Near-infrared to Mid-infrared Observations of Galaxy Mergers: NGC 2782 and NGC 7727

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Abstract

We present the results of near-infrared-to-mid-infrared (NIR-to-MIR) imaging and NIR spectroscopic observations of two galaxy mergers, NGC 2782 (Arp 215) and NGC 7727 (Arp 222), with the Infrared Camera on board AKARI. NGC 2782 shows extended MIR emission in the eastern side of the galaxy, which corresponds to the eastern tidal tail seen in the H1 21 cm map, while NGC 7727 shows extended MIR emission in the north of the galaxy, which is similar to the plumes seen in the residual image at the K-band after subtracting a galaxy model. Both extended structures are thought to have formed in association with their merger events. They show excess emission at 7–15 μm, which can be attributed to emission from polycyclic aromatic hydrocarbons (PAHs), while the observed spectral energy distributions (SEDs) decline longward of 24 μm, suggesting that very small grains (VSGs) are deficient. These characteristics of the observed MIR SED may be explained if PAHs are formed by fragmentation of VSGs during merger events. The star formation rate is estimated from the MIR PAH emission in the eastern tail region of NGC 2782 and it is in fair agreement with those estimated from Hα and [C II] 158 μm. MIR observations are efficient for the study of dust processing and structures formed during merger events.

Key words: galaxies: individual (NGC 2782, NGC 7727) – galaxies: interactions – galaxies: star formation – infrared: galaxies

1. Introduction

Dust grains retain most of the heavy elements and play significant roles in the thermal balance and chemistry in the interstellar medium (ISM). Thermal emission in the far-infrared (FIR) from submicron-sized dust is often used as a useful measure for the star formation rate (SFR) for the optically thick case (Kennicutt 1998), while the SFR is also known to correlate well with the strengths of the emission features in the mid-infrared (MIR, e.g., Peeters et al. 2004; Pope et al. 2008; Shipley et al. 2016), whose major bands appear at 3.3, 6.2, 7.7, 8.6, 11.3, and 16.4 μm. They are thought to originate from very small carbonaceous dust that contains polycyclic aromatic hydrocarbons (PAHs; Tielens 2008) or PAH-like atomic groups, while alternative carriers, such as quenched carbonaceous composites (QCCs, Sakata et al. 1984) or mixed aromatic-aliphatic organic nanoparticles (MAONs, Kwok & Zhang 2011), have also been proposed. In the following, we call these emission features PAH features and the carriers PAHs.

The formation and destruction as well as lifecycle of dust grains in galaxies are vital for understanding star formation and the evolution of galaxies. The properties and the formation/destruction processes of the carriers of the PAH features are of particular interest because they are so conspicuous in the MIR and the relative band ratios should be useful to study the physical conditions of the environment from which the emission features arise (Draine & Li 2001; Tielens 2008). While several theoretical studies have been carried out (e.g., Dwek & Scalo 1980; Jones & Nuth 2011), few have observed the lifecycles of dust grains in the ISM. It still remains unclear where the carriers of the PAH features are formed. They may be formed in carbon-rich stars (Galliano et al. 2008a; Paradis et al. 2009) or in dense clouds (Herbst 1991; Sandstrom et al. 2010). Recent observations with AKARI and SOFIA suggest that PAHs are also formed by fragmentation of large carbonaceous grains in shocks associated with a supernova, a galactic wind, or an outflow from a planetary nebula (Onaka et al. 2010b; Seok et al. 2012; Lau et al. 2016).

The PAH features have been detected not only in the disks of galaxies, but also in the halos of galaxies. Engelbracht et al. (2006) and Beirão et al. (2008) reported detection of PAH emission in the halo of M82. Kaneda et al. (2010) suggested that PAHs have been expelled both by the superwind and the galaxy interaction from the disk of M82. The survival of PAHs in such harsh environments is another interesting issue for the study of the lifecycle and destruction of PAHs (e.g., Micelotta et al. 2010b). The PAH features in galaxy halos seem to have a lower 7.7–11.3 μm band ratio than that in galactic disks (Irwin & Madden 2006; Galliano et al. 2008b). A similarly small ratio is also indicated in the interarm region (Sakon et al. 2007), as well as in a filamentary structure associated with the galactic wind (Onaka et al. 2010b). The small ratio may be attributed to the processing of the band carriers in these tenuous regions or it could be related to their formation process. Observations of the PAH features in extended structures in galaxies are thus important for the study of dust processing.

In this paper, we report the results of near-infrared (NIR) to MIR observations of two galaxy mergers, NGC 2782 (Arp 215) and NGC 7727 (Arp 222), with the Infrared Camera...
Table 1
IRC Observation Log

| Source Name | Mode | Pointing ID | AOT\(^a\) | Observation Date |
|-------------|------|-------------|-----------|-----------------|
| NGC 2782    | imaging (3.2, 4.1, 7, 11 \(\mu\)m) | 1400452.1 | IRC02 a:N | 2006 Oct 31     |
|             | imaging (15, 24 \(\mu\)m) | 1401038.1 | IRC02 a:L | 2007 Apr 29     |
|             | spectroscopy (2.5–5.0 \(\mu\)m) | 1420364.1 | IRCZ4       | 2009 Apr 28     |
|             | spectroscopy (2.5–5.0 \(\mu\)m) | 1420364.2 | IRCZ4       | 2009 Apr 28     |
| NGC 7727    | imaging (3.2, 4.1, 7, 11 \(\mu\)m) | 1402685.1 | IRC02 a:N | 2007 Jun 11     |
|             | imaging (15, 24 \(\mu\)m) | 1402686.1 | IRC02 a:L | 2007 Jun 11     |
|             | spectroscopy (2.5–5.0 \(\mu\)m) | 1420386.1 | IRCZ4       | 2008 Dec 11     |

Note.
\(^a\) See Onaka et al. (2007a) and Onaka et al. (2009) for details on the AOTs in the cold and warm mission phases, respectively.

(IRC) on board AKARI (Onaka et al. 2007a) to study the properties of dust grains associated with extended structures produced by merger events and their possible processing in violent conditions.

