The Diffuse Interstellar Bands
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Exploring the Limits to Observational Diffuse Interstellar Band Studies

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Abstract. The status of DIB research (Herbig 1995) has strongly advanced since the DIB conference in Boulder in 1994. In the same year we reported the discovery of two near IR diffuse bands coincident with C_{60}^+, that was confirmed in subsequent years. Since then a number of DIB observational studies have been published such as DIB surveys, measurements of DIB families, correlations and environment dependences as well as DIBs in extra-galactic sources. Resolved substructures were measured and compared to predicted rotational contours of large molecules. Polarisation studies provided constraints on possible carrier molecules and upper limits. DIBs carriers have been linked with several classes of organic molecules observed in the interstellar medium, in particular to the UIR bands (assigned to PAHs), the Extended Red Emission (ERE) or the recently detected Anomalous Microwave Emission (AME, assigned to spinning dust). In particular fullerenes and PAHs have been proposed to explain some DIBs and specific molecules were searched for in DIB spectra. DIB carriers could be present in various dehydrogenation and ionization states. Experiments in the laboratory and in space contribute to our understanding of the photo-stability of possible DIB carriers. In summary, the status of DIB research in the last 20 years has strongly advanced. We review DIB observational results and their interpretation and introduce the relevant plenary discussion.

Keywords. ISM: lines and diffuse interstellar bands, ISM: molecules, ions, PAHs, fullerenes

1. Introduction

The DIB spectrum consists of hundreds of broad to narrow absorption bands that are to this date still un-identified! The status of DIB research (Herbig 1995) however made important progress in the last two decades. In 1994 Foing & Ehrenfreund reported at the DIB conference (and simultaneously in Nature) a survey of near IR DIBs and the discovery of two near IR diffuse bands attributed to C_{60}^+. The two diffuse bands coincided with laboratory measurements of C_{60}^+ in a Ne matrix (with same 0.1% matrix shift) and were identified toward several other stars (Foing & Ehrenfreund 1997, Ehrenfreund & Foing 1997, Galazutdinov *et al.* 2000). An abundance of 0.3-0.9% of cosmic carbon in the form of C_{60}^+ was estimated. H. Kroto (Nobel Prize 96) stated in 1994: "undeniably exciting,... considerable step forward". Follow-up high quality observations showed that in comparison to many other DIBs the 2 NIR bands attributed to C_{60}^+ survive in regions with strong UV radiation fields (e.g. Orion). Their band width FWHM ≈ 3 cm^{-1} is compatible with C_{60}^+ rotational contours (Foing & Ehrenfreund 1994, 1997, Cox & Foing, in preparation). Galazutdinov *et al.* (2000) showed that the 2 bands have the best mutual correlation among 32 strong DIBs. The latter authors also measured core and broad wings of DIB, and a 3rd possible band at 9410 Å, consistent with C_{60}^+ laboratory measurements. Up to now laboratory gas phase measurements of C_{60}^+ - that would lead to an unambiguous confirmation - have not been successful.

