Organic dust in galaxies

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Abstract. Recent space infrared telescopes, Infrared Space Observatory, Spitzer Space Telescope, and AKARI have made significant progress in our understanding of organic dust in the Universe. In this review, we discuss recent observations with these space telescopes of the unidentified infrared emission (UIE) features in the near to mid-infrared, which come from very small organic dust, and the absorption features from 3 to 7 µm, which characterize large organic dust. They provide us with a new view of organic dust in galaxies. We also briefly discuss latest AKARI observations of H$_2$O and CO$_2$ ices in 2.5–5 µm in the Large Magellanic Cloud in comparison with observations in our Galaxy, which suggests the importance of dust surface chemistry in the formation of organic matters in the Universe.

1. Introduction
The major constituents of interstellar dust are thought to be silicates and carbonaceous grains [1]. However, their exact structures and compositions are still not completely understood. In particular, carbon atom can have various hybridized orbitals and constitute various types of organic dust. The advent of recent space infrared telescopes, such as Infrared Space Observatory (ISO), Spitzer Space Telescope, and AKARI has made significant progress in our understanding of organic dust in the Universe. Here an overview of recent observations with space infrared space telescopes is presented with particular focuses on emission features arising from small organic dust [2], absorption from large organic dust [3], and absorption features of ice species [4] in galaxies. Other carbon-bearing dust, such as C$_{60}$ or related materials, are discussed by others in this conference and are not covered here.

2. Emission features
A family of prominent emission features are ubiquitously seen in the near- to mid-infrared in the general interstellar medium (ISM) and normal spiral galaxies [5, 6, 7, 8, 9, 10, 11]. The major features are observed at 3.3, 3.4–3.5, 6.2, 7.7, 8.6, and 11.3 µm associated with minor features. These features have been attributed to polycyclic aromatic hydrocarbons (PAHs) [12, 13, 14] or materials containing PAH components, such as QCC [15]. Appearance of the emission features is stable in the various environments, leading to an idea that there may be a small number of dominating PAH species, called grand PAH, which is yet to be identified, rather than a number of various PAH species [16]. Recently Kwok and Zhang [17, 18] proposed mixed aromatic-aliphatic organic nanoparticles (MAON) as a more likely candidate of the carriers because the features at 3.4–3.5 µm clearly suggest the presence of aliphatic CH bonds. The exact nature of the feature
carriers is thus still under debate and it is called them the unidentified infrared emission (UIE) features in the following.

The UIE features are seen even in distant galaxies. The highest redshift at which the UIE feature is detected is $z = 4.055$ to date [19]. The intensity of the UIE feature shows a good correlation with the far-infrared intensity and thus the star-formation rate [19]. Since they are not seen in H\(\text{II}\) regions [20], the UIE features are suggested to be a good tracer for star-formation of B-type stars rather than massive star-formation [21]. The equivalent width of the UIE feature is also a good measure for the presence of AGNs [22]. Therefore, they are a useful probe to estimate the nature and star-forming activities of distant galaxies if we understand their properties correctly. The UIE features are absent in low-metallicity dwarf galaxies [11, 23, 24]. This can be interpreted in terms of efficient destruction and/or inefficient production of the feature carriers in these environments [25], delayed formation of carbonaceous dust [26], or carrier formation from fragmentation of carbonaceous dust [27]. It is not clear at present which process plays the most dominant role and the formation process of the carriers in galaxies is still not clearly understood (see § 2.2).

2.1. Band ratio diagnosis

The UIE features have several emission bands arising from different vibrational modes and thus their relative band ratios can be used to estimate the physical conditions of the band carriers [2, 28]. However, systematic variations in the band ratios have so far been seen only in a few cases. One of the clear cases is small ratios of the $7.7\,\mu m$ to the $11.3\,\mu m$ bands seen in elliptical galaxies (Fig. 1) [11, 29, 30, 31]. Similar small ratios of a lesser degree are also seen in the halo of disk galaxies [32, 33], which may be attributed to the dominance of neutral band carriers because the $7.7\,\mu m$ band is thought to come predominantly from ionized carriers [28].

![Figure 1](#)

The most clear systematic variation in the band ratios is found in AKARI/IRC observations of star-forming regions in the Large Magellanic Cloud (LMC) [34]. Figure 2 shows plots of several band ratios against the infrared color. The abscissa color indicates the strength of the star-forming activity and thus the intensity of the incident radiation field. The band ratios show correlations with the color for PDR targets (blue circles), which can be successfully interpreted in terms of an increase of the ionization fraction and the excitation of band carriers (see Fig. 3). Thus it provides the first clear evidence that the central exciting source becomes hotter with the increase of the intensity. On the other hand, H\(\text{II}\) region targets (red triangles), which show emission lines from ionized gas, do not follow the sequence. The variation of the band ratios
I(3.3)/I(11.3)  
I(24µm)/I(15µm)

(a)  
(b)  
(c)  
(d)  

