Interstellar Dust and PAHs in Our Galaxy and Nearby Galaxies: from *AKARI* to *SPICA*

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ABSTRACT

AKARI has revealed various phenomena on the evolution of dust grains, including polycyclic aromatic hydrocarbons (PAHs), through processing in the interstellar space of our Galaxy and nearby galaxies. In particular the mid- to far-infrared (far-IR) all-sky diffuse maps show that PAHs are widely distributed in the Galactic plane, similarly to large grains but with significant spatial variations in their abundance ratios. Following *AKARI*, *SPICA* will elucidate the whole story of the evolution of dust grains in space. The most outstanding uniqueness of *SPICA* is high-sensitivity spectral mapping in a continuous mid- to far-IR range, which matches very well with the *AKARI* heritage. The spectral range includes most of the fundamental vibration modes of minerals, organic matter, and ices. The continuous spectral coverage, not hampered by the atmospheric absorption, is essential to unambiguously identify relatively broad spectral features inherent to solid particles. Among the proposed instruments, the SCI (SPICA Coronagraph Instrument) is indispensable to study a small-scale structure around a central bright source. It is particularly important to investigate materials surrounding dusty AGNs in distant galaxies or young stars in nearby starforming regions, where we can study the properties of dust grains in early Universe and in planetary formation sites, respectively.

1. INTRODUCTION

With *AKARI* (Murakami et al. 2007), we have performed a systematic study of interstellar dust grains in various environments of galaxies including our Galaxy (Kaneda et al. 2009). Because of its unique capabilities, such as near- and far-infrared (far-IR) spectroscopy, and all-sky coverage in the mid- and far-IR, *AKARI* has revealed various phenomena on the evolution of carbonaceous grains including polycyclic aromatic hydrocarbons (PAHs), through processing in the interstellar space. For example, the *AKARI* near- and far-IR spectroscopy have indicated structural changes of hydrocarbon particles and formation of graphite grains, respectively, in harsh environments of galaxies. In addition to such spectral datasets, the 9 μm diffuse map is the world-first all-sky map of the PAH emission (Figure 1), which has revealed that PAHs are widely distributed in the Galactic plane, similarly to large grains but with significant spatial variations in their abundance ratios.

Hence *AKARI* provides global and unbiased views of interstellar dust and PAHs in our Galaxy and nearby galaxies thanks to the all-sky coverage, but not their detailed properties due to its rather poor spatial resolution and limited spectroscopic capabilities. Spectral mapping data of individual targets provided by *SPICA* with its high spatial resolution and continuous wavelength coverage are perfect complements to the *AKARI* heritage. In this paper, we review the results obtained from our *AKARI* observations on the processing of interstellar dust grains in various environments of our Galaxy and nearby galaxies. Then we discuss our future prospect for a study of this topic using a combination of the focal-plane instruments of *SPICA*.

2. OUR GALAXY AS SEEN BY *AKARI*

Figure 1 shows a diffuse map of the Galactic plane in the *AKARI* 9 μm band, along with the spectral response curves of the *AKARI* 9 μm and 18 μm bands in comparison with those of the *WISE* bands at similar wavelengths. It is notable that the *AKARI* 9 μm band covers the major PAH emission features very efficiently. Similarly we obtain diffuse maps of the Galactic plane in the *AKARI* 18, 65, 90, 140, and 160 μm bands, which represent distributions of warm and cool interstellar dust components. The quality of those *AKARI* all-sky images has been much improved from that of the *IRAS* images.

