffuse (cirrus-like) regions of the ISM, which requires the feature carrier to be very small, transiently heated dust grains such as PAH. The new data also confirm the abundance variations which were infered from IRAS data toward HII regions, where the PAH seem to be destroyed. Given the extreme richness and complexity of the ISO data, detailed analysis, modeling and additional laboratory work will be required to get a better understanding of physical properties of PAH molecules in space.

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