PAHs in Comets: An Overview

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Summary. Polycyclic aromatic hydrocarbon (PAH) molecules, ubiquitously seen in the interstellar medium (ISM) of our own and external galaxies, might have been incorporated into comets if they are formed from relatively unprocessed interstellar matter. The detection of PAHs in comets would be an important link between the ISM and comets. This review compiles our current knowledge on cometary PAHs, based on ground-based and space-borne observations of infrared vibrational and ultraviolet fluorescence spectra of comets, and laboratory analysis of interplanetary dust particles possibly of cometary origin and cometary samples returned to Earth by the Stardust spacecraft. The latter provided the most unambiguous evidence for the presence of PAHs in cometary nuclei.

1 Introduction: PAHs as a Link between the Interstellar Medium and the Solar System

The major goals of cometary science are to determine the chemical composition and physical structure of cometary nuclei and to shed light on the origin of the solar system. It is now widely recognized that comets formed in the cold outer regions of the solar nebula (∼5–55 AU from the Sun, well beyond the “snowline”) and have been stored in two distant reservoirs (i.e. the Oort cloud and the Kuiper Belt) for most of the age of the solar system (∼4.6×10⁹ yrs). Because of their cold formation and cold storage, it is therefore also widely believed that comets are the most primitive objects in the solar system.

However, there is no consensus on to what extent comets preserve the composition of the presolar molecular cloud and the early stages of the protosolar nebula. A compelling theory is that comets are made of unaltered pristine interstellar materials with only the most volatile components partially evaporated (Greenberg 1982). Alternatively, it has also been proposed that cometary materials have been subjected to evaporation, recondensation

¹Long-period comets (with orbital periods ranging from 200 yrs up to 10⁷ yrs) originate in the Oort Cloud (∼3000–50,000 AU from the Sun) and formed in the giant planets region from Jupiter to Neptune of the pre-planetary nebula (∼5–40 AU from the Sun), where the nebula temperature ranged from >120 K near Jupiter to <30 K near Neptune. The source of Jupiter-family short-period comets (with periods shorter than 20 yrs), formed further out than long-period comets in the trans-Neptune region, is the Kuiper Belt (∼30–50 AU from the Sun). Halley-family short-period comets (with periods of 20 yrs < P < 200 yrs) originally came from the Oort cloud and then have been scattered into short-period type orbits by the perturbation of Jupiter and/or Saturn.
and other reprocessing in the protosolar nebula and therefore have lost all the records of the presolar molecular cloud out of which they have formed.

Polycyclic aromatic hydrocarbon (PAH) molecules, composed of fused benzene rings (see Fig. 1 for illustration), and a significant constituent of the interstellar medium (ISM) of the Milky Way and external galaxies (see §2), would also be present in comets if they indeed contain unprocessed interstellar matter. The detection of PAHs in comets would be an important link between the ISM and comets and provides important clues on the processes that occurred during the formation of our solar system.

In this review I attempt to compile all possible evidence for the presence of PAHs in comets (§4), focusing on ground-based and space-borne spectroscopy of infrared vibrational and ultraviolet (UV) fluorescent emission spectra of comets, and laboratory analysis of stratospherically collected interplanetary dust particles (IDPs) thought to be cometary in origin and cometary samples returned to Earth by the Stardust spacecraft, with the latter providing the most unambiguous proof. Using the PAHs in the ISM (§2) and circumstellar disks (§3) as a comparison basis, the physical and chemical nature and source of cometary PAHs are discussed in §5.

