AKARI DETECTION OF FAR-INFRARED DUST EMISSION IN THE HALO OF NGC 253

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Received 2009 March 31; accepted 2009 May 12; published 2009 June 1

ABSTRACT

We present new far-infrared (FIR) images of the edge-on starburst galaxy NGC 253 obtained with the Far-Infrared Surveyor (FIS) onboard AKARI at wavelengths of 90 \(\mu\text{m}\) and 140 \(\mu\text{m}\). We have clearly detected FIR dust emission extended in the halo of the galaxy; there are two filamentary emission structures extending from the galactic disk up to 9 kpc in the northern and 6 kpc in the northwestern direction. From its spatial coincidence with the X-ray plasma outflow, the extended FIR emission is very likely to represent outflowing dust entrained by superwinds. The ratios of surface brightness at 90 \(\mu\text{m}\) to that at 140 \(\mu\text{m}\) suggest that the temperatures of the dust in the halo are getting higher in the regions far from the disk, implying that there exist extra dust heating sources in the halo of the galaxy.

Key words: galaxies: halos – galaxies: individual (NGC 253) – galaxies: starburst – infrared: galaxies – ISM: jets and outflows

1. INTRODUCTION

Starbursts are important mechanisms not only for chemical processing of elements, but also as sources of material fed into intergalactic space. Massive starburst phenomena, i.e., supernova explosions and energetic stellar winds, can drive gas from the disks of host galaxies to their halos, which are observed for many local starburst galaxies as superwind or X-ray-emitting hot plasma accelerated along the minor axes (e.g., Lehnert & Heckman 1996). The outflowing hot plasma may be capable of entraining cold neutral dust-bearing gas to a substantial height above the galactic disk, the mechanism of which is still poorly understood. Dust grains are indeed found to spread in the vertical directions at optical wavelengths over larger scales than was thought (Rossa et al. 2004; Dettmar 2005); dust grains should be strongly coupled to magnetic fields once they are charged, and thus could be trapped in the disk region. Grain destruction in the hot halo environment may also prevent such an expulsion (Ferrara et al. 1991). Whether the dust can escape or not is an important question, because this would enrich the intergalactic medium with dust, which could affect observations of high-redshift objects (e.g., Heisler & Ostriker 1988; Davies et al. 1998). The dust expulsion from a galaxy would also play an important role in galactic chemical evolution acting as a sink for heavy elements (e.g., Eales & Edmunds 1996). However, no comprehensive view has been observationally established for the vertical distribution of dust grains in disk galaxies. This is largely owing to a lack of spatially resolved sensitive far-infrared (FIR) images of external galaxies.

NGC 253 is one of best local laboratories to investigate the vertical distribution of such extraplanar dust due to its proximity (distance: 3.5 ± 0.2 Mpc; Rekola et al. 2005), nearly edge-on orientation (inclination angle: 78.5°; Pence 1980), and strong nuclear starburst (Dudley & Wynn-Williams 1999). The halo of NGC 253 has been studied at various wavelengths (e.g., X-ray: Dahlem et al. 1998; Pietsch et al. 2000; Strickland et al. 2002; Bauer et al. 2008; UV: Hoopes et al. 2005; Hα: Hoopes et al. 1996; HI: Boomsma et al. 2005). FIR observations are crucial to look for evidence of the dust outflow since dust emission typically peaks in the FIR. The nuclear source is, however, extremely strong in the FIR, which severely affects the detection of faint extended emission outside the disk. For the IRAS observation of NGC 253, Rice (1993) and Alton et al. (1998) concluded that instrumental effects masked low-level FIR emission outside the disk. With the Infrared Space Observatory (ISO), Rodovich et al. (2001) and Melo et al. (2002) studied the spatial distribution of the FIR emission in NGC 253, where they detected FIR excess emission along the minor axis. Its spatial structures were, however, somewhat controversial mainly due to the poor spatial resolution, and the central peak of the galaxy was saturated (Melo et al. 2002). Spitzer observed NGC 253, the FIR distribution of which is not yet reported in any paper; we find that the Multiband Imaging Photometer for Spitzer (MIPS) archival data show strong artifacts and severe signal saturation in the 70 \(\mu\text{m}\) and the 160 \(\mu\text{m}\) bands, respectively. From submillimeter observations of the nuclear region of NGC 253, Alton et al. (1999) found evidence for a dust outflow along the minor axis at 450 \(\mu\text{m}\) on a small scale \(\lesssim 45''\). Tacconi-Garman et al. (2005) and Sugai et al. (2003) detected extraplanar polycyclic aromatic hydrocarbon (PAH) and H\textsubscript{2} emissions, respectively, both on small scales of \(\sim 10''\) along the minor axis.