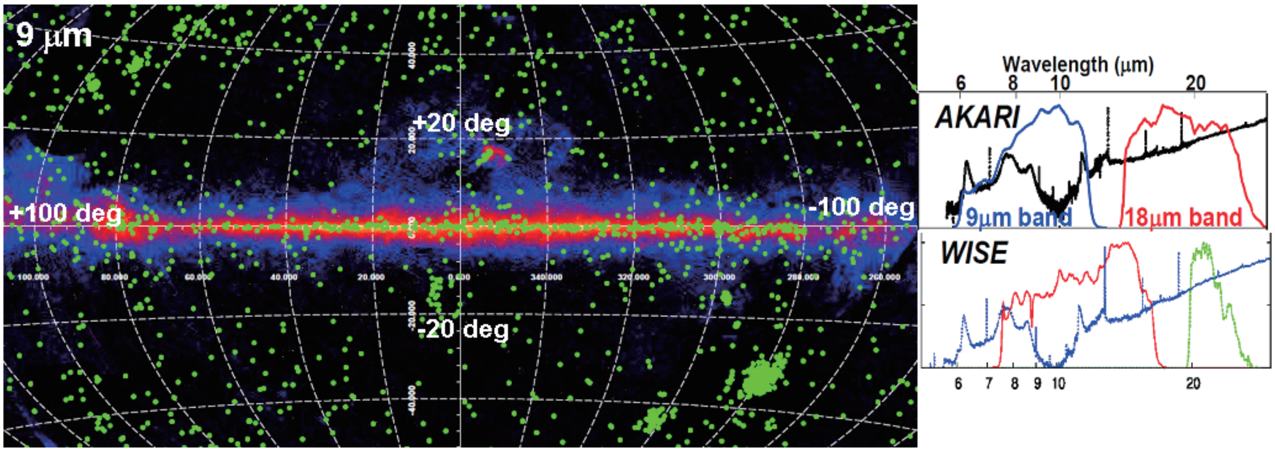

Figure 1. *AKARI* 9 μm diffuse map of the Galactic plane, shown together with the observational positions of near-IR (2–5 μm) spectroscopy. The spectral response curves of the *AKARI* 9 and 18 μm bands are shown on the right-hand side, in comparison with those of the *WISE* bands at similar wavelengths.

Utilizing the *AKARI* all-sky point-source catalogs, we identified C-rich and O-rich AGB stars, based on the color-color diagrams of the 9 and 18 μm band fluxes with the 2MASS *J*, *H*, and *K* band fluxes (Ishihara et al. 2011). As for their spatial distributions, we find that the O-rich AGBs are more concentrated toward the Galactic center, while the C-rich AGBs are rather uniformly distributed throughout the Galactic plane. From the *AKARI* diffuse maps of the Galactic plane, however, we find that interstellar PAHs and far-IR dust are similar in the spatial distribution on both global and local scales. Because it is generally thought that silicate grains, a major far-IR dust component, are supplied into the interstellar space by O-rich stars, while PAHs are produced by C-rich stars, the result indicates that products and their suppliers have different spatial distributions.

Figure 1 also shows the positions of near-IR (2–5 μm) spectroscopic observations, most of which were performed during the *AKARI* warm mission phase after the boil-off of liquid helium cryogen. In particular, the properties of hydrocarbon grains can be probed by the *AKARI* near-IR spectroscopy of the 3.3 μm main feature and 3.4–3.6 μm sub-features. Both of them are attributed to the C-H vibration mode of carbonaceous grains. The former is due to aromatic (sp^2) hydrocarbons, while the latter is probably attributed to aliphatic (sp^3) hydrocarbons (Duley & Williams 1981). They are likely to come from mixed aromatic-aliphatic organic nano-particles (Kwok & Zhang 2011). It has been believed that their intensity ratios do not vary much in the ISM. However *AKARI* reveals that they considerably change, depending on interstellar conditions, which implies structural changes of the organic matter. Those spectral variations seem to be related with the spatial variations in the ratios of the PAH to far-IR intensities which are revealed by the Galactic diffuse maps (Kaneda et al. 2012).

For study of the ISM with *SPICA*, we will select particular regions based on the *AKARI* all-sky maps (also exploiting other databases such as *Herschel*/HIGAL and *Spitzer*/GLIMPSE). Probing the properties of circumstellar and interstellar dust with spectral mapping observations, we understand the lifecycle of matter within our Galaxy.