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**Fig. 1.** Structures of 21 specific PAH molecules. Both compact pericondensed molecules (*pyrene, perylene*) and thermodynamically less favoured catacondensed molecules (*naphthalene, phenanthrene*) and their alkylated homologs were identified in the Stardust samples (Sandford et al. 2006, Clemett et al. 2007). Naphthalene, phenanthrene and their alkylated derivatives were found in IDPs possibly of cometary origin (Clemett et al. 1993). PAHs with up to 7 rings and their alkyl derivatives are abundant in carbonaceous chondrites (Sephton et al. 2004).
2 Ubiquity of PAHs in the Interstellar Medium of the Milky Way and External Galaxies

PAHs reveal their presence in the ISM by emitting a distinctive set of emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 \( \mu m \) (which are also collectively known as the “Unidentified Infrared” [UIR] emission bands)\(^2\). Since their first detection in the planetary nebulae NGC 7027 and BD+30\(^{o}\)3639 (Gillett et al. 1973), PAHs have been observed in a wide range of Galactic and extragalactic regions (see Fig. 2 and Draine & Li 2007).

In the Milky Way diffuse ISM, PAHs, containing \( \sim 45 \) ppm (parts per million, relative to H) C, account for \( \sim 20\% \) of the total power emitted by interstellar dust (Li & Draine 2001b). The ISO (Infrared Space Observatories) and Spitzer imaging and spectroscopy have revealed that PAHs are also a ubiquitous feature of external galaxies (Tielens 2005; Smith et al. 2007). Recent discoveries include the detection of PAH emission in a wide range of systems: distant Luminous Infrared Galaxies (LIRGs) with redshift \( z \) ranging from 0.1 to 1.2 (Elbaz et al. 2005), distant Ultraluminous Infrared Galaxies (ULIRGs) with redshift \( z \sim 2 \) (Yan et al. 2005, 2007), distant luminous submillimeter galaxies at redshift \( z \sim 2.8 \) (Lutz et al. 2005), the distant Cloverleaf lensed QSO at redshift \( z \sim 2.56 \) (Lutz et al. 2007), elliptical galaxies with a hostile environment (containing hot gas of temperature \( \sim 10^7 \) K) where PAHs can be easily destroyed through sputtering by plasma ions (Kaneda et al. 2005), faint tidal dwarf galaxies with metallicity \( \sim Z/3 \) (Higdon et al. 2006), and galaxy halos (extending \( \sim 6.5 \) kpc from the plane of NGC 5907 [Irwin & Madden 2006] and \( >9.5 \) kpc from the plane of M 82 [Engelbracht et al. 2006]).

However, the PAH features are weak or even absent in AGNs (as first noticed by Roche et al. 1991) and low-metallicity galaxies (Thuan et al. 1999; Houck et al. 2004; Engelbracht et al. 2005; Hunt et al. 2005; Madden et al. 2006; Wu et al. 2006; Rosenberg et al. 2006; Draine et al. 2007). The exact reason for the deficiency or lack of PAHs in low-metallicity galaxies and AGNs is not clear. It is generally interpreted as the destruction of PAHs (1) by hard UV photons (e.g. see Plante & Sauvage 2002) or supernova-driven shocks

\(^2\) These “UIR” emission features are now generally identified as vibrational modes of PAHs (Léger & Puget 1984; Allamandola et al. 1985): C–H stretching mode (3.3 \( \mu m \)), C–C stretching modes (6.2, 7.7 \( \mu m \)), C–H in-plane bending mode (8.6 \( \mu m \)), and C–H out-of-plane bending mode (11.3 \( \mu m \)). Other C–H out-of-plane bending modes at 11.9, 12.7 and 13.6 \( \mu m \) have also been detected. The wavelengths of the C–H out-of-plane bending modes depend on the number of neighboring H atoms: 11.3 \( \mu m \) for solo-CH (no adjacent H atom), 11.9 \( \mu m \) for duet-CH (2 adjacent H atoms), 12.7 \( \mu m \) for trio-CH (3 adjacent H atoms), and 13.6 \( \mu m \) for quartet-CH (4 adjacent H atoms). Other prominent features are the C-C-C bending modes at 16.4 \( \mu m \) (Moutou et al. 1996), 17.1, 17.8, 18.9 \( \mu m \) (Beintema et al. 1996; Smith et al. 2004; van Kerckhoven et al. 2000; Werner et al. 2004).
(O’Halloran et al. 2006) in metal-poor galaxies, and (2) by extreme UV and soft X-ray photons in AGNs (Voit 1991, 1992; Siebenmorgen et al. 2004). Observations also suggest that PAHs are destroyed in star-forming regions with very strong and hard radiation fields (Contursi et al. 2000; Förster Schreiber et al. 2004; Beirão et al. 2006).