We performed FIR observations of NGC 253 with the Far-Infrared Surveyor (FIS; Kawada et al. 2007) onboard AKARI (Murakami et al. 2007). The fundamental advantage the AKARI/FIS offers over any other previous or currently existing instruments is a combination of its high saturation limits, high sensitivity, and relatively high spatial resolution, which is essential for detecting faint FIR dust emission extending to the halo of an edge-on starburst galaxy. Hence the AKARI/FIR images of NGC 253 are expected to be much less affected by very strong nuclear emission of the galaxy than those previously obtained with IRAS and ISO.

2. OBSERVATIONS

We observed NGC 253 with the AKARI/FIS in part of the AKARI mission program “ISM in our Galaxy and Nearby Galaxies” (ISMGN; PI: H. K.). The observation log is listed in Table 1. The FIS observation was performed in the special fast reset mode called Correlated Double Sampling (CDS) mode in order to avoid signal saturation near the nuclear region of the galaxy. Thus fluxes were later cross-calibrated with the other ordinary integration modes by using the internal calibration.
lamps of the FIS. A 10′ × 30′ region was covered by using one of the FIS observation modes, FIS01, a 2-round-trip slow scan with a scan speed of 15″ s−1 and a cross-scan step of 240″ between the first and the second round trip. Due to limited visibility to AKARI, NGC 253 could be observed with the FIS only once, and therefore we could not cover the whole disk of the galaxy; the scan passed the central part of the galaxy and the scan direction is nearly parallel to the minor axis.

The FIR images were processed from the FIS Time Series Data (TSD) by using the AKARI official pipeline developed by the AKARI data reduction team (Verdugo et al. 2007). The images were further cleaned by removing the aftereffects of cosmic-ray hits and the latency of the illumination of the internal calibration lamps with the algorithm developed in Suzuki (2007) and Suzuki et al. (2009), where the correction for the variations of detector responsivity was also performed. Any residual nonuniformity of the responsivity within the detector arrays was carefully removed by assuming spatially flat blank skies near both ends of the scan, which are far enough from the galactic disk.

With the FIS, we obtained N60 (centered at a wavelength of 65 μm with the effective band width of 22 μm), WIDE-S (90 μm with 38 μm), WIDE-L (140 μm with 52 μm), and N160 (160 μm with 34 μm) band images. The two narrowbands, N60 and N160, however, suffer ghost image problems originating from the very bright central source (Kawada et al. 2007). They also have relatively low S/Ns for detecting halo emission. Since our purpose is to firmly detect dust in the halo and estimate its temperature and mass, but not to discuss the spectral energy distribution of the dust emission, we below concentrate on the results of the two widebands, WIDE-S and WIDE-L, for which 5σ detection limits in the above observation mode are 0.7 and 1.2 Jy, respectively. Nevertheless, the nuclear source was so extremely bright that it may have been somewhat affected by instrumental effects. Hence, in this Letter, we do not discuss any detailed spatial structure of FIR emission near the nuclear region.