NGC 2787 is a spiral galaxy classified as Sa(s) Peculiar (Sandage & Tammann 1981) or as SAB(s)a Peculiar by de Vaucouleurs et al. (1991) at a distance of 39.5 Mpc (Kniernan et al. 2013). It is a minor merger with an age of 200–300 Myr (Smith 1994; Kniernan et al. 2013). NGC 2782 shows long tidal tails extending both in the west and east directions on the H\(\alpha\) map (Smith 1994). A tidal dwarf galaxy candidate (TDGC) was discovered in the eastern side of the galaxy (Yoshida et al. 1994). It harbors a starburst both in the central and circumnuclear regions (Jogee et al. 1999). Gas motion in the central part of the galaxy is studied in detail by interferometric CO observations (Hunt et al. 2008). NGC 2782 was originally classified as a Seyfert galaxy, but no direct sign of an AGN had been obtained (Boer et al. 1992) until recent X-ray observations found clear evidence for the presence of a low-luminosity AGN (Tzanavaris & Georgantopoulos 2007; Bravo-Guerrero & Stevens 2017). Star formation in the tidal tails was studied extensively based on observations of CO (J = 1–0), H\(\alpha\), and [C II] 158 \(\mu\)m (Smith et al. 1999; Kniernan et al. 2013).

NGC 7727 is also a merger at a distance of 25 Mpc and an age of 1.3 Gyr old (Georgakakis et al. 2000). It is classified as Sa Peculiar by Sandage & Tammann (1981) and SAB(s)a Peculiar by de Vaucouleurs et al. (1991). The K-band image suggests plumes extending to the north of the galaxy from the nucleus (Roerberg & Joseph 2004). We present the results of IRC NIR-to-MIR imaging observations of the two galaxies, as well as NIR spectroscopy of the central regions of both galaxies. Star formation in interacting galaxies has been extensively studied in the IR (e.g., Smith et al. 2007; Brassington et al. 2015). In this paper, we concentrate on the dust properties in extended structures in the two galaxies.

2. Observations and Data Reduction

The AKARI/IRC imaging observations of NGC 2782 and NGC 7727 were carried out as part of the mission program “ISM in our Galaxy and nearby galaxies” (ISMG, Kenada et al. 2009) in the cryogenic mission phase. The observations were made with the two-filter modes of the IRC, 10’’ × 10’’ images at bands N3 (3.2 \(\mu\)m), N4 (4.1 \(\mu\)m), S7 (7 \(\mu\)m), and S11 (11 \(\mu\)m) were obtained with the AOT IRC02 a:N in the same pointing observation, while images at bands L15 (15 \(\mu\)m) and L24 (24 \(\mu\)m) were obtained with AOT IRC02 a:L in a different pointing observation. Details of the operations of both AOTs are given in Onaka et al. (2007a). NIR IRC spectroscopy of the two galaxies was carried out in the warm mission phase of AKARI with the grism mode (AOT: IRCZ4 b:Ns), which provided long-slit spectroscopy of a 5'' × 40'' area for 2.5–5.0 \(\mu\)m with a spectral resolution of about 0.03 \(\mu\)m (Ohyama et al. 2007). The performance of the IRC in the warm mission phase is given in Onaka et al. (2010a). A log of the present observations is summarized in Table 1.

The imaging data were processed by the data reduction toolkit for the IRC imaging version 20110304. Then, we corrected for the effects of array anomalies in the NIR images (N3 and N4), such as muxbleed and column pulldown, with our own developed software, which subtracts fitted polynomial functions from the data of the affected rows and columns (cf., Carey et al. 2006). For the MIR images (S7, S11, L15, and L24), we applied the Richardson–Lucy method with noise suppression using the wavelet transform (Richardson 1972; Lucy 1974; Starck & Murtagh 1994) to reduce the noise and restore the images, taking into account the point spread functions (PSFs) of each filter band. Then, the restored MIR images were convolved with a Gaussian to have the same FWHM of 7''. Finally, we took a median of the emission outside of the galaxy and associated extended structures as the sky background, and subtracted it from the observed image. The uncertainty in the estimate of the sky background is included in the photometry error.

NIR spectroscopy was made toward the center of the galaxy. Due to the pointing accuracy of AKARI, the actual positions at which spectroscopic observations were made were slightly off the center (see Section 3 and Table 2). The data were processed by the data reduction toolkit for the phase 3 (warm mission phase) IRC spectroscopy version 20160324, which included the latest wavelength calibration (Baba et al. 2016). The spectrum was extracted for the brightest part of an area of 5'' × 8'' (6 pixels in the slit direction) in the slit for each galaxy. The central positions of the spectra are listed in Table 2 and the spectrum-extracted areas are indicated by the white rectangles in Figures 3 and 6. For NGC 2782, we have taken spectra with two pointing observations at slightly different positions (~1''). The flux levels are slightly different, but the spectral shapes are almost the same. We scale the fainter spectrum (Pointing ID: 1420364.1) to the brighter one (Pointing ID: 1420364.2) and co-add them together to reduce the noise. The position in Table 1 refers to the spectrum extracted from the data of 1420364.2. NGC 7727 was observed only once.

In addition to the IRC observations, we retrieved Spitzer/Infrared Spectrograph (IRS) data of NGC 2782 from the Combined Atlas of Sources with Spitzer/IRS Spectra (CASSIS;
3. Results

3.1. NGC 2782

NIR-to-MIR 6-band IRC images of the central part ($5' \times 5'$) of NGC 2782 are shown in Figure 1. The NIR images of N3 and N4 (Figures 1(a) and (b)) both clearly show extended emission in the eastern side of the galaxy, which is also seen in optical images (Smith 1994). In the MIR images of the galaxy (Figures 1(c)–(f)) it is invisible, suggesting that this extended structure consists only of stellar components without dust. In fact, no gas emission has been detected in this region. It is likely a stellar remnant of the minor galaxy that passed through the major galaxy with its interstellar materials being stripped off (Smith 1994).

