A new approach to study dust in the haloes of nearby galaxies using mid-infrared extinction in the *AKARI*/IRC 7 and 11 μm bands

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ABSTRACT

Dust in the haloes of galaxies plays a vital role in understanding the circulation of matters on galactic scales. Despite the importance, it is difficult to detect the dust emission from the galactic haloes, even if present, due to the lack of efficient heating sources in the haloes. Here, we propose a new approach to study dust in the haloes of nearby galaxies by observing the 9.7-μm silicate absorption feature with the *AKARI*/IRC-S7 (7 μm) and S11 (11 μm) bands. We analyzed the data of the 5 nearby galaxies with moderately large inclination angles, NGC 2403, NGC 1313, NGC 6496, NGC 6951 and M 51. As a result, all the sample galaxies show the gradients of I_7/I_{11} toward the expected directions with respect to the disks. From the I_7/I_{11} maps, we estimate the masses of dust in the haloes, assuming that the dust-extinction-corrected I_7/I_{11} ratios do not have large-scale gradients over the disks of the galaxies. The result suggests that a surprisingly large amount of dust may exist in the haloes of galaxies.

Keywords: galaxies: spiral—galaxies: ISM—Galaxy: halo—ISM: dust, extinction

1. INTRODUCTION

Dust in the halo of galaxies plays a vital role in understanding the circulation of matters on a galactic scale. A significant amount of dust can be blown away from a galactic disk into a halo by star-formation activities. Subsequently halo gas is enriched with dust, eventually cools, and then falls back onto the galactic disk to form new stars. Furthermore, dust in the halo may be widespread to the intergalactic medium, which causes a large systematic uncertainty in estimating the cosmological distances of background galaxies through reddening. Such galactic-scale circulation will enrich the physical and chemical properties of galaxies over cosmic time. However, due to the lack of efficient heating sources in the galactic haloes, in general, it is difficult to directly detect the dust emission from the haloes, even if present. Accordingly, the properties of dust in galactic haloes are stilly poorly understood. Here we propose a new approach to study dust in the haloes of nearby galaxies using the mid-infrared extinction in the *AKARI*/IRC 7 and 11 μm bands.

2. METHOD

We use the 9.7 μm silicate absorption feature to measure the dust in a halo. Here we consider the polycyclic aromatic hydrocarbon (PAH) emission from a disk as a background source for the mid-IR extinction. Figure 1(a) is a schematic image showing how to measure the dust in a halo. For the purpose of detecting the 9.7 μm silicate absorption from dust in a halo, the *AKARI* 7 and 11 μm bands are the best combination, because the 11 μm band efficiently covers the silicate absorption feature while both bands are expected to be dominated by the PAH emission from a disk, as shown in Figure 1(b). For comparison, we also show the wavelength coverage of the *Spitzer* 8 μm and *WISE* 12 μm bands in Figure 1(b), which demonstrates the uniqueness of the *AKARI* 7 and 11 μm bands for this study. The PAH interband ratios are known to be relatively stable on a galaxy scale (Egusa et al. 2013) Therefore, an I_7/I_{11} map is expected to show a galactic-scale gradient along the direction of the inclination for galaxies with moderately large inclination angles. From the I_7/I_{11} maps, we estimate the masses of dust in the haloes, assuming that the dust-extinction-corrected I_7/I_{11} ratios do not have large-scale gradients over the disks of the galaxies, as described below.

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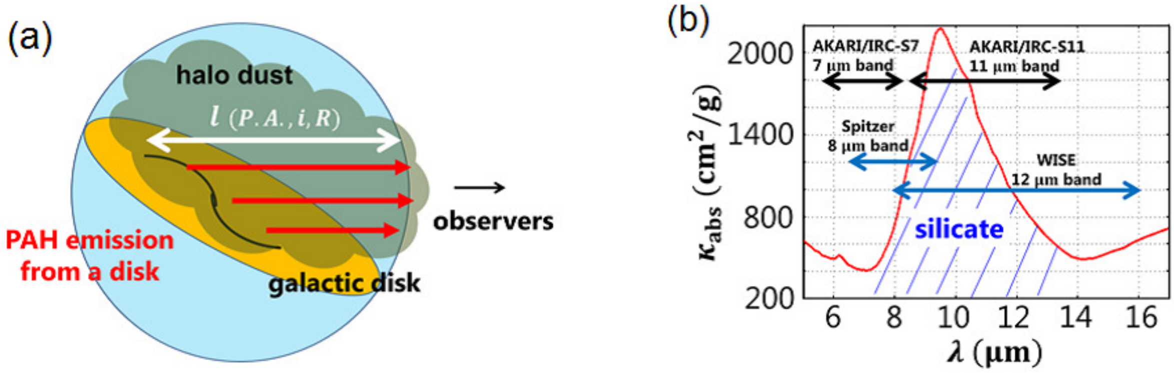

Figure 1. (a) Schematic image showing that the PAH emission from a disk is partly absorbed by the halo dust through the silicate feature. The degree of the absorption changes with the inclination angle and the distance from the rotation axis. (b) Dust mass absorption coefficient as a function of wavelength (Weingartner et al. 2001), where the ranges of the *AKARI*/IRC-S7, S11, *Spitzer*-8 μm and *WISE*-12 μm bands are overplotted.