### 3. RESULTS

Figure 1 shows the WIDE-S (90 μm) and WIDE-L (140 μm) images of NGC 253 obtained with the AKARI/FIS. Note that the spatial coverage of the WIDE-S image is relatively small and shifted as compared to that of the WIDE-L image due to the difference in the field of view between the corresponding detector arrays. The background sky levels are estimated by averaging surface brightness of nearby blank sky in four regions with the area of 95″ × 95″ for each, where two in the south and two in the north with respect to the disk are selected to avoid any overlap with faint extended emission from the galaxy, and then subtracted from the images. Background fluctuation levels are also estimated from these regions, which are approximately 0.6 MJy str−1 for both band images. We have applied boxcar smoothing with the width of 57″ to both band images in order to bring out low surface brightness emission in the halo. The resultant spatial resolution is still significantly higher than the actual resolution (∼ 180″) of the ISO map of NGC 253 (Melo et al. 2002).

As can be seen in the figure, we clearly detect FIR dust emission extended in the halo of the galaxy at both wavelengths. In the 90 μm image, there are two filamentary components extending from the galactic disk up to 9′ or 9 kpc and 6′ or 6 kpc by adopting the distance of 3.5 Mpc (Rekola et al. 2005), in the northern and northwestern directions; the former is clearly seen also in the 140 μm image. The ISO image showed excess emission in the northern direction, probably corresponding to the former component (Radovich et al. 2001). However, we do not see any star-like patterns centered at the nucleus as seen in the IRAS and ISO images (Radovich et al. 2001). Instead, dust halo emission is highly suppressed in the southern part of the galaxy, and thus there is a significant difference in the spatial distribution of dust emission between the northern and southern halo regions.

In Table 2, we derive the flux densities of the center, halo 1, and halo 2 regions, the positions of which are given in Figure 1, by integrating the surface brightness within a circular aperture diameter of 4″ in each band image of Figure 1. Since the aperture size is sufficiently large, we do not consider aperture corrections. Instead we consider the flux uncertainties including both systematic effects associated with the FIR detectors and absolute calibration uncertainties, which are estimated to be no more

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**Table 1**

| Name     | R.A. (J2000) | Decl. (J2000) | Observation ID | Date       |
|----------|--------------|--------------|---------------|------------|
| NGC 253  | 0 47 33.1    | −25 17 17.5  | 1402148       | 2007 Jun 21|

**Notes.** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
than 20% for WIDE-S, and 30% for WIDE-L (Kawada et al. 2007). The values obtained with the AKARI/FIS in Table 2 show overall agreements with the IRAS and ISO results (Radovich et al. 2001); as for the flux densities in the center region, our results show slightly higher values than those with IRAS and ISO, even though the latter fluxes were obtained with twice larger aperture size (8’). For ISO, the discrepancy will be probably due to the effect of the signal saturation (Melo et al. 2002).

For the emissivity power-law index of $\beta = 1$, the ratios of the WIDE-S to the WIDE-L flux density correspond to the temperatures of FIR dust of 31 K, 20 K, and 23 K for the center, the halo 1, and the halo 2 region, respectively, which are averaged over the circular aperture of the diameter of 4’. We calculate dust mass by using the equation (e.g., Hildebrand 1983)

$$M_d = \frac{4\pi\rho D^2}{3} \frac{F_\nu}{Q_\nu B_\nu(T)},$$

(1)

where $M_d$, $D$, $a$, and $\rho$ are the dust mass, the galaxy distance, the average grain radius, and the specific dust mass density, respectively. $F_\nu$, $Q_\nu$, and $B_\nu(T)$ are the observed flux density, the grain emissivity, and the value of the Planck function at the frequency of $\nu$ and the dust temperature of $T$. We adopt the grain emissivity factor given by Hildebrand (1983), the average grain radius of 0.1 $\mu$m, and the specific dust mass density of 3 g cm$^{-3}$. We use the 90 $\mu$m flux densities in Table 2 and the above dust temperatures. The dust masses thus derived from the halo 1 and halo 2 regions are 1.1 x $10^5$ $M_\odot$ and 9.1 x $10^4$ $M_\odot$, respectively.