The images at the bands S7, S11, and L15 show an arc-like bright emission structure in the western side of the galaxy (see also Figure 3), which is also seen as one of the ripples in optical images (Smith 1994; Jogee et al. 1999). In the N3 and N4 images, the emission of the stellar disk overlaps with the arc-like ripple structure, but it can still be recognized. It becomes faint in the L24 image. In addition to the ripple, the S7 and S11 images show extended emission in the eastern side of the galaxy. We call it the tail structure. The tail structure is not seen in the N3 and N4 images, suggesting that it is not associated with stellar emission, but comes from the ISM of the galaxy.

To show the tail structure more clearly, an artificial color image of N3 in blue and S7 in green was created as shown in Figure 2, onto which the red contours of H I 21 cm intensity are superposed (Smith 1994). The H I 21 cm data show a very long tail in the western side, at which the IR emission is not detected, and a relatively compact tail in the eastern side, which nicely delineates the tail structure seen at S7 (green color). Since both H I tails must have been formed by the collision event, the tail structure seen at S7 and S11 is inferred to have also been formed together with the eastern H I tail during the collision event. Further east, the stellar remnant is clearly seen only at N3 (blue color). The white color of the center and ripple regions suggests that they are bright both at N3 and S7.

Figure 3 shows an enlarged S7 image to indicate these structures clearly. The blue dashed rectangles in the tail structure indicate the locations of massive H I clouds, as well as the TDGC (Smith 1994; Kniereim et al. 2013). The emission at S7 shows good correlation with the regions of massive H I clouds. There may be an enhancement in S7 even at the position of the TDGC. Figure 3 also suggests that the emission at S7 becomes strong along the optical dust lanes (Jogee et al. 1999) that are indicated by the black straight dashed lines.

Figure 4 shows the NIR and MIR spectra of the central part of NGC 2782. Note that the units of the spectra are different; the NIR spectrum (Figure 4(a)) is in units of MJy sr$^{-1}$, while the spectra in Figure 4(b) and (c) are in units of Jy, for which the source sizes are assumed as described in Section 2. The NIR spectrum (Figure 4(a)) is extracted from the white rectangle in Figure 3 and the MIR spectra are taken nearly at the center of the galaxy (Table 2). The observed positions of each spectrum are not exactly the same, thus a relative comparison of the spectra requires discretion. The NIR spectrum clearly shows the presence of the PAH 3.3 $\mu$m band as well as the emission from aliphatic C-H bonds at 3.4 $\mu$m. The emission of H I Br$\alpha$ at 4.05 $\mu$m is barely seen, but no other gas emission features are detected. In the IRS SL spectra, the PAH features at 6.2, 7.7, 8.6, and 11.3 $\mu$m are clearly seen in both compact and extended components (Figure 4(b)). The [Ne II] 12.8 $\mu$m overlaps with the PAH 12.7 $\mu$m feature. The compact component is slightly brighter than the extended component up to around 12 $\mu$m, above which the flux of the compact component sharply increases. In the IRS LL spectra, the PAH 17 $\mu$m complex, [Ne III] 15.6 $\mu$m, [S II] 18.7 and 33.5 $\mu$m, and [Si II] 34.8 $\mu$m are seen in both components. The compact component is relatively brighter in the ionized gas lines, while the extended component has relatively brighter [Si II], suggesting the dominance of emission from photo-dissociation regions (PDRs). There seems to be no clear sign of the presence of an AGN, such as strong [Ne V] 14.3 $\mu$m or [O IV] 26 $\mu$m emission, in both spectra (Armus et al. 2007; Farrah et al. 2007). The upper limits of both line intensities relative to the [Ne II] 12.8 $\mu$m intensity are estimated as about 20%, which suggests that the AGN contribution to the MIR emission is less than 10% (Petric et al. 2011). The presence of an AGN is not confirmed by the present spectroscopy.
3.2. NGC 7727

Figure 5 shows 6-band IRC images of the central part (5′ × 5′) of NGC 7727. Compared to NGC 2782, the flux is concentrated at the galaxy center. In the S7 image, plume-like structures appear in the northern side of the galaxy (see also Figure 6), which...
becomes clearer in the S11 image. In the L15 image, the structures become fainter, but their trace is still visible. They almost fade away at L24. In the N3 and N4 images, part of the plumes are barely seen as emission extending to the northeast. Figure 6 shows an enlarged S7 image to indicate these structures clearly, as well as the region where the IRC NIR spectrum is extracted. Similar, but more diffuse plume structures are seen in the residual image in the K-band after subtracting a galaxy model (Rothenberg & Joseph 2004). The structures are named plume 1 and plume 2, as shown in the figure. We note that the intensity distribution around the center is slightly shifted toward the east from the center position of the galaxy indicated by the white cross. We estimate the intensity of the central part of the galaxy within the yellow circle (see Section 4).

Figure 7 shows the AKARI/IRC NIR spectrum of the central region of NGC 7727. There seem to be no clear emission nor absorption features in the spectrum. A shallow, broad dent around 4.5 \( \mu m \) may be attributed to the CO fundamental vibration absorption, but the present data do not have sufficient quality to confirm it. Compared to the NIR spectrum of NGC 2782 (Figure 4(a)), the NIR continuum of NGC 7727 is bluer, suggesting the dominance of the contribution from the stellar continuum over the emission from the ISM. The absence of H\text{I} recombination lines and PAH features suggests low star formation activity in the central region of NGC 7727.

4. Discussion

4.1. NGC 2782

The MIR images at S7 and S11 show a tail structure in the eastern side of the galaxy, which has a good correspondence with the structure of the eastern H\text{I} tidal tail. In Figure 4, the spectral range that each filter of the IRC covers is indicated by the arrows. The emission of the PAH 6.2 and 7.7 \( \mu m \) bands dominates band S7 (Ishihara et al. 2007). In the S11 image, the 11.3 and 12.7 \( \mu m \) PAH bands are dominant features together with [Ne\text{II}] 12.8 \( \mu m \). Although there is no spectroscopic information for this observation with AKARI, we assume that the S7 and S11 images also trace the PAH emission for regions other than the center (cf., Onaka et al. 2010b). On the other hand, L15 and L24 do not contain strong dust band features and they trace mostly the continuum emission.

