PAHs and the Universe
C. Joblin and A.G.G.M. Tielens (eds)
EAS Publications Series, **46** *(2011) 463-468*
www.eas.org

SUMMARY OF THE MEETING

A. Omont[1]

Abstract. This symposium has shown that the field of astrophysical PAHs remains extremely active and lively. Thanks to *Spitzer* Space Telescope, the number of PAH papers has spectacularly increased, including now up to the young Universe. Laboratory and theoretical works have progressed in proportion. Salient features of the six sessions of the symposium are briefly reviewed. Comprehensive analyses of the rich and complex infrared spectra of interstellar PAHs are now well established, based on a large database of observational data. PAHs are fully confirmed as excellent tracers of star formation, but their emission strongly depends on metallicity. Various observations, especially in harsh environments, have confirmed the complexity of the lifecycle of PAHs in space, and the need for multiple formation modes. Electronic properties remain a major issue for astronomical PAHs, including their possible connection with the diffuse interstellar bands, and the possible importance of protonated PAHs. Progress in studying complex carbonaceous compounds, such as those of various soots, and in synthesizing very large PAHs may give important clues for understanding interstellar PAHs. Significant progress was also reported in modeling the important role of PAHs in the physics and chemistry of the interstellar medium.

1 Introduction

Coming back to this field after some time, I am not surprised to find it quite mature for its 25th anniversary. However, I am also struck seeing it so active and lively. Of course, as any well established field, after the explosion of its opening, it had to face renewal and serious challenges. But this symposium has shown that new directions are constantly opened, while older ones are renewed and benefit from breakthroughs in observational, laboratory and theoretical capabilities. The size of the attendance of this meeting including a very lively, enthusiastic and

[1] Institut d'Astrophysique de Paris, UMR 7095, CNRS, UPMC Univ. Paris 06, 98bis Bd. Arago, 75014 Paris, France

DOI: 10.1051/eas/1146048

outstanding new generation is the best proof of the current impact of the field and its appeal to young researchers.

Before spotting various highlights of the meeting, I would like to stress two major features that we may agree on being the main drivers of many of the new achievements that we heard about in the last days

First, after ISO, *Spitzer* and its mid-infrared spectrometer have considerably widened the field of PAH studies, especially the extragalactic world up to amazingly large distances close to ten billion light years. This is strikingly demonstrated by the figure displayed by O. Berné showing the rapid increase in papers on PAHs in the last ten years, and furthermore that the number of papers on PAHs in extragalactic systems increased even more rapidly.

The other major trend is the amazing strength of the synergy between astrophysics, laboratory and theory in the works which were reported. Indeed, very large efforts have been invested in ambitious, astronomy orientated laboratory projects exploiting sophisticated techniques. At the same time, the development of a variety of theoretical and computing techniques has spectacularly improved the efficiency of quantum chemistry methods, as reviewed by F. Pauzat and others.

Astrophysical PAHs remain highly appealing even outside the strict realm of astronomy, because of their strong connection with astrochemistry and exotic interstellar organic molecules, and also with interstellar dust and thus with the origin of planetary systems as traced by the presence of PAHs in meteorites and comets. With SOFIA, JWST and SPICA, exciting new instrumentation will come on line to probe the many mysteries associated with interstellar PAHs. I will thus list in turn the most salient features of each of the six sessions of the symposium.

2 Rich (IR) spectra of interstellar PAHs

The interpretation of the rich and complex interstellar mid-IR PAH spectra remains difficult, even for the main classical features from 6.2 to 12.7 μm, and *a fortiori* the weaker features although many of them are now well established, especially in the 15–20 μm range. However, we have now a very comprehensive general analysis of PAH mid-IR spectra, mainly from the Ames-Dutch group, as reported by E. Peeters. It is based on a rich set of observational data of a broad variety of astronomical sources, and PAH spectroscopic data that is now available in the impressive Ames database. The main classes of spectra are well established for various classes of sources including interstellar HII regions, reflection nebulae, circumstellar material of most post-AGB stars, planetary nebulae, Herbig Ae-Be stars, plus peculiar objects. Various characteristics of the spectra reflect first the ionization state and the size of the PAHs. In addition, specific interpretations for various details have been proposed, involving mainly chemical modifications such as hetero-atoms - mainly N - metal compounds, carbon isotopes, aliphatic fraction, etc.