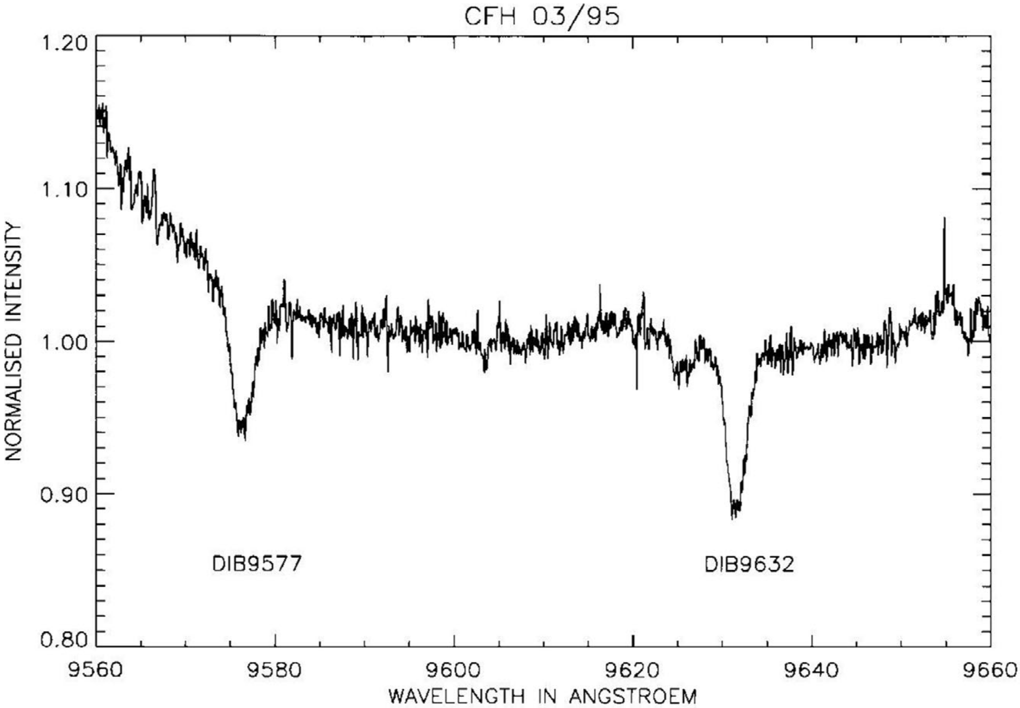

Figure 1. First evidence for C_{60}^{+} in the diffuse interstellar medium obtained with the Canada France Hawaii Telescope (Foing & Ehrenfreund 1997).

2. Surveys and environmental studies

A number of DIB observational studies have been published in the last two decades such as DIB surveys (e.g., Herbig 1995, Jenniskens & Désert 1994, Ehrenfreund *et al.* 1997, Tuairisg *et al.* 2000, Cox *et al.* 2005, Hobbs *et al.* 2008); measurements of DIB families, correlations and environment dependences (e.g., Cami *et al.* 1997, Krełowski *et al.* 1999, Sonnentrucker *et al.* 1997, 1999, Ádámkovics *et al.* 2005) and extragalactic DIBs (Ehrenfreund *et al.* 2002, Cox *et al.* 2006). Resolved substructures were detected (e.g., Sarre *et al.* 1995, Ehrenfreund & Foing 1996) and compared to predicted rotational contours of large molecules (Cossart-Magos & Leach 1990). Polarisation studies provided constraints on the DIB carriers and upper limits (Cox *et al.* 2007a, 2011). DIB surveys have recently been extended to higher sensitivity (Hobbs *et al.* 2008) and to the infrared (Geballe *et al.* 2011, Cox *et al.* in preparation).

Correlation studies towards single cloud stars in the range 4000-7000 Å (Cami *et al.* 1997) point to 1 DIB – 1 carrier, and families (in particular the 5797, 6379, 6613 Å DIBs) that show similar behavior. The study of environmental dependence shows a "skin effect", expressed as a rise & fall of DIB equivalent width/E_{B-V} versus E_{B-V} (Jenniskens *et al.* 1994), and the effect of the UV radiation field on DIB carriers (Vos *et al.* 2011).

Modelling the UV photo-ionisation properties of the DIB carriers (Sonnentrucker *et al.* 1997) led to estimates of an ionisation potential (IP) $\geqslant 10$ eV for the carriers of the 5780, 5797, 6613 Å DIBs. This IP is reminiscent of PAHs or fullerene cations, and could explain the correlation of DIBs with Ca^{+} column densities and velocities. From a survey of DIBs in Rho Oph (Vos *et al.* 2011) towards 80 stars the DIB ratio of 5797/5780 shows a strong dependence on the UV radiation field. The 5797 DIB is more correlated with H & H_2. In