Figure 8 shows the band ratio maps of NGC 2782. The intensity ratios of the 6.2 and 7.7 \( \mu m \) bands to the 11.3 \( \mu m \) band are supposed to be sensitive to the ionization fraction and the size distribution of PAHs (Draine & Li 2001; Tielens 2008). The ratio of S7 to S11 can be regarded as a proxy for this band ratio. Figure 8(a) shows that it is almost constant over the entire galaxy, including the central and extended regions, at around the values of \( \sim 1.2 \). The figure does not indicate any systematic trend with the extended structures. The constant ratio suggests that the properties of PAHs, in particular their ionization fractions, do not vary appreciably in the galaxy.

The L24–S11 color map shows that the ratio is high at the central part of the galaxy. This trend is also seen in the spectrum (Figure 4(c)). The ripple region may have slightly larger ratios (\( \sim 1.8 \)), but the region with larger ratios does not show good spatial correlation with the structure seen in the S7 image (Figure 3). The ratio is relatively low at the eastern tail. In general, the ratio of the 25–12 \( \mu m \) increases with the incident radiation field and thus with the star formation activity (Dale et al. 2001; Sakon et al. 2006; Onaka et al. 2007b). Alternatively, the MIR continuum emission also increases with the presence of an AGN (Armus et al. 2007; Tommassin et al. 2010). Since no clear sign of AGNs is recognized in the spectrum, the large L24–S11 ratio more likely comes from the enhanced star formation in the central part of the galaxy, as
Ripples are thought to be formed during galaxy collisions and several mechanisms have been proposed for the ripple formation in mergers. Smith (1994) gave a summary of the mechanisms in detail, including radial oscillations in the stars and gas due to head-on collision (Wallin & Struck-Marcell 1988), ripples from the debris of the smaller mass galaxy (Quinn 1984; Hernquist & Quinn 1988), tidal structures falling back into the remnant (Hernquist & Spergel 1992), stripped matter from a companion disk galaxy (Hernquist & Quinn 1988), a distorted spiral density wave pattern perturbed by an encounter with another galaxy (Thomson & Wright 1990; Howard et al. 1993), and star formation triggered by shocks due to galactic winds (Fabian et al. 1980). The present result does not show evidence for an increase in the star formation in the ripple.
To investigate the spectral energy distribution (SED) of each region in NGC 2782 in greater detail, we performed photometry at the center, ripple, and tail regions enclosed by the circle and the solid rectangles in Figure 3. The data of N3 are used as a reference point to estimate the contribution from the stellar component. The spectrum of the stellar component is simply assumed to be given by the average stellar spectrum of the fluxes of red giant stars used in the flux calibration, as in Onaka et al. (2010b). The assumed stellar contribution is less than 10%, except for the N4 data, in which it amounts to around 40%.

Figure 9 shows the SEDs of the three regions in NGC 2782. As a reference SED we also plot the results of simple calculations of the DUSTEM model8 (Compiègne et al. 2011). All the models are scaled to the observations at 11 μm. In the DUSTEM calculation, we assume the standard parameters for the model of the diffuse ISM of our Galaxy. We employ the dust properties, size distributions, and ionization fraction of PAHs described in Compiègne et al. (2011) and assume that the mass fraction of PAHs (size between 0.35 and 1.2 nm) as 8.6%, and that of very small grains (VSGs, sized between 0.6 nm and 20 nm) as 1.8%, and that of large grains (LGs, sized between 4 nm and 2 μm) as 89.6%. We also assume that the incident radiation field strength $U$ in units of the solar neighborhood is unity. The SED hardly changes as long as $U$ is less than 10 in this spectral range. We assume that the flux at N3 is a summation of the dust emission estimated from model calculations and the contribution from stellar components described above. In Figure 9(a), the IRC and IRS spectra of the central region (Figure 4) are also plotted by the thin purple lines. For the IRS spectra, the compact and extended components are added together (Section 2). Since the regions where the spectra are extracted are not exactly the same as the photometric points, each spectrum is scaled to the photometric data points. There are some differences, but the model spectrum is generally in agreement with the observed spectrum at wavelengths below 13 μm, where the spectrum of models with $U < 10^3$ does not change appreciably. Excess emission in the NIR relative to the model is also indicated by the IRC spectrum (see below). In Figures 9(b) and (c), we also plot the results of the model spectrum without VSGs to show the VSG contribution. There is no contribution from LGs at wavelengths shorter than 30 μm for $U < 10$ (Li & Draine 2001).

The model flux is slightly larger than the observations at 7 μm, in particular in the tail region. It may be attributed to a decrease of the ionization degree of PAHs, since the emission at 6.2 and 7.7 μm is dominated by ionized PAHs, while the emission at 11.3 μm comes mostly from neutral PAHs (Draine & Li 2001; Tielens 2008). Low ratios of the PAH 6.2 and 7.7 μm to 11.3 μm bands are suggested in halos of galaxies (Irwin & Madden 2006; Galliano et al. 2008b), structures associated with an Hα filament in the dwarf galaxy NGC 1569 (Onaka et al. 2010b), and the interarm region of NGC 6946 (Sakon et al. 2007). The low band ratios seen in these tenuous regions may have a common origin or arise from the processing of PAHs in these environments. The low band ratio in the tail region of NGC 2782 is inferred from the medium-band photometry. Spectroscopy of the tail region is needed to quantitatively confirm the variation in the band ratio.

Figure 9 indicates that the SED of the center region increases toward longer wavelengths, while in the ripple and tail regions the SEDs start falling at 15 μm. The standard diffuse ISM dust model overpredicts the flux at 24 μm of the ripple region, where the model without VSGs better fits the observed SED. Comparison with the dust model again supports that the star formation activity is not enhanced in the ripple region.