PAH band ratios have been further analysed in detail in various observations, and in models *e.g.* by F. Galliano. An interesting spectral decomposition of PAH emission has been proposed by O. Berné and the Toulouse group. It is based on the identification of a few main spectral components, attributed to specific compounds. The addition with various weights of these components may account for the spectra observed in different spatial regions.

Although overwhelming, the infrared range is by no way the only spectral range where PAHs show up in the interstellar medium. I will discuss optical bands below. PAHs have long been proposed to be main contributors to the major band seen around 2175 Å in the UV extinction curve. B. Draine very convincingly reviewed the arguments in favor of this natural key attribution. As reported by C. Joblin, a major effort is undertaken to detect far-IR modes of PAHs with Herschel. Detection of such modes would represent a major breakthrough because these modes should be more specific than in the mid-IR. However, as she discussed, it is not an easy task. Finally I note the absence in the meeting of a specific discussion of the likely important contribution of PAH rotation to the radio emission of the interstellar medium around 30 GHz.

3 PAHs, star formation and metallicity

Because of their UV excitation, it is well established that the mid-IR features of PAHs are major tracers of star formation, as shown by their ubiquitous presence in star formation regions of various types of galaxies. The correlation between 8 μm PAH emission and the ionizing photons produced by star formation was comprehensively and quantitatively reviewed by D. Calzetti, with the conclusion that it is almost perfect. This emission can thus be used as a star formation rate indicator. However, the 8 μm emission is heavily dependent on metallicity, and the 8 μm emission may also be triggered by evolved (non star-forming) stellar populations.

Detailed evidence for the correlation of PAHs and metallicity was given by several other communications and posters, including E. Peeters, F. Galliano, L. Hunt and K. Sandstrom. This utilizes large samples of galaxies, as well as the SMC where the PAH fraction is especially low and spatially variable.

4 The lifecycle of PAHs in space. PAH evolution and processing

PAHs are relatively stable and natural carbonaceous products in hydrogen-rich environment. However, they are submitted to various destruction processes. Still they exist in a diversity of environments including hostile ones . This implies that they can form easily by a variety of processes.

PAHs are much faster destroyed in hot plasmas than dust, as seen in the halo of M 82; this confirms that they are efficiently dissociated in each collision with energetic particles, while dust is only slowly sputtered (H.Kaneka). However, PAHs are observed in a significant fraction of the supernova remnants of the comprehensive study reported by J. Rho. Such shocked processed PAHs are strongly correlated with carbon dust and shock conditions. PAHs also evolve as a function of the UV

https://doi.org/10.1051/eas/1146048 Published online by Cambridge University Press

intensity in photo-dissociation regions, possibly in connection with PAH clusters (M. Rapacioli).

As reported by I. Cherchneff, the inner envelope of carbon stars is a natural location of PAH formation as intermediates to the amorphous carbon dust synthesis. In this context, it is important to note the finding of PAHs and onion-like graphene sheets in meteorite nanograins. Understanding the characteristics of dust formation in carbon star may give interesting clues to the relationship between PAHs and carbonaceous dust products.

However, direct formation and growth of PAHs from large molecules or carbon dust in molecular clouds remains very likely a crucial process to explain the ubiquity of interstellar PAHs as discussed by P. Woods, W. Geppert and V. Menella.

The frequent detection of PAHs in many circumstellar disks, including most Herbig Ae stars, also shows their importance in the process of formation of planets and comet nuclei. In such cases, the well defined geometrical conditions allow a precise modeling of their interaction with the UV field and their destruction, as developed in sophisticated models by R. Siebenmorgen.

5 Electronic properties

Electronic properties remain a major issue for astronomical PAHs in many respects. Research about these properties justify a good part of the major laboratory projects across the world. A good knowledge of excited state properties is needed for understanding the complex cascade and relaxation processes resulting in interstellar IR emission induced by UV absorption. Major efforts address the spectroscopy of PAHs in difficult laboratory conditions of cold temperature and gas phase isolated PAHs, relevant for astrophysical conditions. They aim at determining not only spectral characteristics – accurate positions, widths and intensities of spectral lines – but also fluorescence and relaxation pathways. As reported by T. Pino, laser spectroscopy is especially useful, including multi-photon processes, induced fluorescence, etc., both in gas phase and matrix isolation spectroscopy.