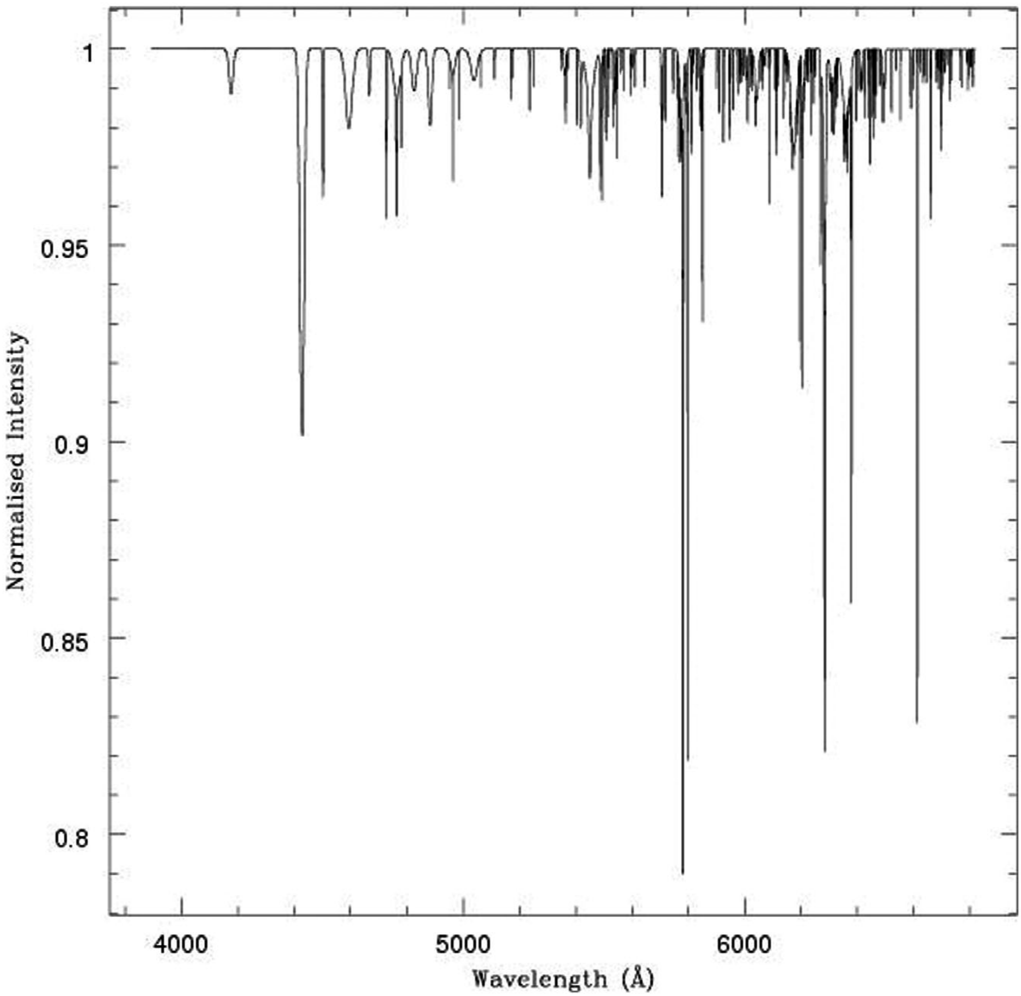

Figure 2. DIB survey in BD+63 1964, E_{B-V}=1 (from Tuairisg *et al.* 2000). The survey reached a sensitivity limit of 5 mÅ.

the Magellanic Clouds (LMC/SMC), Ehrenfreund *et al.* (2002), Cox *et al.* (2006, 2007b) measure a weakening of DIBs as result of UV field and low metallicity.