The SED of the tail falls faster than the ripple region at longer wavelengths and even the model without VSGs cannot explain the observations at 15 and 24 μm well. Since LGs do not contribute to the emission at 24 μm for $U = 1$, it is difficult to explain the observations unless we change the properties of PAHs, which are the dominant contributor in this spectral region next to VSGs. Since larger PAHs contribute to emission at longer wavelengths (Draine & Li 2007), we investigate the effect of the size distribution of PAHs in the Appendix. A simple investigation suggests that even extreme models with only very small PAHs (0.35–0.5 nm) cannot fully explain the observed SEDs. The discrepancy at 24 μm may be attributed to the model emissivity of PAHs rather than to the size distribution. The emission at 15–24 μm dominantly arises from stochastically heated VSGs and large PAHs. Although simple model calculations cannot explain the observed SED of the tail.

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8 https://www.iias.u-psud.fr/DUSTEM/
region consistently, the sharp decline strongly suggests a deficiency of VSGs, and possibly of large PAHs.

In the spectral range 7–30 μm, there are several pure rotational transitions of molecular hydrogen (H2). The L24 band does not have any H2 lines in its spectral range (both S(0) 28.2 μm and S(1)17.0 μm are out of its spectral range), while L15 includes S(1)17.0 μm, S11 has S(2)12.3 μm and S(3) 9.7 μm, and S7 covers S(4)8.0 μm, S(5)6.9 μm, and S(6) 6.1 μm lines. Therefore, there is a possibility that the H2 line emissions could make the observed steep decline at 24 μm if they make significant contributions to these bands. Roussel et al. (2007) studied the H2 0–0 S(0)–S(7) transitions in 57 normal galaxies of the Spitzer Infrared Nearby Galaxies Survey (SINGS, Kennicutt et al. 2003). They showed that the observed fluxes of the S(0)–S(3) transitions are in the range (1–400) × 10^{-18} W m^{-2}, They detected the S(4) to S(7) transitions only in three galaxies in the range (100–250) × 10^{-18} W m^{-2}, with upper limits of about 20 × 10^{-18} W m^{-2}. They observed either nuclear regions or bright star-forming complexes of the sample galaxies and the observed H2 emissions originate mostly from PDRs. Larger fluxes (>50 × 10^{-18} W m^{-2}) are seen toward the galaxies, where star formation activity is large. Their observed areas are typically ~300 arcsec^2, which are about an order of magnitude smaller than the area of the tail region (4200 arcsec^2) for deriving the flux for NGC 2782. The tail region does not have high star-forming activity (see below). Thus, we estimate that the expected fluxes of S(0)–S(3) transitions in the tail region are of the order of 10^{-17} W m^{-2} at most, even if we take into account the difference in the size of the observed areas. They are an order of magnitude smaller than the observed fluxes of the tail region at S7, S11, and L15 (Figure 9(c)). Roussel et al. (2007) indicated that the ratio of the summation of the S(0) to S(2) fluxes to the IRAC band 4 (8 μm) flux is relatively constant at around 10^{-2}, which supports the present rough estimate. Although we cannot completely rule out this possibility without spectroscopy, it does not seem to be very likely that the contribution from the H2 emission is significant in the tail region.

In the center region, the model with U = 1 underpredicts the flux at 4.1 μm, which can be attributed to an uncounted component. Lu et al. (2003) reported excess emission in the NIR in normal galaxies, while similar excess is also seen in the diffuse Galactic emission (Flagay et al. 2006). Smith & Hancock (2009) discussed the origin of excess emission at 4.5 μm in dwarf galaxies. Onaka et al. (2010b) investigated excess emission in the NIR of the dwarf galaxy NGC 1569, suggesting that the free–free emission estimated from Brα emission is insufficient to explain the observed emission, and favoring the contribution from hot dust. Although it probes only a part of the center region of NGC 2782, we also estimate the contribution from the free–free emission using the observed intensity of Brα in the IRC NIR spectrum (Figure 4(a)). The intensity of Brα is estimated to be about 4.5 × 10^{-9} W m^{-2} sr^{-1}, which suggests that the free–free emission is less than 0.05 MJy sr^{-1}. Therefore, the observed NIR continuum cannot be attributed to the free–free emission and a contribution from the hot dust component is also suggested for the center region of NGC 2782.

The SED of the center region shows excess emission over the model of U = 1 at 15 and 24 μm, suggesting the presence of warm dust. To study the warm dust in the center region quantitatively, we employ data at longer wavelengths. We retrieved the Post-Basic Calibrated Data of NGC 2782 obtained with Spitzer/MIPS at 70 and 160 μm (AORKEY: 4348416) from the Spitzer Heritage Archive. Since the MIPS 160 μm data do not have the spatial resolution to resolve the
structures of the galaxy, we simply performed aperture photometry with a radius of 23′′ for all the IRC bands, as well as the MIPS 70 and 160 μm bands, to match the PSF of the MIPS 160 μm. The sky background is estimated from the median of the emission outside of the galaxy and subtracted from the data. The total integration time of the MIPS observations at 70 and 160 μm is short, about 120 s and 42 s, respectively, and extended emission is difficult to detect. The present aperture photometry was performed to derive a rough estimate of the SED of the central 23′′ region of NGC 2782 from NIR to FIR.

Figure 10 shows the SED of the center region of the IRC and MIPS observations. The SED of the IRC bands is almost identical to that shown in Figure 9(a). To compare with the DUSTEM model, we introduce a distribution of U and tune the relative abundances of PAHs, VSGs, and LGs to fit the observation (Figure 10). The model fits the observations fairly well if we assume that the distribution of U is given by a power law (Dale et al. 2001) with an index of −0.017, a minimum and maximum U of 7.6 and 10⁶, respectively, and the mass fractions of PAHs, VSGs, and LGs of 2.8%, 8.2%, and 89%, respectively. The spatial distribution of the infrared emission in galaxies varies with the wavelength and the available FIR data do not have a spatial resolution to resolve small structures. Therefore, the derived parameters of the power-law index and the maximum U should be regarded as rough estimates. The derived parameters support evidence of enhanced star formation activity in the center region. The derived PAH abundance is small relative to the standard value (8.6%), but is still within the range of normal galaxies (Draine et al. 2007). The small PAH abundance might be related to the destruction of PAHs due to the presence of an AGN. As described above, however, the present IR spectra do not show clear evidence of an AGN. Only recent X-ray observations indicate the presence of a low-luminosity AGN (Tzanavaris & Georgantopoulos 2007; Bravo-Guerrero & Stevens 2017).