3. NEARBY GALAXIES AS SEEN BY *AKARI*

External galaxies provide much wider ranges of physical conditions for the ISM. Among them, nearby galaxies, which are spatially resolved well with *SPICA*, are important targets to understand large-scale circulations of matter in galaxies. Figure 2 shows the distribution of the PAH emission in the starburst galaxy M 82, which is widely extended toward the halo regions. In M 82, copious amounts of large grains and PAHs are flowing out of the disk through galactic superwinds. We found that there is an excellent correlation between the PAH and Hα distributions (Kaneda et al. 2010). The spectro-polarimetry showed that Hα is significantly (5–15 %) polarized (Yoshida et al. 2011), which suggests that Hα photons from the galactic disk are scattered by PAHs in the halo. Moreover it was found that the estimated dust flow velocity decreases with the height from the disk, which implies that PAHs may be falling back toward the disk (Yoshida et al. 2011).

Using the *AKARI* near-IR spectroscopy, we clearly detect the PAH 3.3 μm emission and the 3.4–3.6 μm features in the halo regions, which are located at a distance of 2 kpc away from the galactic center, thus confirming the presence of very small PAHs even in the harsh environment of the M 82 halo (Yamagishi et al. 2012). The observed spectral properties are quite different from those commonly understood; the 3.4–3.6 μm features are unusually abundant in the halo, suggesting the dominance of aliphatic structures over aromatic ones by shattering of hydrogenated amorphous carbon grains in shocks. Hence, for nearby active galaxies, spectral mapping with *SPICA* will reveal dust processing through material circulation on a galactic scale, although M 82 is obviously too bright for *SPICA*.

PAHs and dust in elliptical galaxies provide us with another extreme case representing the end of the lifecycle of matter. With *Spitzer* and *AKARI*, we find that the PAH emission in elliptical galaxies exhibits unusual band ratios (Kaneda et al. 2008); the usually strongest 7.7 μm feature is notably weak, whereas the 3.3 μm and 11.3 μm features are relatively strong.

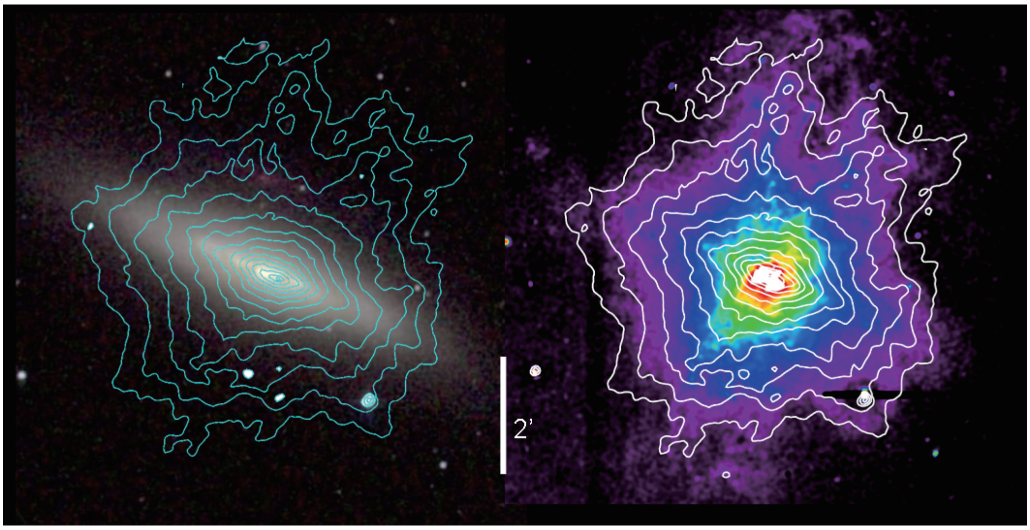

Figure 2. Contour maps of M 82 in the *AKARI* 7 μm (PAH) band overlaid on (*left*) the 2MASS *J* band and (*right*) Hα images (Kaneda et al. 2010).