Figure 2. UIE band ratios versus the infrared color of 24 to 11 µm for the LMC star-forming regions [34]. (a) 3.3 µm band, (b) 6.2 µm band, (c) 7.7 µm band, and (d) 8.6 µm band to the 11.3 µm band intensities. The blue circles indicate the PDR targets, while the red triangles show the H II region targets. The infrared color indicates the strength of star-formation activity. The band ratios of the PDR targets show systematic variations with the infrared color, while those in H II region targets do not show a clear correlation.

can be seen more clearly in the two band-ratio diagram (Fig. 3), in which grids of simple model calculations are also overlaid [34]. As described above, the trend of the PDR targets can be accounted for by an increase of the effective temperature of the exciting source ($T_*$) and the ionization fraction ($f_i$). The different behavior of the H II region targets can be explained by a decrease of small-sized band carriers (an increase of the number of carbon atoms in the smallest carriers, $n_{c,min}$), suggesting destruction of small carriers in ionized regions. This study strongly demonstrates the importance of the 3.3 µm band for the study of processing of the carriers and the UIE band diagnostics.

Figure 3. Two band-ratio diagram of the 3.3 to the 11.3 µm band ratio versus the 7.7 to the 11.3 µm band ratio for the LMC star-forming regions [34]. (a) PDR targets (blue circles) and (b) H II region targets (red triangles). In (a) a model grid of the ionization fraction $f_i$ and the effective temperature $T_*$ of the exciting sources is also plotted. The number of carbon atoms in the smallest band carriers $n_{c,min}$ is fixed as 20. In (b), a model grid of $f_i$ and $n_{c,min}$ is plotted. The effective temperature $T_*$ is fixed as 30000K in the grid of (b).
2.2. Formation of UIE band carriers in galaxies

Formation sites of the UIE band carriers in galaxies are not yet clearly identified. They may be formed either in stellar outflows [36, 37, 38] or molecular clouds [39, 40, 41]. Observations of AKARI/IRC also suggest that the band carriers may be formed by fragmentation of large carbonaceous grains in a supernova remnant [42] and a filament produced by a star-burst activity in a dwarf galaxy [43]. Figure 4 shows another interesting case. It shows the AKARI/IRC two-color artificial image of the interacting galaxy NGC 2782 [44]. This galaxy shows a very long tidal tail in the west with an extended structure in the east in the H\textsc{i} 21 cm (red contours), both of which are thought to have resulted from collision with a minor galaxy that has passed through the major galaxy [45]. Interestingly, a similar structure to H\textsc{i} in the east is seen in the 7 \mu m image of AKARI/IRC (Fig. 4b). Since the IRC 7 \mu m band efficiently probes the UIE 6.2 and 7.7 \mu m bands [43], the AKARI observations suggest that the UIE band carriers were formed in the collision event, possibly from fragmentation of larger carbonaceous grains. In fact, a simple SED analysis of this structure suggests a decrease of nanometer-sized dust [44]. These observations strongly suggest that fragmentation of large carbonaceous grains is one of the major processes to produce the UIE band carriers.

Figure 4. AKARI/IRC artificial two-color image of NGC 2782 [44]. The blue is AKARI/IRC 3.2 \mu m, the green is AKARI/IRC 7 \mu m, and the red contours indicate H\textsc{i} 21 cm intensity [45]. Similar extended structures are clearly seen both in H\textsc{i} and at 7 \mu m in the enlarged figure (b), suggesting that the UIE carriers may have been produced in the gas stripping process during the collision event.

3. Absorption features

CH stretching modes of carbonaceous dust have been observed at \sim 3.4, 6.8, and 7.2 \mu m and CC vibrations at \sim 6.2 \mu m in absorption in our Galaxy [3, 46]. The 3.4 \mu m features consist of several components, which correspond to \textit{sp}^3 CH\textsubscript{2} and CH\textsubscript{3} as well as \textit{sp}^2 CH vibrations. These features arise from large carbonaceous grains. Since they require a high column density to be observed, they are not easily seen in normal spiral galaxies, but are detected in dust torii around AGNs [47, 48]. Figure 5 shows the infrared spectrum of IRAS 08572+3915 (z = 0.05835) taken with AKARI/IRC with a fit with four Gaussian components, which is in good agreement with the results taken with the United Kingdom Infrared Telescope (UKIRT) [47].

These recent analyses of the absorption features both in our Galaxy and an AGN suggest that large carbonaceous grains are dominated by \textit{sp}^2 carbon, but that most of hydrogen atoms
are associated with $sp^3$ C. The suggested structure of large carbonaceous grains can be shown in the ternary diagram of amorphous carbon (Fig. 6) [49]. Large carbonaceous grains both in our Galaxy and an AGN have similar structures within uncertainties. Note that the results of [47] have been revised based on the new absorption coefficient [3]. The results suggest that the backbone structure of large carbonaceous grains is hydrogen-poor and $sp^2$ carbon-dominant, while most hydrogen is attached in $sp^3$ carbon. Based on existing amorphous carbons, these results lead to a new view of organic dust in the ISM [3, 47]. Interstellar organic dust may consist of the hydrogenated amorphous carbon mantle on top of the pure aromatic carbon core. It produces PAHs or PAH-containing small dust by shattering [3]. This view is also consistent with the evolution of latest model of organic dust that suggests aromatization of organic dust in the ISM [50]. Latest observations with AKARI indicate a decrease of aliphatic to aromatic CH bonds with the radiation field intensity, supporting this new view of evolution of the cosmic organic dust [51].