Knierman et al. (2013) detected a number of star cluster candidates (SCCs) both in the western and eastern tails. In the western tail, one Hα source is found, but no CO and [C II] 158 μm line emission has been detected. They attribute the absence of the CO and [C II] emission to a low carbon abundance in the western tail. No detection of the MIR emission in the western tail is compatible with their interpretation.

In the eastern tail, several Hα sources are detected, as well as CO and [C II] emission. Knierman et al. (2013) made estimates of the SFRs of the regions enclosed by the blue dashed rectangles in Figure 3 from the intensities of Hα and [C II]. Here, we use the PAH emission to estimate the SFRs of these regions. We measure the fluxes in the S7 band for each region (TDGC, HI-N, HI-M, and HI-S; see Figure 3) and subtract the assumed stellar contribution. The stellar contribution is at most 6% and thus does not affect the conclusion. We assume that the emission at S7 mainly comes from the PAH 6.2 μm and 7.7 μm bands and apply the PAH band–SFR relations provided by Shipley et al. (2016) to estimate the SFR, assuming that the distance is 39.5 Mpc (Knierman et al. 2013). The S7 band collects almost the entire PAH 6.2 and 7.7 μm band fluxes, but it could also have a contribution from other components. Thus, the SFR from the S7 band should be taken as an upper limit. Also note that the spatial resolution of the present observation is different from those of Knierman et al. (2013), and the regions where the estimate is made are not exactly the same.

Figure 11 shows a comparison of the SFRs thus estimated from the flux at S7 with those from Hα and [C II] for each region. It indicates that the SFR from the PAH bands (S7) is close to that from Hα (TDGC and HI-N) or in-between those from Hα and [C II] (HI-M and HI-S). A good correlation between the PAH emission and [C II] has been reported for star-forming galaxies, which can be interpreted as the PAHs being the dominant agency for gas heating (Helou et al. 2001). The Hα emission indicates the strength of the heating radiation. Considering the uncertainties described above, the agreement is sufficiently good. The present results suggest that the PAH emission may also be used as a useful measure for the SFR in these extended structures, although a change in the dust size distribution is suggested. However, the present sample size is too small to draw a general conclusion. We definitely need many more samples to confirm its applicability. To investigate the size distribution and its effect on the estimate of the SFR...
quantitatively, we need FIR data with a sufficient spatial resolution and sensitivity that allow us to resolve and detect emission from extended structures in the FIR.

4.2. NGC 7727

Figure 12 shows S7–S11 and L24–S11 color maps of NGC 7727. The S7–S11 color is almost constant over the entire galaxy. The L24–S11 color does not change over the galaxy except for a slight increase in a very small region around the center. The plume regions in the north may suggest a small increase in the band ratio. Compared to the color maps of NGC 2782 (Figure 8), the L24–S11 band ratio of NGC 7727 is small, suggesting low star formation activity in NGC 7727.

Figure 13 shows the SEDs of the three regions indicated by the circle and the solid rectangles in Figure 6. The same spectra of the DUSTEM model shown in Figure 9 are also plotted with the assumed stellar contribution. Compared to NGC 2782, the contribution from the stellar continuum is estimated to be large. The data at N4 (4.1 μm) are well-explained by the model, suggesting that the assumed spectrum approximates the stellar contribution. The NIR spectrum of the center shows a steeply decreasing continuum toward longer wavelengths (Figure 7). This is in agreement with the dominance of the stellar contribution. The DUSTEM model predicts weak PAH emission at 3.3 μm (Figure 13(a)), which is not seen in the spectrum. This may suggest the absence of the small PAHs that predominantly emit the 3.3 μm band.

The contribution from the H2 emission can be estimated in a manner similar to that seen in Section 4.1. Since the sizes of the areas from which the fluxes are estimated in the plume regions of NGC 7727 are about the same (600 and 324 arcsec2, for plume 1 and plume 2, respectively) as those in the observations of the SINGS galaxy sample (Roussel et al. 2007), we expect the contribution from the H2 emission to be about an order of magnitude smaller (an order of 10^{-17} Wm^{-2}) than the observed fluxes (Figures 13(b) and (c)), unless the plume regions have high star formation activity. Spectroscopic studies are certainly needed to confirm this expectation.

There are clear discrepancies in the flux at 7 μm for all three regions, which are larger than that in the tail region of NGC 2782. The model (indicated by open squares) overpredicts the flux at 7 μm relative to that at 11 μm. Since the observed S7–S11 ratio seems to be almost the same as that for NGC 2782 (Figures 8(a) and 12(a)), the difference should be attributed to the larger contribution of the stellar component in NGC 7727. The stellar spectrum has a steep spectral dependence and thus the ISM contribution of NGC 7727 becomes flatter at 7–11 μm compared to NGC 2782. The resultant ISM SED cannot be explained by the standard PAH emission spectrum. The relatively constant S7–S11 color suggests that this characteristic of the SED may hold for the entire galaxy.

In addition to the low band ratios seen in halo regions, a filament, and an interarm region, elliptical galaxies show peculiar MIR spectra that have clear PAH 11.3 μm emission with very weak or almost no emission at 6.2, 7.7, and 8.6 μm, which are the strongest bands in normal PAH emission spectra (Kaneda et al. 2005, 2007). The IRC NIR spectroscopy also shows that the 3.3 μm emission band is absent in the elliptical galaxy NGC 1316 (Kaneda et al. 2007). These characteristics may be interpreted in terms of emission from large and neutral PAHs. These characteristics seem to be in accordance with the observed MIR SEDs of NGC 7727. In NGC 7727, large and neutral PAHs may dominate due to the weak star formation activity. NGC 7727 is classified as SAB(s)a pec (de Vaucouleurs et al. 1991), and it may be at the stage of an elliptical galaxy after merging. We need spectroscopy to confirm this interpretation.