\( \text{Fig. 2. Observed} \ 5-20 \mu m \ \text{spectra for:} \ a: \ \text{Reflection nebula NGC 7023 (Werner et al. 2004);} \ b: \ \text{Orion Bar photodissociated region (PDR; Verstraete et al. 2001);} \ c: \ \text{M17 PDR (Peeters et al. 2005);} \ d: \ \text{Planetary nebula NGC 7027 (van Diedenhoven et al. 2004);} \ e: \ \text{Seyfert Galaxy NGC 5194 (Smith et al. 2007). Also shown (f) is the emission calculated for the astro-PAH model of Draine & Li (2007), illuminated by starlight with an intensity } U = 1 \ \text{and } 10^5 \ \text{times of the local interstellar radiation field of Mathis et al. (1983). Taken from Draine & Li (2007).} \)

\( ^3 \text{Alternatively, these low-metallicity galaxies may be truly young and PAHs have simply not had time to form due to the delayed injection of carbon molecules from low-mass stars into the ISM (Dwek 2005).} \)
3 PAHs in Circumstellar Dust Disks

Dust disks around young stars, depending on their age, are the source material or the remnants of newly-formed planets, asteroids, and comets. There exists observational evidence for the presence of PAHs in protoplanetary disks around the intermediate-mass ($\sim 2-10 M_\odot$) pre-main-sequence (PMS) Herbig Ae/Be (hereafter HAEBe) stars and their low-mass ($< 2 M_\odot$) analog T Tauri stars, as well as debris disks around main-sequence (MS) stars (see Fig. 3 for illustration).

- From an analysis of the space-borne and ground-based spectra of 41 HAEBe stars in the 3 $\mu$m region, Brooke et al. (1993) reported a firm detection of the 3.3 $\mu$m PAH C–H stretching emission feature in $\sim 20\%$ of these objects.
- Acke & van den Ancker (2004) found that the PAH features have been detected in $\sim 57\%$ of the 46 HAEBe stars for which the ISO spectroscopic data are available.
- Recent Spitzer observations have obtained the PAH spectra of over 20 HAEBe stars (Sloan et al. 2005; Keller et al. 2008). Spectral variations among these stars and their deviations from typical interstellar PAH features were reported (see Fig. 3).
- Geers et al. (2006) analyzed the Spitzer IRS spectra of 38 T Tauri stars and found PAHs in at least 8% (or probably as much as 45%) of these objects. The PAH spectra of T Tauri stars appear to be quite different from those of HAEBe stars and those typical in the ISM (see Fig. 3).
- The PAH emission features have also been detected in UV-poor dust debris disks around F- and G-type MS stars (e.g. SAO 206462 of spectral type F8V with $T_{\text{eff}} \approx 6250$ K [Coulson & Walther 1995], and HD 34700 of spectral type G0V with $T_{\text{eff}} \approx 5940$ K [Sylvester et al. 1997; Smith, Clayton, & Valencic 2004; see Fig. 3]). However, in an extensive Spitzer IRS spectroscopic survey of 111 T Tauri stars in the Taurus star-forming region, Furlan et al. (2006) found that the PAH emission bands are not seen in dust disks around T Tauri stars of spectral type later than G1.
- Ground-based spatially resolved spectroscopy has revealed that the 3.3–12.7 $\mu$m PAH emission features in some HAEBe disks are spatially extended (on a scale of several hundred AU for the 6.2–12.7 $\mu$m bands; van Boekel et al. 2004; Geers et al. 2004; Habart et al. 2006).
- Jura et al. (2006) reported the detection of the PAH emission features in HD 233517, an evolved oxygen-rich K2III red giant ($T_{\text{eff}} \approx 4390$ K) with circumstellar dust. But Jura (2003) argued that the IR excess around HD 233517 is unlikely to be produced by a recent outflow in a stellar wind. Jura et al. (2006) hypothesized that there is a passive, flared disk orbiting HD 233517 and the PAH molecules in the orbiting disk may be synthesized in situ as well as having been incorporated from the ISM.
Sloan et al. (2007) observed the PAH emission features in the circumstellar disk of HD 100764, a carbon-rich red giant ($T_{\text{eff}} \approx 4850$ K), and found that they are shifted to longer wavelengths than normally seen, consistent with a “Class C” PAH spectrum (Peeters et al. 2002; the PAH spectra of HD 233517 and SU Aur also belong to “Class C”; see Fig. 3).