3. DIB substructures and molecular rotational contours

Ehrenfreund & Foing (1996) modelled the observed substructures of the 5797, 6379 and 6613 Å DIBs using rotational contours of large molecules indicating a peak separation of 4B J_{max} = $4(kTB/2)^{1/2}$ and contour wing width = $kTdB/2B$. The peak separation of 1.5 cm^{-1} of the 6613 Å DIB was attributed to 12-18 C chains, 40 C PAH or 60 C fullerene. One should also consider the isotopic substructure contribution (Webster 1996). Galazutdinov *et al.* (2002, 2006) and Cami *et al.* (2004) have measured marginal changes in the DIB substructure profile as a function of environmental conditions in single cloud lines of sight. No measured DIB polarisation provided strong constraints. Cox *et al.* (2007a) using the MUSICOS at spectrograph Pic du Midi detected no circular polarization and no linear polarisation down to 0.06-0.16% for 6 DIBs even in lines of sight with strong

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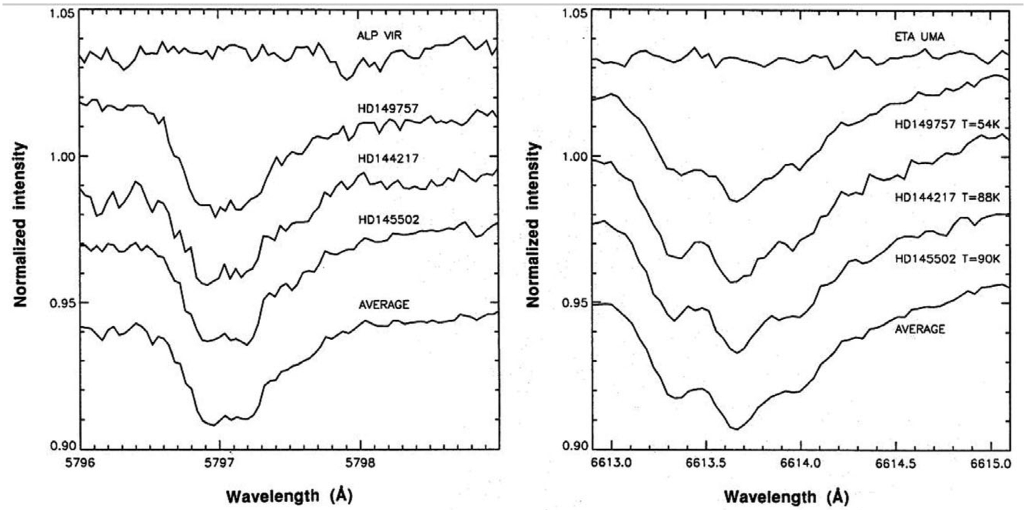

Figure 3. DIB substructures reported in Ehrenfreund *et al.* (1995, 1996), also measured at higher precision by Sarre *et al.* (1995), Kerr *et al.* (1996). These substructures correspond to rotational contours of large molecules.

continuum polarisation. Using the ESPaDOnS spectrograph at CFHT (with a S/N $\sim$ 1000) Cox *et al.* (2011) searched for the polarisation signature in 45 DIBs and obtained only upper limits on f_P of $\sim$0.02 to $\sim$0.2 even for weak DIBs, excluding grains as DIB carriers.

4. Correlations with other spectral features and large aromatic molecules

DIBs carriers have been linked with organic molecules observed in the interstellar medium (Sarre 2006) in particular to the UIR bands (assigned to PAHs), the Extended Red Emission (ERE) or the recently detected Anomalous Microwave Emission (AME, assigned to spinning dust). Fullerenes and PAHs have been proposed to explain some DIBs and specific molecules were searched in DIB spectra (e.g. Foing & Ehrenfreund 1994, Salama *et al.* 1996, 2011, Foing & Ehrenfreund 1997, Ruiterkamp *et al.* 2005). With the Infrared Space Observatory (ISO) in 1997, the search for C_{60} bands was conducted (FULLISM, Ehrenfreund, Foing, Cami, Breitfellner, Burgdorf) in 10 objects. A DIB at 7.215 micron possibly matching a C_{60} vibration band with an equivalent width of 2 Å was detected towards Cyg OB 12. The search for other C_{60} transitions suffered from SWS fringing effects. Using Spitzer, Cami *et al.* (2010) report the detection of 2 strong bands at 17.4 and 18.8 microns assigned to C_{60}/C_{70} in the young planetary nebula Tc-1, as well as 1 weaker band of C_{60} and 3 weaker bands of C_{70}. A match with vibration band positions with an accuracy of 0.2% was reported. Electronic transitions are molecule specific, and therefore DIB studies are crucial for the unambiguous identification of molecules.