The emission of the center region at 11–24 μm can be explained by the DUSTEM model with U = 1, while the SED of the plume regions declines very sharply at 24 μm compared to the DUSTEM model. The fluxes at 24 μm for both plumes are less than 3σ and upper limits are plotted in Figures 13(b) and (c). If the fluxes are at the levels that the models predict, they should be detectable and thus the sharp decline at 24 μm is secure. This is a similar trend to that seen in the tail region of NGC 2782. Figures 13(b) and (c) suggest that even models without VSGs cannot explain the observed SED at 24 μm. In the Appendix, we discuss the effects of the size distribution of PAHs similar to NGC 2782. It is difficult to explain the observed SEDs solely by the change of the size distribution, so a revision of the PAH emissivity at 15–24 μm may be needed. Although it may not be typical PAH emission, excess emission at 7–15 μm is certainly present (Figure 13). The sharp decline at 24 μm relative to the excess suggests that the dust that emits

Figure 12. Band ratio maps of NGC 7727. (a) S7–S11 and (b) L24–S11. The pixels with fluxes of less than 4σ are masked and shown in black.
The blue dotted lines indicate the assumed stellar contribution. DUSTEM calculations corresponding to the black and red lines, respectively. The red open squares indicate the color-corrected photometric points of the model with and without VSGs, respectively. They are scaled to the observations at 11 μm. The formation of PAHs from fragmentation of carbonaceous dust has been discussed theoretically (Jones et al. 2013; Seok et al. 2014) and suggested in various celestial objects observationally (Onaka et al. 2010b; Seok et al. 2012; Lau et al. 2016). Pilleri et al. (2012, 2014) also studied the photofragmentation of VSGs into PAHs in PDRs. FIR data with a sufficient spatial resolution and sensitivity are needed to obtain a clear answer regarding whether the fraction of PAHs increases relative to LGs by fragmentation and/or if the entire dust size distribution is changed (Section 4.1).

If the observed SEDs are the result of fragmentation of VSGs into PAHs during the merger events, the size distribution of PAHs and VSGs must have been preserved since then. This proposed scenario requires that the destruction timescale of PAHs and the formation timescale of VSGs are longer than the merger ages. The merger age is estimated as about 200–300 Myr for NGC 2782 (Smith 1994; Knierman et al. 2013) and 1.3 Gyr for NGC 7727 (Georgakakis et al. 2000). In our Galaxy, the lifetime of carbonaceous dust is estimated as 170 Myr (Serra Díaz-Cano & Jones 2008) and that of PAHs is estimated as ∼100–500 Myr (Micelotta et al. 2010a). Recently, Bocchio et al. (2014) re-evaluated whether the lifetime of carbonaceous dust is as short as ∼62 ± 56 Myr by merging the inertial and thermal sputtering into a single process. We try a very rough estimate to translate the lifetime in our Galaxy to the tail region in NGC 2782 and the plume regions in NGC 7727. Supernova shocks are the dominant destruction process, thus the lifetime must be related to the SFR. The estimated total SFR in the tail region of NGC 2782 is 0.02–0.13 M_☉ yr⁻¹ (Figure 11, Knierman et al. 2013). Chomiuk & Povich (2011) collected various estimates of the SFR of our Galaxy and derived an average value of 1.9 ± 0.4 M_☉ yr⁻¹, while Licquia & Newman (2015) applied a hierarchical Bayesian statistical method and obtained 1.65 ± 0.19 M_☉ yr⁻¹. The area of the tail region indicated in Figure 3 is about 150 kpc² at a distance of 39.5 Mpc, which is about half the size of the surface area of our Galaxy disk. If it is inversely proportional to an average SFR per area, the destruction timescale in the tail region can be an order of magnitude longer than the Galactic value. Thus, it may be longer than the merger age. We do not have much information on the SFR in the plume regions of NGC 7727. Although their PAH features do not seem to be typical and thus there is a large uncertainty, we use the S7 band flux to infer their SFRs. The observed fluxes at S7 in the plume regions are smaller by about

4.3. Formation and Destruction of PAHs and VSGs

In both galaxies, excess emission at 7–15 μm and a sharp decline of the emission at 24 μm are seen in the extended structures. The sharp decline in the extended structures relative to the Milky Way and the center regions of the galaxy is secure based on the present observations, though the contribution from line emission needs to be investigated by spectroscopy. If the observed SEDs originate mostly from the dust emission that the DUSTEM model simulates, then the decline must be interpreted in terms of the variation in the dust size distribution. The absolute abundance of VSGs depends on the assumed emissivity, but comparison with the DUSTEM model indicates that these regions have a small abundance of VSGs relative to the diffuse ISM of our Galaxy and the center regions of the galaxy. Since those extended structures are thought to have been formed in the merger events, the deficiency of VSGs must be related to the events. The excess emission at 7–15 μm is attributed to the PAH features. In general, VSGs are assumed to consist of amorphous carbonaceous dust (Compiègne et al. 2011). The presence of PAHs and the deficiency of VSGs suggest a possible scenario in which VSGs fragmented into PAHs in the structures formed during the merger events.
an order of magnitude than that of the tail region of NGC 2782 (Figures 9(c), 13(b), and (c)), suggesting that the SFR per area is also smaller. The lifetime of PAHs in these regions may be two orders of magnitude longer than the Galactic value and thus may be longer than its merger age.

