GOODS-Herschel: the impact of galaxy-galaxy interactions on the far-infrared properties of galaxies

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ABSTRACT

Aims. We study the impact of galaxy-galaxy interactions on the far-infrared properties of galaxies and its evolution at 0 < z < 1.2.

Methods. Using the high-z galaxies in the fields of Great Observatories Origins Deep Survey (GOODS) observed by the Herschel Space Observatory in the framework of the GOODS-Herschel key program and the local IRAS or AKARI-selected galaxies in the field of Sloan Digital Sky Survey Data Release 7, we investigate the dependence of galaxy properties on the morphology of and the distance to the nearest neighbor galaxy.

Results. We find that the star-formation rates (SFRs) and the specific SFRs (SSFRs) of galaxies on average depend on the morphology of and the distance to the nearest neighbor galaxy in this redshift range. When a late-type galaxy has a close neighbor galaxy, the SFR and the SSFR increase as it approaches a late-type neighbor, which is supported by Kolmogorov-Smirnov (K-S) and Monte Carlo (MC) tests with a significance level of >99%. However, the SFR and the SSFR decrease or do not change much as the galaxy approaches an early-type neighbor. The bifurcations of SFRs and SSFRs depending on the neighbor’s morphology seem to occur at \( R_n \approx 0.5 r_{\text{vir, nei}} \) (virial radius of the neighbor), which is supported by K-S and MC tests with a significance level of >99%. For all redshift bins, the SSFRs of late-type galaxies interacting with late-type neighbors are increased by factors of about 1.8 for 0.7 < z < 1.2 compared to those of non-interacting galaxies when the pair separation is smaller than \( 0.5 r_{\text{vir, nei}} \). For the pair separation, the dust temperature of both local and high-redshift late-type galaxies interacting with early-type neighbors seems to be lower than or similar to that of non-interacting galaxies.

Conclusions. Our results suggest that galaxy-galaxy interactions and mergers have been strongly affecting the SFR and the dust properties of star-forming galaxies over at least 8 billion years.

Key words. galaxies: active – infrared: galaxies – galaxies: evolution – galaxies: interactions – galaxies: formation – galaxies: starburst

1. Introduction

In the hierarchical picture of galaxy formation, galaxies are formed and grow through continuous interactions and mergers with other galaxies. These galaxy-galaxy interactions and mergers are expected to strongly affect galaxy properties such as morphology, luminosity, structure parameters, star-formation rate (SFR), or dust properties (see Struck 2006 for a review).

Since Toomre (1977) first suggested that the merger between spiral galaxies can form elliptical galaxies, there is growing evidence for a change in galaxy morphology (e.g., Park et al. 2008) and galaxy structure with merger (e.g., Nikolic et al. 2004; Patton et al. 2005; Hernández-Toledo et al. 2005; Park & Choi 2009). For example, Park et al. (2008) showed that galaxy morphology and luminosity strongly depend on the distance to and the morphology of the nearest neighbor galaxy. When a galaxy is located within the virial radius of its nearest neighbor, its morphology tends to be the same as that of the neighbor. This indicates an important role of hydrodynamical interactions with neighbors within the virial radius. This morphological conformity was also found between hosts and their satellite galaxies (Ann et al. 2008; Wang et al. 2010b), and between galaxies in galaxy clusters (Park & Hwang 2009).

For the star-formation activity (SFA), Larson & Tinsley (1978) first noted that morphologically normal and peculiar galaxies show very different optical color distributions, which suggests that the SFA of peculiar galaxies is enhanced compared to those of normal galaxies. Many studies have extensively investigated this enhancement of SFA in paired galaxies...
changes: the virial radius ($r_{\text{vir}}$), characteristic pair-separation scales where the SFA abruptly decreases, the nearest neighbor galaxy where the e-folding scale of the nearest neighbor has a late morphological type, but is decreased or reversed in paired galaxies. Section 2 describes the data used in this study, and the dependence of galaxy properties on the distance to and the morphology of the nearest neighbor galaxies is given in Sect. 2. Discussion and conclusions are given in Sects. 3 and 5, respectively. Throughout, we adopt $h = 0.7$ and a flat ΛCDM cosmology with density parameters $\Omega_{\Lambda,0} = 0.73$ and $\Omega_{m,0} = 0.27$.