We conclude that neutral PAHs, rather than ionized ones, become dominant in very soft radiation fields, typical of elliptical galaxies, which causes the faint C-C vibration features at 6–8 μm. It should be noted that the PAH 3.3 μm and 11.3 μm emission does not represent any star-forming activity in this case.

Figure 3 shows the spatial distributions of large grains and PAHs in the elliptical galaxies, NGC 4125 and NGC 4589. The distribution of the PAH 11.3 μm emission was obtained with the *Spitzer*/IRS spectral mapping observations (Kaneda et al. 2011), while that of the dust emission was obtained by the *AKARI*/FIS slow-scan observations. The figure reveals that the PAHs exist only near the galactic centers, while the large grains are distributed more widely, even considering the difference in spatial resolution. Recently we obtain the far-IR deep imaging data of these galaxies with the *Herschel*/PACS in our open time program. The lower panels in Figure 3 show the 100 μm images after optimized high-pass filtering; far-IR dust emissions in both galaxies are spatially resolved well, exhibiting distributions quite similar to PAHs. Since PAHs are likely to be old remnants originating in mass losses from intermediate-mass stars, while large silicate grains are currently being produced from low-mass old stars, this similarity may have deep physical implications for evolution of the ISM in old galaxies. A problem is that the sensitivity of *Herschel* is not high for extended emission due to high IR background from its warm telescope; The cold telescope of *SPICA* is indispensable to explore diffuse dust components in faint galaxies such as elliptical galaxies to understand the end of the lifecycle of matter.

4. FROM *AKARI* TO *SPICA*

Following *AKARI*, *SPICA* will elucidate the whole story of the evolution of solid matter (i.e. dust grains) in space. The most outstanding uniqueness of *SPICA* is high-sensitivity spectral mapping in a continuous mid- to far-IR range, which matches very well with the above *AKARI* heritage. The spectral range includes most of the fundamental vibration modes of minerals, organic matter, and ices. The continuous spectral coverage, not hampered by the atmospheric absorption, is essential to unambiguously identify relatively broad spectral features inherent to solid particles. Among the proposed instruments, the SCI (SPICA Coronagraph Instrument) is indispensable to study a small-scale structure around a central bright source. It is particularly important to investigate materials surrounding dusty AGNs in distant galaxies or young stars in nearby star-forming regions, where we can study the properties of dust grains in early Universe and in planetary formation sites, respectively. Dust grains are created and supplied into the interstellar space mostly by evolved stars through mass loss, the formation site of which could also be probed in detail by the SCI.

It is physically straightforward that the mid-IR wavelength range of *SPICA* is most suitable for detection of materials with temperatures of about 100 K. Such warm materials are often found in compact regions surrounding the central sources that heat or excite the ambient material. For example, planet-forming disks around Sun-like stars and dusty tori around typical AGNs have equilibrium temperatures of ~100 K at ~10 AU and ~100 pc, respectively, from the central sources. They correspond to a spatial scale of $1''$at distances of 10 pc and 20 Mpc for the star and AGN, respectively. Since λ/D is $0.''7$ at a wavelength of 10 μm, this spatial separation is rather too close for *SPICA*, and therefore, due to diffraction, signals from central bright sources would severely contaminate their outskirt regions which are to be studied with *SPICA*. This situation is schematically shown in Figure 4. The SCI can reconcile the mismatch between the *SPICA*'s unique spectral region and the characteristic spatial scale. Considering the balance between heating (proportional to r^{-2}) and cooling rates (proportional to T^4), the angular size of a region with temperature T increases with $T^{-1/2}$ and thus $\lambda^2_{\rm peak}$, the square of the peak wavelength of the thermal emission to be observed and spatially resolved. Since the angular resolution is degraded in proportion to $\sim \lambda/D$, coronagraphy at shorter wavelengths is much more compelling than that at longer wavelengths.