Theoretical calculations show PAHs below 40 C are likely partially dehydrogenated in the diffuse medium (Vuong & Foing 2000, Le Page *et al.* 2001). Many dehydrogenation states give a factorial number of isomers, and no defined narrow signatures except for low hydrogenated or bare PAHs. Partial hydrogenation may gives possible weak broad absorption features. The search for fully hydrogenated small PAHs is only possible in environments with a low UV radiation field and abundant H. According to our results no

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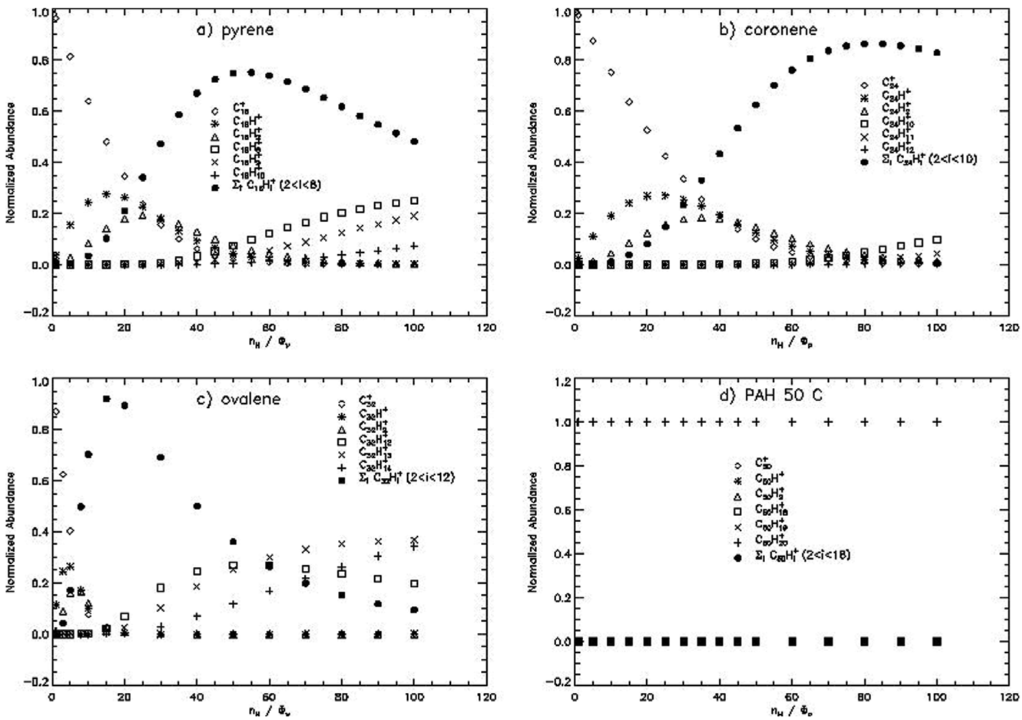

Figure 4. Calculation of hydrogenation states for various PAHs (Vuong & Foing 2000) as a function of ratio nH/UV. Below 40 C partial dehydrogenation in diffuse medium conditions is predicted. Above 50 C fully dehydrogenated PAHs seem stable.