Fig. 3. Observed 5–20 $\mu$m spectra for: (a) Protoplanetary disk around HAeBe star HD 141569A (B9.5V; $T_{\text{eff}} \approx 10,000$ K; Sloan et al. 2005); (b) Protoplanetary disk around T Tauri star SU Aur (G1III; $T_{\text{eff}} \approx 5945$ K; Furlan et al. 2006); (c) Debris disk around HD 34700 (G0V; $T_{\text{eff}} \approx 6000$ K; Li et al. 2008); (d) Circumstellar disk around red giant HD 233517 (K2III; $T_{\text{eff}} \approx 4390$ K; Jura et al. 2006); (e) Reflection nebula NGC 2023 (illuminated by HD 37903 [B1.5V; $T_{\text{eff}} \approx 22,000$ K; Verstraete et al. 2001). Also shown (f) is the emission calculated for phenanthrene C$_{14}$H$_{10}$ and its cation C$_{14}$H$_{10}^+$ at $r_h = 1$ AU from the Sun (Li & Draine 2008).

4 Evidence for PAHs in Comets
The presence of PAHs in comets was an open issue in the pre-Stardust era. One of the most important discoveries of the Stardust Discovery Mission was the first ever most unambiguous detection of PAHs in a comet. Below, I
Fig. 4. IR emission spectrum of comet Halley obtained by Baas et al. (1986) with the 3.8 m United Kingdom IR Telescope (UKIRT) on Mauna Kea on 1986 April 25 at a heliocentric distance of $r_h = 1.6$ AU. In addition to the major feature at 3.36 $\mu$m (often known as the “cometary organic feature”; the 3.33 $\mu$m $\nu_2$ band and 3.37 $\mu$m $\nu_9$ band of methanol CH$_3$OH account for about half its total intensity; Bockelée-Morvan et al. 1995), there were also subsidiary peaks at 3.28 $\mu$m and 3.52 $\mu$m ($\nu_3$ band of methanol; Hoban et al. 1993). Taken from Baas et al. (1986).

Fig. 5. IR emission spectrum of comet Levy obtained by Davies et al. (1991) with UKIRT on 1990 August 27 at $r_h = 1.4$ AU. The 3.28 $\mu$m feature was as prominent as the broad 3.4 $\mu$m (which was resolved into two components peaking at 3.35 $\mu$m and 3.41 $\mu$m). The dotted curve was the relative transmission of the atmosphere above Mauna Kea. Comet Levy had the strongest 3.28 $\mu$m feature relative to the 3.4 $\mu$m feature among all comets. Taken from Davies et al. (1991).
Fig. 6. Comparison of the near-UV emission spectrum of comet Halley measured by TKS-Vega at $r_h = 0.83$ AU (on 1986 March 9) with the experimentally-measured laser-induced fluorescence spectrum of phenanthrene (upper curve). Three main peaks coincide at 347, 356, and 364 nm. Taken from Moreels et al. (1994).