3. DATA ANALYSIS

We verify the above method for the 5 nearby spiral galaxies NGC 2403, NGC 1313, NGC 6946, NGC 6951 and M 51 which have moderate star-formation rates ($\sim$1 $M_\odot$/yr), sufficiently large sizes for discussing galactic spatial structures ($\geq$1 arcmin) and moderately large inclinations (20 ~ 60 deg.). The *AKARI* data were taken in the ISMGN mission program (Kaneda et al. 2009). In this paper, we take NGC 2403 as an example (Table 1). Figure 2 shows the *AKARI* 7 μm and 11 μm band images of NGC 2403, where the image sizes are $10' \times 10'$. We smoothed the images with different Gaussian kernels so that the sizes of their PSFs may become the same. Then we divided the 7 μm image by the 11 μm image to obtain the I_7/I_{11} map in Figure 3. Here, we masked the region with S/N < 5 or with brightness greater than or equal to 16 MJy/sr in the *AKARI* 24 μm band image. We referred to the 24 μm image to remove star-forming regions, where the PAH interband ratios may be significantly different from typical ones.

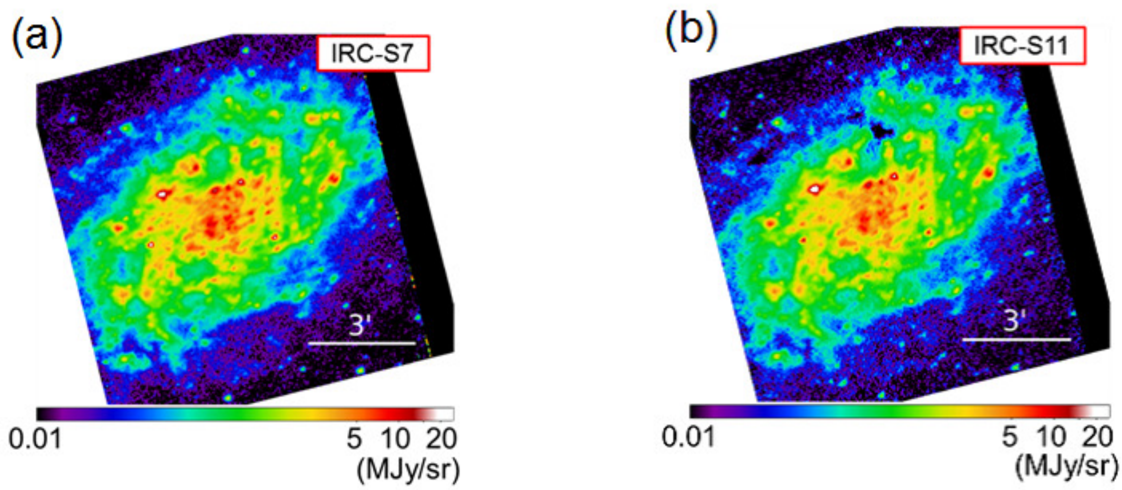

Figure 2. *AKARI*/IRC-S7(a) and S11(b) images of NGC 2403, one of our sample galaxies.

Table 1. Parameters of NGC2403

Distance (D)	3.13 ± 0.14 Mpc (Freedman et al. 2001)
Position angle (P.A.)	62.9 deg (de Blok et al. 2008)
Inclination angle	127 deg (Bendo et al. 2010)
Star formation rate	0.77 $M_\odot$ yr^{-1} (Bell et al. 2003)

4. RESULT

Figure 3 reveals the gradient of I_7/I_{11} toward the expected directions with respect to the disks (i.e., perpendicular to the P.A.). Based on the picture in Figure 1(a), we estimate the total mass of dust in the halo, using the following equations:

$$\left(\frac{I_7}{I_{11}}\right)_{\rm obs} = \left(\frac{I_7}{I_{11}}\right)_{\rm corr} \exp\left(-\left(\tau_7 - \tau_{11}\right)\right), \tag{1}$$

$$\tau_{7\,\rm or\,11} = \rho_{\rm dust}\,\kappa_{\rm abs,\,7\,or\,11}\,l, \tag{2}$$