2. Data
2.1. GOODS sample

We used a spectroscopic sample of galaxies in GOODS, which is a deep multiwavelength survey covering two carefully selected regions including the Hubble Deep Field North (HDF-N) and the Chandra Deep Field South (CDF-S). Hereafter, the two GOODS fields centered on HDF-N and CDF-S are called GOODS-N and GOODS-S, respectively. The combined area of the two fields is approximately 320 arcmin$^2$.

The GOODS fields were observed by Herschel in the GOODS-Herschel key program (Elbaz et al. 2011). The full 10′ × 16′ GOODS-N field was observed with both PACS (100 and 160 μm) and SPIRE (250, 350, and 500 μm). A smaller region within the GOODS-S field (≈10′ × 10′) was observed with PACS only. We supplemented these data with public SPIRE images covering the full 10′ × 16′ GOODS-S field, which was originally taken in the HerMES key program (Olive et al., in prep.).

Source extraction on these PACS and SPIRE images was performed at the prior positions of Spitzer 24 μm-selected sources, and details are described in Elbaz et al. (2011). Note that this extraction method with 24 μm-selected sources recovers more than 99% of Herschel sources (Magdis et al. 2011). We used flux densities in PACS bands down to 3σ limits of 1.1 and 2.7 mJy (0.8 and 2.4 mJy) at 100 and 160 μm in GOODS-N (GOODS-S, respectively). SPIRE measurements are used down to 5σ limits of 5.7, 7.2, and 9.0 mJy at 250, 350, and 500 μm, respectively (see Table 1 in Elbaz et al. 2011 for more details about the noise properties). By combining Herschel data with the existing multi-wavelength data, we made a band-merged catalog of GOODS galaxies using the photometric data at HST ACS BViz, CFHT/WIRCam JK (North; Wang et al. 2010a) and VLT/ISAAC JHK (South; Retzlaff et al. 2010), Spitzer IRAC 3.6, 4.5, 5.8, 8 μm and MIPS 24 and 70 μm, Herschel PACS 100 and 160 μm, and Herschel SPIRE 250, 350, and 500 μm.

Fig. 1. (a–b)) Dust temperature ($T_{\text{dust}}$), (c–d)) IR luminosity, (e–f)) stellar mass, and (g–h)) evolution-corrected, rest frame $r$-band absolute magnitude vs. spectroscopic redshift for galaxies in (left) SDSS and (right) GOODS. Red dots indicate FIR-selected galaxies. Black dots denote galaxies without FIR detection in the spectroscopic sample of galaxies (only 3% of SDSS galaxies in the total sample are shown). Open blue circles denote galaxies with $T_{\text{dust}}$ measurements. Blue solid lines in (g–h)) define the volume-limited samples of SDSS galaxies at $0.005 \leq z \leq 0.0656$ and of GOODS galaxies at $0.4 \leq z \leq 1.2$, respectively. The bottom curve in (g) indicates the apparent magnitude limit ($m_r = 17.77$) for the main galaxy sample in SDSS using the mean $K$-correction relation given by Eq. (2) of Choi et al. (2007).

Silverman et al. 2010; Xia et al. 2011), respectively. The rest frame $r$-band absolute magnitude $M_r$ of galaxies was computed based on the ACS plus near-infrared (NIR) photometry with $K$-corrections (Blanton & Roweis 2007). It was computed in fixed bandpasses, shifted to $z = 0.1$ to be compared with local SDSS galaxies. The $1.1(z – 0.1)$ term was added to $M_r$ for the evolution correction (Wolf et al. 2003). We calculated stellar masses using the photometric data upto IRAC 4.5 $\mu m$ with a Salpeter IMF (Salpeter 1955). We used the code Z-PEG with a galaxy evolution model PÉGASE.2 (Fioc & Rocca-Volmerange 1999; Le Borgne & Rocca-Volmerange 2002; see Elbaz et al. 2011 for details).

We adopted the galaxy morphology information [early types (E/S0) and late types (S/Irr)] from Hwang & Park (2009) that is based on the visual inspection of ACS $BViz$ images. We performed additional visual classification for the galaxies in the volume-limited sample of galaxies shown in the right panels of Fig. 1 that are not included in Hwang & Park (2009).