summarize all tentative evidence in the pre-Stardust era which may suggest the presence of PAHs in comets and finally, the more definite proof from the Stardust mission.\(^4\)

- Baas et al. (1986) by the first time reported the detection of a discrete emission feature at 3.28 $\mu$m in comet Halley after perihelion, at heliocentric distances of $r_h = 1.6$ AU (on 1986 April 25; see Fig. 4) and 2.0 AU (on 1986 May 24). This feature was also seen in comet Levy at $r_h = 1.4$ AU (on 1990 August 27; Davies et al. 1991; see Fig. 5). It was tentatively attributed to the C–H stretching mode of PAHs (e.g. see Bockelee-Morvan et al. 1995). However, other species, such as CH$_4$ and OH prompt emission are also contributing at this wavelength (e.g. see Mumma et al. 2001).

Using a $\chi^2$-fitting technique, Lisse et al. (2006) found the 6.2, 7.7, 8.6 and 11.3 $\mu$m emission features of PAHs in the spectrum of the Deep Impact ejecta of comet Tempel 1 (at $r_h = 1.51$ AU), obtained with Spitzer 45 minutes after impact. This identification did not rely on a search for individual spectral features, but from the decrease of the residual $\chi^2$ after

\(^4\)We should note that PAHs (e.g. naphthalene, phenanthrene, pyrene, chrysene, perylene, benz[ghi]perylene, and coronene; see Fig. 4 with varying degrees of alkylation have been identified in primitive carbonaceous chondritic meteorites (Sephton et al. 2004; Derenne et al. 2005). Although most primitive meteorites are asteroidal (originated in the asteroid belt, somewhere between 2–5 AU from the Sun), Campins & Swindle (1998) argued that some meteorites may have a cometary origin (but so far no known meteorites appear to come from comets).
Fig. 7. PAH mass spectrum distribution for a *Stardust* sample obtained with the two-step laser mass spectrometry. The most commonly found PAH species are naphthalene (C$_{10}$H$_8$), phenanthrene (C$_{14}$H$_{10}$), pyrene (C$_{16}$H$_{10}$), perylene (C$_{20}$H$_{12}$), and their alkylated homologs. Interspersed within these species is a rich suite of auxiliary peaks which appears to represent the presence of O and N substitution, where the heterofunctionality being external to aromatic structure. Taken from Clemett et al. (2007).

Using the same technique, Lisse et al. (2007) re-analyzed the ISO spectrum of Hale-Bopp at $r_b = 2.8$ AU taken on 1996 October 6 and found PAH signals in this comet (but see Crovisier et al. 2000, Crovisier & Bockelée-Morvan 2008).

In the ground-based 7.8–13.2 µm mid-IR spectra of comet Tempel 1 obtained with Gemini-N 61–94 minutes after impact, Harker et al. (2007) possibly detected emission from PAHs at 8.25 and 8.6 µm (perhaps also at 12.4 and 12.9 µm). It is unclear whether the 11.3 µm PAH feature was present or not since it might have been hidden by the much stronger 11.3 µm crystalline olivine feature.
- Moreels et al. (1994) reported the detection of four emission bands at 347, 356, 364 and 374 nm in the near-UV spectrum of comet Halley at \(r_h = 0.83\) AU obtained with the Three-Channel-Spectrometer (TKS) on board the Vega-2 spacecraft (see Fig. 6). They attributed these bands to the fluorescence of phenanthrene \(\text{C}_{14}\text{H}_{10}\). But the production rate of phenanthrene alone required to account for the observed band intensities \(\sim 1.5 \times 10^{27} \text{ mol s}^{-1}\) would be \(\sim 100\) times higher than that of PAHs derived from the 3.28 \(\mu\text{m}\) feature (Bockelée-Morvan et al. 1995). More recently, Clairemidi et al. (2004) identified in the TKS-Vega spectrum of the inner coma of comet Halley a broad-band emission feature between 340 and 390 nm with 3 peaks at 371, 376 and 382 nm. They tentatively attributed these bands to pyrene \(\text{C}_{16}\text{H}_{10}\).