DIB counterpart for small PAHs is expected. Current observations also show no visible DIBs that coincide with 10 PAHs (between $C_{11}H_{10}$ & $C_{42}H_{18}$) that were measured using laboratory gas phase spectroscopy (Salama *et al.* 2011). Also no PAHs match could be found with DIBs in the UV range (Gredel *et al.* 2011).

5. Possible DIB carriers investigated in space

Experiments in the laboratory and in space allow us to monitor the photo-degradation of possible DIB carriers. A space experiment exposing PAHs and fullerenes was performed during a short duration of 2 weeks on the BIOPAN/FOTON capsule (Ehrenfreund *et al.* 2007). This was a validation experiment for the a long duration exposure on ISS, that was performed using the EXPOSE-R facility (hosting 10 international astrobiological experiments). The ISS-EXPOSE-R provided a long exposure to solar UV and space conditions (Bryson *et al.* 2011). The returned samples are currently under investigation. The O/OREOS satellite measured the photo-stability of PAHs and quinones in 650 km orbit (Mattioda *et al.* 2012). Spectroscopic observations from space (using in the past Copernicus, IUE, FUSE, HST, ISO, Herschel, Planck, Spitzer, and in the future Gaia, JWST) allow us to diagnose atoms and molecules linked with DIB carriers and to analyze related environmental conditions (e.g., Planck collaboration, 2011). Those observations strongly contribute to our understanding of the DIB puzzle.

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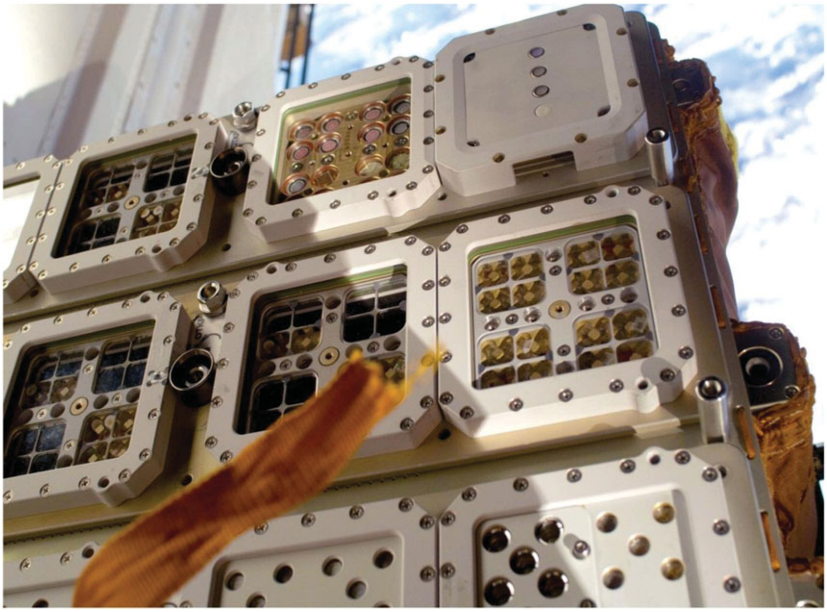

Figure 5. Investigation of PAHs and fullerenes thin films in space, on the EXPOSE-R facility on the International Space Station.

6. Introduction to discussion on Exploring the Limits to Observational DIB Studies

The following topics were proposed to start-up the discussion session at the IAU 297 DIB symposium:

- The DIB spectrum consists of hundreds of broad to narrow absorption bands that are to this date still un-identified!
- C_{60}^{+} DIB identification
- DIB surveys, strengths, widths, magic wavelengths, correlations, families
- IR and UV DIBs
- High resolution structures and no polarisation → molecules
- Environment variations (diffuse medium, effect of UV, ionisation),
- Extragalactic DIBs
- DIBs and ERE extended red emission spectral features
- Relations with carriers of IR bands (PAHs & Fullerenes)
- Effect of dehydrogenation
- Survival of carriers (size, ionisation)
- Spectroscopy of potential carriers
- Space exposure experimencitetts

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