The estimated very short destruction timescale of carbonaceous dust in our Galaxy suggests rapid recycling of carbonaceous dust in our Galaxy. To compensate for the rapid destruction, it is generally suggested that dust grows in dense clouds on a similar timescale (e.g., Jones & Nuth 2011; Bocchicchio et al. 2014). Direct conversion of these values into the formation timescales of carbonaceous dust in the tail and plume regions is not straightforward, but these investigations suggest that formation of carbonaceous dust, and thus VSGs, requires dense clouds and must also be related to the star formation activity. The suggested low SNRs per area in the extended regions of both galaxies also indicate a longer timescale for the formation of carbonaceous dust, including VSGs. Although these estimates are very rough, the destruction of PAHs and the formation of VSGs may take a longer time than the merger ages due to the low star formation activity of both galaxies. Then, the size distribution of PAHs and VSGs could have been preserved after the merger events until now.

Note that the above discussion was made on the basis of medium-band photometry. While emission of molecular hydrogen should not contribute to the present results significantly, as discussed above, contributions from other lines or features cannot be ruled out completely. Spectroscopic study is needed to support the above discussion and interpretation.

5. Summary

We present NIR-to-MIR imaging and NIR spectroscopic observations of two mergers, NGC 2782 and NGC 7727, with AKARI/IRC. The MIR-to-FIR SED suggests enhanced star formation activity in the central part of NGC 2782. No evidence for the presence of an AGN is obtained in the present observations. The ripples seen in optical images of NGC 2782, thought to have been formed by the merger event, are also seen in the MIR images. The SED suggests no enhancement in the star formation in the ripples. The IR SED of NGC 7727 is dominated by the stellar component. Neither PAH 3.3 μm emission nor H/ recombination lines are detected in the central part of the galaxy, suggesting low star formation activity.

NGC 2782 shows extended emission (tail structure) at 7–15 μm, whose structure corresponds to the eastern tidal tail seen in the H/ map. NGC 7727 shows extended emission (plumes) at 7–15 μm, structure similar to what has been seen in the K-band image. Both structures are thought to have formed from merger events. The SED of the tail of NGC 2782 at 7–15 μm can be explained by PAH emission with a smaller ionization degree of PAHs relative to the diffuse ISM of our Galaxy. The SEDs of the plume regions of NGC 7727 suggest PAH emission with much lower ionization degrees. It may be similar to that seen in elliptical galaxies. Spectroscopic studies are needed to confirm the nature of their emission.

Extended emission in both galaxies declines more rapidly at 24 μm than the model SED of the ISM of our Galaxy, suggesting a deficiency of VSGs. While it must be confirmed by spectroscopy that emission lines or other features do not contribute to the observed fluxes significantly, the observed SEDs of the extended emission can be interpreted confidently if VSGs fragment into PAHs during the merger events. Because of the low star formation activity in both regions, the timescales for the destruction of PAHs and formation of VSGs may be longer than the merger ages. Then, the present infrared SEDs retain the imprint of the size distribution of PAHs and VSGs created during the merger events.

The SFR of the tail region of NGC 2782 estimated from the 7 μm band is in agreement with those estimated from Hα and [C II] 158 μm. The present results suggest that the PAH emission may also be used as an SFR measure for extended structures of galaxies, despite possible processing of dust grains in these regions. However, the size of the present sample is too small to draw a general conclusion. We need much larger samples to test its applicability. The present results also suggest that MIR observations are very efficient for identifying and studying extended structures formed by merger events and studying processing of dust in merger events. Further studies with FIR data that allow us to quantitatively investigate the size distribution of dust in structures associated with merger events will provide a unique opportunity to investigate the dust lifetime and processing on a galactic timescale and its effect on the estimate of the SFR from the PAH emission.

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Facilities: AKARI, Spitzer.

Appendix

Model Calculations of the Modified PAH Size Distribution

To explain the sharp decline seen at 15–24 μm in the SEDs of the tail region of NGC 2782 and the plume regions of NGC 7727, we investigate the effects of the PAH size distribution with a simple model analysis. The size distribution of PAHs in the original model is given by a log-normal distribution between 0.35 and 1.2 nm. Larger PAHs contribute to emission at longer wavelengths (Draine & Li 2007). We decrease the maximum size and compare the model with the observations in Figure 14 (black lines). The spectra are normalized at 11 μm for comparison. We found that the observed flux at 24 μm relative to that at 11 μm can be explained if we assume the presence of only small PAHs of 0.35–0.5 nm. The assumed size distribution is very extreme and contrived, and is used only for investigation of the size effect. However, even a model with such an extreme size distribution cannot be reconciled with the observed flux at 15 μm satisfactorily. In addition, because of the size distribution being biased toward smaller PAHs, the model flux at 7 μm well exceeds the observation.

The 6.2 and 7.7 μm PAH bands are enhanced when PAHs are ionized (Draine & Li 2001; Tielens 2008). In the standard
model, the size-dependent ionization fraction of PAHs is assumed and the ionization fraction of small PAHs is around 38% (Compiègne et al. 2011). To investigate the effect of the ionization fraction in addition to the size distribution, we also calculate the model with the same size distribution of only small PAHs, assuming that they are all neutral. The resultant model spectrum is shown by the red lines in Figure 14. A small neutral PAH model may explain the observations at 7, 11, and 24 μm, but the discrepancy at 15 μm is increased. It should also be noted that the models with only small PAHs predict very strong PAH emission at 3.3 μm, which should be detectable in the N3 image. Considering these facts, simple modifications of the size distribution and the ionization degree of PAHs have difficulties consistently explaining the observed SEDs, suggesting that modification of the PAH emissivity may be needed to fully explain the observed SEDs of the tail of NGC 2782 and the plume regions of NGC 7727.

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**Figure 14.** Normalized SEDs of (a) the tail region of NGC 2782 (filled circles) and (b) the plume regions of NGC 7727 (the filled black circles are for plume 1 and the filled blue diamonds are for plume 2). The black and red lines show the DUSTEM model with only small PAHs and that with small, neutral PAHs, respectively (see the text). The black and red open squares indicate the photometric points of the model spectra of the black and red lines, respectively, considering the color corrections of the filter responses. The blue dotted lines indicate the assumed stellar component. The spectra are normalized at 11 μm for comparison.

**Normalized SEDs of** NGC 2782 and 7727. **The black and red lines show the DUSTEM model with only small PAHs and that with small, neutral PAHs, respectively.**
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