- Clemett et al. (1993) identified small PAH molecules (including naphthalene \(\text{C}_{10}\text{H}_{8}\) and phenanthrene) and their alkylated derivatives in the microprobe two-step laser desorption laser ionization mass spectrometry (L2MS) of IDPs possibly of cometary origin.

- Very recently, Sandford et al. (2006), Keller et al. (2006), and Clemett et al. (2007) analyzed the cometary materials returned to Earth by the Stardust spacecraft and clearly demonstrated that PAHs are present in comet Wild 2, the Stardust mission target: (1) The L2MS (two-step laser desorption laser ionization mass spectrometry) spectra of the Stardust samples revealed the presence of naphthalene, phenanthrene, pyrene, perylene \(\text{C}_{20}\text{H}_{12}\) and their alkylated homologs extending up to at least C4-alkyl (Sandford et al. 2006, Clemett et al. 2007; Fig. 7). (2) The Raman spectra of the Stardust samples exhibit pronounced “D” \(\sim 1360 \Delta \text{ cm}^{-1}\) and “G” \(\sim 1580 \Delta \text{ cm}^{-1}\) bands, characteristic of highly disordered \(\text{sp}^2\)-bonded aromatic carbon (Sandford et al. 2006; Fig. 8A); and (3) The Fourier transform infrared (FTIR) spectra clearly show an absorption fea-

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6Stratospheric IDPs are believed to have originated primarily from asteroids and short-period comets (i.e. collisional debris from main belt asteroids and cometary dust captured in Earth’s atmosphere when spiraling toward the Sun due to Poynting-Robertson drag). Atmospheric entry velocities, as determined from the atmospheric entry temperatures measured from the stepped He-release method (Nier & Schlutter 1993) and the atmospheric entry model of Love & Brownlee (1994), have been used to distinguish between IDPs arising from comets and asteroids, based on the marked differences between typical asteroidal and cometary orbits – asteroidal IDPs spiraling in toward the Sun from low inclination, low eccentric asteroidal sources will enter Earth’s atmosphere, on average, at relatively lower velocities than cometary IDPs (Flynn 1989, Joswiak et al. 2007). Very recently, Joswiak et al. (2007) analyzed 31 IDPs and distinguished two groups: 12 porous cometary IDPs with atmospheric entry velocities > 18 km s\(^{-1}\), an average density of \(\sim 1.0 \text{ g cm}^{-3}\), and an anhydrous mineralogy; 4 more compact asteroidal IDPs mainly composed of hydrated minerals with atmospheric entry velocities < 14 km s\(^{-1}\), and an average density of \(\sim 3.3 \text{ g cm}^{-3}\).
ture at 3050 cm$^{-1}$, corresponding to the aromatic C–H stretching mode at 3.28 µm (Keller et al. 2006; Fig. 8B).

**Fig. 8.** Left (A): Raman spectra of two *Stardust* particles (top panel) compared with the spectra of organics from extraterrestrial (IDPs and primitive meteorites; middle panel) and terrestrial (bottom panel) carbonaceous materials. All exhibit “D” and “G” (6.2, 7.7 µm C–C stretching) bands characteristic of disordered sp$^2$-bonded aromatic carbon. Taken from Sandford et al. (2006). Right (B): Continuum-subtracted FTIR absorption spectrum of a *Stardust* sample. Both aromatic (∼3050 cm$^{-1}$) and aliphatic (∼2967, 2928, 2872 cm$^{-1}$) C–H stretching bands are clearly seen. Taken from Keller et al. (2006).