$$M_{\rm dust} = \frac{4}{3}\pi R^3 \rho_{\rm dust}, \tag{3}$$

where $\rho_{\rm dust}$ is the dust mass per volume in a halo, l is the line-of-sight length from the disk to the edge of the halo (see Figure 1 (a)), R is the halo radius ($D \times \theta$) where D is the distance to the galaxy and θ is the angular radius of the galactic disk along the P.A. direction. We adopted $\theta = 9.5'$ which is the major axis radius in the visible light, and assumed a spherical shape. $\kappa_{\rm abs,\,7\,or\,11}$ is the dust mass absorption coefficient (Draine 2003) averaged over the wavelength range of the 7 μm or 11 μm band, where we assume that the spectrum of the background source is either Galactic-diffuse-like or flat. $\rho_{\rm dust}$ is a free parameter, and we determine $\rho_{\rm dust}$, minimizing the I_7/I_{11} gradient along the direction vertical to P.A. As a result, we obtain $\rho_{\rm dust} = (7 \pm 1) \times 10^{-27}$ $\left[\rm g\ cm^{-3}\right]$ and $M_{\rm abs} = (9 \pm 1) \times 10^7 \left(\frac{R}{5\ \rm kpc}\right)^3$ $[M_\odot]$ for the Galactic-diffuse-like background spectrum, while $\rho_{\rm dust} = (5 \pm 1) \times 10^{-27}$ $\left[\rm g\ cm^{-3}\right]$ and $M_{\rm abs} = (7 \pm 1) \times 10^7 \left(\frac{R}{5\ \rm kpc}\right)^3$ $[M_\odot]$ for the flat spectrum. Figure 4 shows the extinction-corrected I_7/I_{11} map with $\rho_{\rm dust} = (7 \pm 1) \times 10^{-27}$ $\left[\rm g\ cm^{-3}\right]$. The resultant I_7/I_{11} ratios of 0.9–1.1 are consistent with the input Galactic-diffuse-like background spectrum.

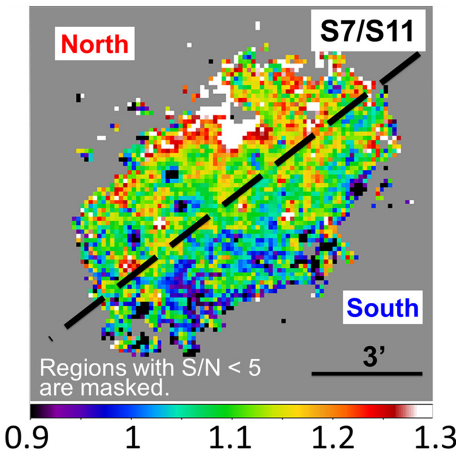

Figure 3. I_7/I_{11} map of NGC 2403. Regions with S/N < 5 are masked. The map shows a galactic-scale gradient along the inclination. The black dashed line corresponds to the major axis of the galaxy (i.e., P.A. direction).

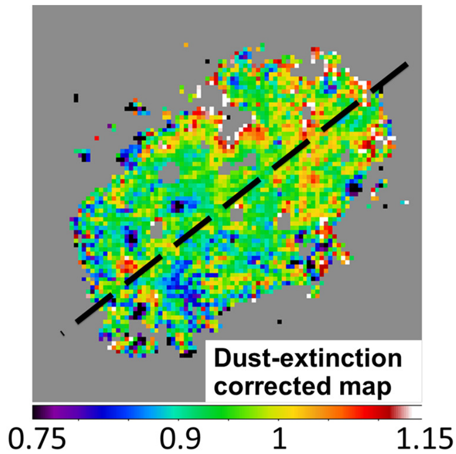

Figure 4. Same as Figure 3, but dust-extinction corrected.

5. DISCUSSION & FUTURE STUDY

We estimate the total (i.e., disk plus halo) dust mass in NGC 2403 from the far-IR and sub-millimeter emission. Using the *Herschel* PACS and SPIRE data as well as the *AKARI* FIS and IRC data, we created the spectral energy distribution (SED) of the galaxy. We fitted the SED with a two-temperature dust model, where we adopted the same $\kappa_{\rm abs}$ as in (Draine 2003) and used in the above. As a result, we obtain the total dust mass of $M_{\rm em(total)} = (7 \pm 3) \times 10^6\ M_\odot$ estimated from the emission, which is one order of magnitude lower than $M_{\rm abs} = (9 \pm 1) \times 10^7 \left(\frac{R}{5\ \rm kpc}\right)^3$ $[M_\odot]$ estimated from the absorption. One possibility is the presence of very cold dust in the halo which is missed in the SED fitting. Another possibility is that the dust in the halo has the properties much different from dust in galactic disks. In a separate paper, we will make detailed discussions and also report the results of the other galaxies.

6. SUMMARY

Dust in the haloes of galaxies plays a vital role in understanding the circulation of matters on galactic scales. Despite the importance, it is difficult to detect the dust emission from the galactic haloes. Here, we propose a new approach to study dust in the haloes of nearby galaxies by observing the 9.7-μm silicate absorption feature with the *AKARI* 7 μm and 11 μm bands. We analyzed the data of the 5 nearby spiral galaxies NGC 2403, NGC 1313, NGC 6946, NGC 6951 and M 51 which have moderately large inclination angles. As a result, all the sample galaxies show the gradients of I_7/I_{11} toward the expected directions with respect to the disks. We estimate the total masses of dust in the haloes ($M_{\rm abs}$) from the I_7/I_{11} maps. For NGC 2403, we also estimate the total dust mass in the galaxies from the far-IR and sub-millimeter emission ($M_{\rm em}$). Consequently we find that $M_{\rm abs}$ is one order of magnitude higher than $M_{\rm em}$. One possibility is the presence of very cold dust in the halo which is too cold to emit the thermal radiation. Another possibility is that the dust in the halo has the properties much different from dust in galactic disks.

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