We computed the IR luminosity ($L_{\text{IR}}$) for 903 and 828 galaxies with spectroscopic redshifts in GOODS-N and -S, respectively, detected in at least one out of the five PACS/SPIRE bands. We fitted the flux densities at $\lambda_{\text{rest}} \geq 30 \mu m$ by allowing the normalization of the SED templates of Chary & Elbaz (2001, CE01) to vary and choosing the one that minimizes the $\chi^2$ values. When there were two or less data points to fit (i.e. $N \leq 2$), we fitted the flux densities without allowing the normalization of the templates (i.e. standard CE01 technique). There were some cases with only one FIR band used for $L_{\text{IR}}$ measurement, but the IR luminosities extrapolated from a single passband were found to agree very well with those measured with all FIR bands with an average uncertainty of $\sim 30\%$ (see Fig. 23 of Elbaz et al. 2011). Therefore, this does not introduce any bias in our results.

To determine the dust temperature, we fitted the observational data with a modified black body (MBB) model by fixing the emissivity parameter to $\beta = 1.5$. We required at least one flux measurement at each “Wien” and “Rayleigh-Jeans” side of the FIR peak (i.e., at least two measurements in total; see Hwang et al. 2010b for detailed selection criteria). This left us 284 and 104 galaxies with $T_{\text{dust}}$ measurements in GOODS-N and -S, respectively.

2.2. Sloan digital sky survey sample

For local galaxies, we used a spectroscopic sample of galaxies in the SDSS Data Release 7 (Abazajian et al. 2009, SDSS DR7) complemented by a photometric sample of SDSS galaxies, whose redshift information is not available in the SDSS database, but available in the literature (Hwang et al. 2010a). In addition, we used the FIR data for these galaxies compiled in Hwang et al. (2010b) by cross-correlating IRAS Faint Sources Catalog – Version 2 (Moshir et al. 1992) and AKARI/Far-Infrared Surveyor (FIS; Kawada et al. 2007) all-sky survey Bright Source Catalogue (BSC$^1$) ver. 1.0 with the SDSS samples.

The \( r \)-band absolute magnitude \( M_r \) was also computed in fixed bandpasses, shifted to \( z = 0.1 \), using Galactic reddening correction (Schlegel et al. 1998) and \( K \)-corrections (Blanton & Roweis 2007). The evolution correction given by Tegmark et al. (2004), \( E(z) = 1.6(z - 0.1) \), was also applied. Note that the amount of evolution correction is different between GOODS and SDSS galaxies. These values are taken from the redshift evolution of the characteristic luminosity in the luminosity function of local and high-\( z \) galaxies separately, so we kept different values. Change of these values does not affect our conclusions.

By adopting a method similar to the one applied to GOODS galaxies, we computed the IR luminosity of 14,444 galaxies (among the total sample of 926,748 SDSS galaxies) whose IRAS 60 \( \mu \)m or AKARI 90 \( \mu \)m flux densities are reliable\(^2\) using the CE01 SED templates by allowing normalization of the templates. We fitted the flux densities without allowing the normalization of the templates if there were two or less data points to fit. To determine the dust temperatures, we again fitted the observational data with a modified black body (MBB) model by fixing the emissivity parameter to \( \beta = 1.5 \) only for 238 galaxies detected at AKARI 140 or 160 \( \mu \)m so that we were able to obtain flux density measurements longward of the FIR peak as well as the one shortward of the peak in a similar way to GOODS-Herschel galaxies (see Hwang et al. 2010b for detailed selection criteria).

The stellar mass estimates were obtained from the MPA/JHU DR7 value-added galaxy catalog\(^3\) (VAGC), which are based on the fit of SDSS five-band photometry (Kauffmann et al. 2003; Gallazzi et al. 2005). We converted these estimates based on Kroupa IMF (Kroupa 2001) to a Salpeter IMF by dividing them by a factor of 0.7 (Elbaz et al. 2007).

We adopted the galaxy morphology information from the Korea Institute for Advanced Study (KIAS) DR7 VAGC\(^4\) (Park & Choi 2005; Choi et al. 2010). We performed additional visual classification for the galaxies in the SDSS database that are not included in KIAS DR7 VAGC.