### 5 Discussion

There is a long series of pieces of evidence which show that comets have (at least partially) preserved the pristine materials in the parent interstellar cloud out of which the solar system has formed: (1) the striking similarities in the composition of cometary and interstellar ices; (2) the large deviations of the isotopic ratios for several elements from their terrestrial values (especially the high deuterium abundance); (3) the ortho-to-para ratios of cometary water, NH$_3$, and CH$_4$ in several comets which imply a spin temperature of ∼30 K (which may be characteristics of their formation temperature); (4) the presence of volatiles, supervolatiles (e.g. CO), and rare gases (e.g. N$_2$) which may indicate that they were incorporated into cometary nuclei at low temperatures (e.g. 22 K for pure CO ice) and probably also (5) the high

\footnote{However, large-scale extensive radial mixing in the solar nebula must have occurred at the early stage of the formation of the solar system, as indicated by}
abundance of cometary HNC (see Crovisier 2006). The definite detection of PAHs in comet Wild 2 by Stardust provides another piece of evidence for the connection between comets and the ISM and has profound implications for the nature of the PAHs in the ISM and dust disks.

Admittedly, the hypothesis of PAHs as the carrier of the “UIR” bands widely seen in the ISM (§2) and circumstellar dust disks (§3) is still a hypothesis, although the evidence in support is very strong – so far there is no actual precise identification of a single specific PAH molecule in interstellar space or dust disks, although the PAH model is quite successful in explaining the general pattern of band positions, relative intensities, and profiles observed in the “UIR” emission spectra, in terms of mixtures of highly vibrationally excited neutral and charged PAHs.

Details of the “UIR” spectra (precise band positions, bandwidths, and relative band intensities) remain hard to mimic exactly with the use of available PAH spectra obtained by experimental measurements or quantum chemical calculations (e.g. see Fig. 3f). Therefore, in modeling the observed PAH emission spectra, astronomers usually take an empirical approach by constructing “astro-PAH” absorption properties that are consistent with spectroscopic observations of PAH emission from dust in various astrophysical environments (e.g. see Désert et al. 1990, Schutte et al. 1993, Li & Draine 2001, Draine & Li 2001, 2007). The resulting “astro-PAH” absorption cross sections, although generally consistent with laboratory data (see Fig. 2 of Draine & Li 2007), do not represent any specific material, but approximate the actual absorption properties of the PAH mixture in astrophysical regions.

It is not surprising that the astronomical PAH emission spectra do not closely resemble the laboratory spectrum of any single individual PAH species since interstellar or circumstellar PAHs are most likely a complex mixture of many individual molecules, radicals, and ions. As a matter of fact, Allamandola et al. (1999) have demonstrated that the laboratory absorption spectra produced by co-adding different PAH spectra were able to provide a detailed match to the observed emission spectra.

One may still argue that the approach taken by Allamandola et al. (1999) was not perfectly appropriate because they compared the astronomical emission spectra with the co-added laboratory absorption spectra, while the IR emission spectrum of a PAH molecule does not only depend on its IR absorption spectrum, but also depends on its absorption at shorter wavelengths, its heat capacity, and the intensity and spectral shape of the illuminating radiation field (e.g. see Draine & Li 2001). This, together with the detection the detection of a large number of crystalline olivine and pyroxene minerals in the Stardust comet samples that, based on their solar isotopic compositions, appear to have formed in the inner regions of the solar nebula (Brownlee et al. 2006). Also, the silicate dust in the diffuse ISM is predominantly amorphous (Li & Draine 2001a).

Cernicharo et al. (2001) reported the detection of benzene (C₆H₆), the basic aromatic unit, in the protoplanetary nebula CRL 618.
of individual specific PAH molecules in the Stardust samples, suggests that it would be of great value to study the excitation, emission, and destruction of a large number of specific PAH molecules in the ISM, dust disks, and cometary comae, as well as the mechanism of releasing PAHs from the ice mantles of dust in comets and dust disks to the gas phase and their lifetime against photodestruction and photoionization (e.g. see Joblin et al. 1997, Li & Lunine 2003, Li & Draine 2007).

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