Figure 2 gives the ROSAT/PSPC X-ray (0.1–2.4 keV) contour map of NGC 253 overlaid on the WIDE-S (90 $\mu$m) image with the same color levels as in Figure 1. The contours are drawn at surface brightness levels of 1.6, 3.0, 4.4, 5.8, 9.3, and 12.8 x $10^{-3}$ counts s$^{-1}$ arcmin$^{-2}$. Bottom: HI contours overlaid on an Hα image, same as Figure 3 of Boomsma et al. (2005), but with the circular apertures in Figure 1 added.
sputtered away at the same rate as in the above homogeneous scenario (e.g., Tacconi-Garman et al. 2005).

There appears to be a difference between WIDE-S (90 \( \mu \)m) and WIDE-L (140 \( \mu \)m) in spatial structure of the dust halo emission (Figure 1), which suggests that the dust temperature is not uniform in the halo. In Figure 3, we calculate the ratios of surface brightness at 90 \( \mu \)m to that at 140 \( \mu \)m. We adjust the peak positions of the images precisely by interpolating data between pixels so that they can coincide within the accuracy of 1\( \arcsec \) before the calculation. In dividing the images, we use the heavily smoothed images of Figure 1, whereby we reduce the effects of differences in the beam size between the WIDE-S (FWHM: 39\( \arcsec \)) and WIDE-L (58\( \arcsec \)) bands (Kawada et al. 2007). The area in the WIDE-L image with brightness levels lower than 4.0 MJy str\(^{-1}\) is about seven times larger than the above background fluctuation is masked. As a result, the ratio map in Figure 3 reveals that the temperatures of the dust in the halo are significantly lower than those in the nuclear and disk regions. More interestingly, the ratio map suggests that the temperatures of the dust in the halo 1 and halo 2 regions are getting higher in the regions far away from the disk. By assuming \( \beta = 1 \), again, the maximal ratios correspond approximately to the dust temperatures of 48 K for the center region, 33 K for the halo 1, and 31 K for the halo 2 regions, while the dust temperatures elsewhere in the halo are below 20 K. Uncertainties in the temperature for the halo 1 and halo 2 regions originating from the errors of surface brightness are about 2 K, and thus the increase in the temperature is significant.

The excess dust in the halo is more or less heated by stellar UV photons propagating up from the disk of NGC 253. Figure 3 implies that there exist extra dust heating sources in the halo of the galaxy in addition to the stellar photons coming from the disk. As seen in Figure 2, the high-temperature region in the halo 1 of Figure 1 spatially corresponds to the border between the HI plume (Boomsma et al. 2005) and the X-ray halo emission (e.g., Bauer et al. 2008), which may reflect that the dust in the halo 1 is heated by shock through interaction between the X-ray superwind and pre-existing HI halo clouds as proposed by the model (a) of Strickland et al. (2002). In contrast, no corresponding HI structures have been found near the high-temperature region in the halo 2 (Figure 2), and thus we may have to seek another heating mechanism for the dust in this region, where there is enhancement in the X-ray emission; one possibility is that the dust may be heated up to higher temperatures through collisions with plasma electrons (Dwek 1986).

**Figure 3.** WIDE-S (90 \( \mu \)m)/WIDE-L (140 \( \mu \)m) ratio map of NGC 253 overlaid on the WIDE-S contour map with the same contour levels as in Figure 1.

4. CONCLUSIONS

With the AKARI/FIS, we clearly detect FIR dust emission extended in the halo of the edge-on starburst galaxy NGC 253. We find that there are two filamentary emission structures extending from the galactic disk up to 9 kpc in the northern and 6 kpc in the northwestern direction. From its spatial coincidence with the X-ray plasma outflow, the extended FIR emission is very likely to represent outflowing dust entrained by superwinds. The temperatures of the dust in the halo are getting higher in the regions far away from the disk, implying that there exist extra dust heating sources in the halo of the galaxy other than stellar UV photons from the disk.

We thank all the members of the AKARI projects, particularly those belonging to the working group for the ISMGN mission program. We also express many thanks to the anonymous referee for giving us useful comments. AKARI is a JAXA project with the participation of ESA. This research is supported by the Grants-in-Aid for the scientific research No. 19740114 and the Nagoya University Global COE Program, “Quest for Fundamental Principles in the Universe: from Particles to the Solar System and the Cosmos,” both from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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