Figure 5. Optical depth of the 3 µm region absorption of IRAS 08572+3915 derived from near-infrared spectrum taken with AKARI/IRC plotted against the rest wavelength. The black solid line indicates the observed spectrum and the red dashed line shows the fitted spectrum. The green, blue, purple, and brown lines are 4 Gaussian components in the fit, corresponding to $sp^3$ CH$_2$ and CH$_3$ stretching vibrational modes. The dashed dark green line seen in the shorter wavelength side indicates absorption of H$_2$O ice. Due to the low resolution of the IRC spectrum, the decomposition of the longest two components has ambiguity, but it is basically in good agreement with the results of [47].

Figure 6. Ternary diagram of hydrocarbon materials, in which various forms of hydrocarbons are plotted for reference [49]. “ta-C” denotes tetrahedral amorphous carbon, while “ta-C:H” indicates hydrogenated tetrahedral amorphous carbon and “a-C:H” denotes hydrogenated amorphous carbon. The red and green circles indicate the hydrocarbons in our Galaxy with different absorption strengths [3]. The blue star symbol indicates the hydrocarbons in the AGN IRAS 08572+3915 [47] estimated with the revised absorption strengths of [3].
4. Ice absorption features

ISO, Spitzer and AKARI observations towards young stellar objects (YSOs) in our Galaxy show that H$_2$O ice is the most abundant ice species and that the column density of the second abundant CO$_2$ ice is very well correlated with that of H$_2$O ice [52, 53, 54]. The good correlation strongly suggests concurrent formation of both ice species on the grain surface [55, 56]. AKARI/IRC observations of M82 suggest a correlation between the ratio of the column densities of both ice species and the ultraviolet radiation intensity [57], while a similar correlation between the two ice species is not seen in a larger sample of galaxies observed with AKARI [58]. It may be due to various components on the line of sight that erase the intrinsic correlation.

AKARI observations indicate that CO$_2$ ice is clearly more abundant relative to H$_2$O ice towards massive YSOs in the LMC than those in our Galaxy [59, 60] (Fig. 7). It can be accounted for by the high dust temperature in the LMC [62], which enhances the mobility of CO and thus the formation of CO$_2$ ice on the dust surface [60]. Alternatively it can also be explained by the reduced H$_2$O ice abundance relative to CO$_2$ ice due to the strong ultraviolet radiation and the low dust-to-gas ratio at low-metallicity in the LMC [61]. Recent ground-based near-infrared observations towards these YSOs find a paucity of CH$_3$OH ice relative to H$_2$O ice compared to our Galaxy, which can also be interpreted consistently in terms of the high dust temperature in the LMC due to the rapid diffusion or evaporation of hydrogen atoms that reduces hydrogenation of CO to form CH$_3$OH ice [63]. CH$_3$OH ice is a key to the formation of complex organic molecules [64]. Hence, the paucity of CH$_3$OH ice predicts a difficulty of formation of complex organic matter in the LMC, suggesting an impact of dust surface chemistry on the formation of organic matter in the Universe.

![Figure 7](image-url) Correlation of column densities between CO$_2$ and H$_2$O ices towards massive YSOs in the LMC [59, 60]. The solid line indicates the correlation with the slope of 0.34 for the LMC YSOs, while the dashed line shows the correlation slope (0.17) for Galactic massive YSOs [52, 53]. The plot clearly shows the overabundance of CO$_2$ ice relative to H$_2$O ice in massive YSOs in the LMC compared to our Galaxy.

5. Summary

Recent observations of space infrared telescopes, ISO, Spitzer, and AKARI, have made significant progress in our understanding of organic dust in the Universe. The UIE features give us information on small organic dust. Although the exact nature of the feature carriers remains unsettled, recent studies steadily unveil their properties. Observations of the LMC suggest possible processing of small organic dust in ionized regions and demonstrate the importance of the 3.3$\mu$m band emission for the band diagnostics. Several observations of AKARI/IRC also suggest that fragmentation of large carbonaceous grains is one of the major processed for the formation of the UIE band carriers. Observations of absorption features in the near- to mid-infrared both for our Galaxy and AGNs suggest that large organic dust is $sp^2$ carbon-dominant.
and hydrogen-poor, and most hydrogen is attached to \( sp^3 \) carbon. These results lead us to a new view of organic dust and its evolution in the Universe. Observations of ice species in the low-metallicity LMC suggest a distinct difference from the ices in our Galaxy, indicating the importance of the environmental effect on the surface chemistry of dust grains, which affects the formation of complex organic molecules.

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