A major challenge for astrophysical PAHs is that their dominant forms may be a variety of species that are unstable in usual laboratory conditions – ionized, protonated, deprotonated, dehydrogenated – rather than regular neutral PAHs. P. Sarre especially stressed the importance of protonated and deprotonated PAHs, and their fast reactions, providing calculations of their electronic properties and spectra.

The identification of the carriers of the **Diffuse Interstellar Bands (DIBs)** is still the main issue in the field of interstellar compounds possibly associated with PAHs. Ted Snow gave a comprehensive summary of the state of the DIB problem. He stressed that while more than 600 DIBs have now been catalogued, with more coming, not one DIB has been definitively identified, after almost 90 years of trying! However, almost certainly carbon-based molecules are responsible, and candidates include linear chains, buckyballs, PAHs, and others. There is some hope that UV COST/HST spectroscopy gives important clues about this identification.

https://doi.org/10.1051/eas/1146048 Published online by Cambridge University Press

Nick Cox further reviewed the hypothesis that DIBs are connected with PAHs or other large "related" molecules such as fullerenes, nanotubes or carbon rings.

Some significant progress in this field was reported during the symposium, especially the confirmation of C_{60} in reflection nebulae through mid-IR detection of several lines by K. Sellgren.

6 PAHs and carbonaceous grains

The connection of PAHs with carbonaceous grains is obvious from the similitude of their basic graphene structure, and the possibility to exchange carbonaceous matter through PAH accretion onto grains and PAH generation in grain shattering.

Furthermore, PAHs could also condensate onto water rich ices in dense clouds. As discussed by Bouwman *et al.*, the UV induced PAH-grain photochemistry may then play an important role in interstellar chemistry.

However, the relationship of PAHs with carbonaceous grains is much more intimate because of their similitude of structure and possible family ties. C. Jaeger gave a fascinating review of the various solid forms of carbon and carbonaceous particles. Compared to diamond and even graphite, amorphous hydrogenated carbon and soot particles are much more likely akin to PAHs.

Among various topics, she reported Matrix-Assisted-Laser Desorption and Ionization combined with mass spectrometry to produce and characterize amazingly heavy PAHs up to $\sim$3000 atomic mass units, such as $C_{222}H_{42}$!

Her summary about soot formation and its multiple processes may give important clues for interstellar PAHs. She described how different may be soot formation at high temperature, leading to fullerene-like carbon, and at low temperature ending with soot with plane layers. It is clear that carbonaceous transition objects between molecules and solids may have an amazing diversity including: PAH clusters, PAH oligomers, 3D fragments of fullerenes, oligomers of fullerene fragments, and small nested buckyonions!

7 The role of PAHs in the physics and chemistry of the interstellar medium

When seeing the important contribution of PAHs in the electromagnetic emission of the interstellar medium of galaxies, it is not surprizing that they also play a crucial role in its physics and chemistry.

Talks and posters by L. Verstraete, J. Montillaud and others showed that PAHs intervene in many physical processes. Their determining contribution to the ionization of the interstellar gas is the most well known. It is also now agreed that their rotation emission may dominate the radio continuum emission of galaxies at wavelengths around 1 cm. However, there are still many pending questions to be further investigated by observations, modelling, laboratory and theory.

The role of PAHs in the chemistry of the interstellar medium is probably at least equally important, as discussed in many talks and posters, and especially in

https://doi.org/10.1051/eas/1146048 Published online by Cambridge University Press

the comprehensive review by V. Bierbaum. It was also stressed by A. Simon that metallic compounds, especially Fe-PAH, may be important.

8 Conclusion

To conclude, there is no doubt that the symposium was timely and highly successful. The field is blooming and will continue for long. Certainly, the symposium, its dense scientific program and its wonderful organization by Christine and the local organizing committee will significantly contribute to a new start of the exploration of galaxies through their PAHs. Exciting new instrumentation is coming for probing their many mysteries, with SOFIA, JWST, SPICA, etc, and one may again anticipate an excellent synergy with the major progress expected in laboratory and theoretical techniques.