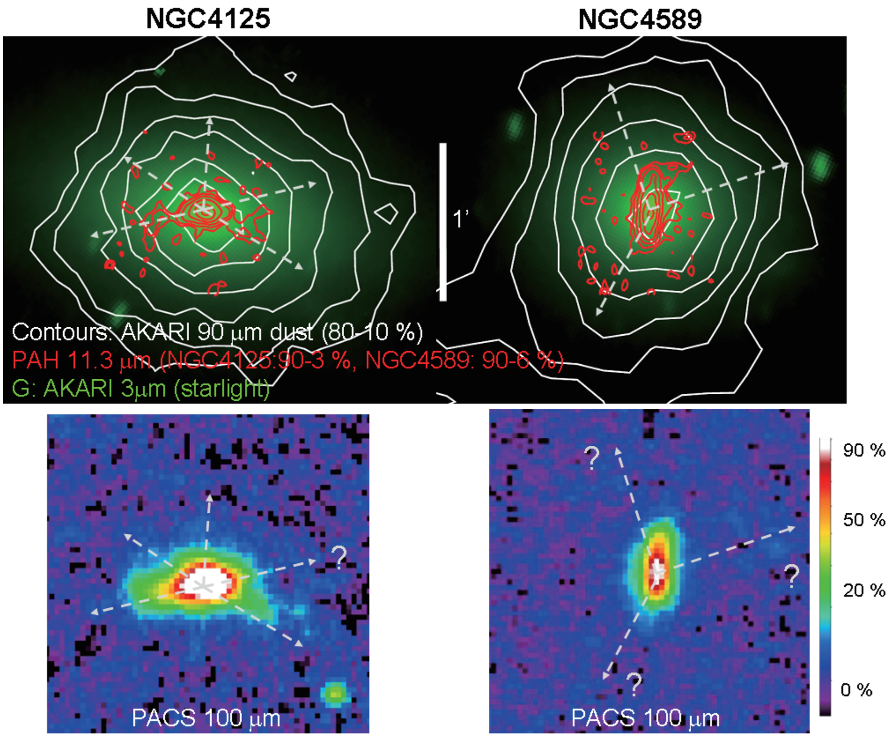

Figure 3. *Upper*: *AKARI* 90 μm band (*white contours*), *Spitzer*/IRS PAH 11.3 μm spectral mapping (*red contours*), and *AKARI* 3 μm band (*green*) images of the elliptical galaxies NGC 4125 and NGC 4589. *Lower*: The *Herschel*/PACS 100 μm maps of the same galaxies.

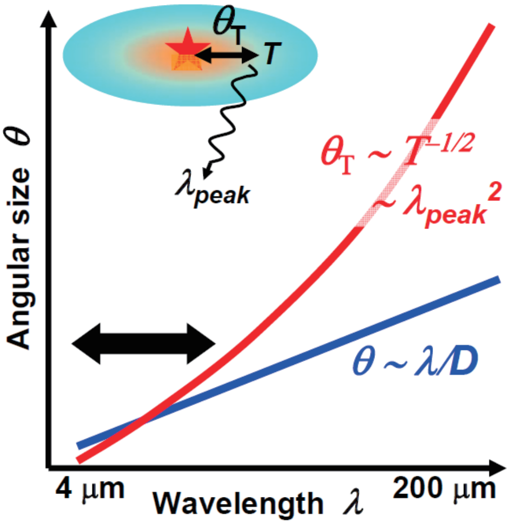

Figure 4. Schematic image to show why we need a mid-IR coronagraph to study warm materials around a central source.

5. CONCLUDING REMARKS

With the unique capabilities of all-sky survey and near-IR spectroscopy, *AKARI* reveals various phenomena about dust grains on large spatial scales in galaxies including our own. With better angular resolution and low IR background, *SPICA* will connect small- and large-scale phenomena. Spectral imaging with continuous 4–210 μm coverage will unravel the whole story of the evolution of solid matter in space from early Universe to planet formation.

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