### 2.3. Comparison of GOODS and SDSS galaxies

In the right panels of Fig. 1 we plot several physical parameters of the GOODS galaxies as a function of redshift, and define a volume limited sample to be analyzed (\( 19.5 \leq M_r \leq 24 \), with \( 0.4 \leq z \leq 1.2 \)). Similarly, we plot the SDSS galaxies in the left panels of Fig. 1, and define a volume limited sample of galaxies with \( 19.5 \leq M_r \leq 24 \) and \( 0.005 \leq z \leq 0.0656 \). The comoving volume for this SDSS sample is \( 2.0 \times 10^7 \, \text{Mpc}^3 \), which is much larger than that for the GOODS galaxies (\( 2.4 \times 10^5 \, \text{Mpc}^3 \) for GOODS-N at \( 0.4 \leq z \leq 1.2 \)). Note that the FIR detection limits for local SDSS and high-\( z \) GOODS galaxies are not the same even if we fix the mass and luminosity of galaxies in Sect. 3. However, because we are interested in the difference of SFA depending on the morphology of and the distance to the nearest neighbor galaxy in a given redshift range, the different FIR detection limits between local and high-\( z \) galaxies do not affect our conclusions.

In Fig. 2 we plot the dust temperature versus FIR flux density ratio (\( S_{60,\text{IRAS}}/S_{100,\text{IRAS}} \)) for SDSS galaxies, which shows a good correlation between the two quantities (see also Chanial et al. 2007). From the fit with an ordinary least-squares bisector method (Isobe et al. 1990), we derive a transformation relation between the two quantities,

\[
T_{\text{dust}} (K) = (43.0 \pm 0.3) + (37.0 \pm 1.5) \log(S_{60,\text{IRAS}}/S_{100,\text{IRAS}}).
\]

Because the number of SDSS galaxies with \( S_{60,\text{IRAS}}/S_{100,\text{IRAS}} \) is larger than that with \( T_{\text{dust}} \) measurements, we transformed the FIR flux density ratio into the dust temperature using this equation to increase the statistics (see Fig. 6).

### 2.4. Nearest neighbor galaxy

To investigate the effects of interactions with the nearest neighbor galaxy, we first identified the nearest neighbor of a target galaxy that is the closest to the target galaxy on the projected sky and that satisfies the conditions of magnitude and relative velocity. We searched for the nearest neighbor galaxy among galaxies that have magnitudes brighter than \( M_r = M_{r, \text{target}} + 0.5 \) and have relative velocities less than \( \Delta \nu = \nu_{\text{target}} - \nu_{\text{target}} - 660 \, \text{km} \, \text{s}^{-1} \) for early-type target galaxies and less than \( \Delta \nu = 440 \, \text{km} \, \text{s}^{-1} \) for late-type target galaxies. Because the redshift uncertainties are larger for the GOODS galaxies, we use velocity difference limits that are 10% larger than those that we have allowed for SDSS galaxies in previous studies (\( \Delta \nu = 600 \) and 400 km s\(^{-1}\)) for early- and late-type target SDSS galaxies, respectively, as seen in Fig. 1 of Park et al. (2008). The use of different values for the relative velocity condition depending on galaxy morphology is supported by different velocity distributions of neighboring galaxies depending on galaxy morphology, as shown in Fig. 1 of Park et al. (2008) and Fig. 2 of Park & Choi (2009) for SDSS galaxies and Fig. 3 of Hwang & Park (2009) for GOODS galaxies. Because we used volume-limited samples of galaxies with \( M_r \leq -19.5 \), we restrict our analysis to target galaxies brighter than \( M_{r, \text{target}} = -20 \) so that their neighbors (\( M_{r, \text{nei}} \leq M_{r, \text{target}} + 0.5 \)) are searched within the volume-limited samples.

The virial radius of a galaxy within which the mean mass density is 200 times the critical density of the universe (\( \rho_c \)), is calculated by

\[
r_{\text{vir}} = (3\gamma L/4\pi)(200\rho_c)^{-1/3},
\]

where \( L \) is the galaxy luminosity, and \( \gamma \) the mass-to-light ratio. Here, the mass associated with a galaxy plus dark halo

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\(^2\) Flux quality flags are either "high" or "moderate" for IRAS sources and "high" for AKARI sources.

\(^3\) http://www.mpa-garching.mpg.de/SDSS/DR7/

\(^4\) http://astro.kias.re.kr/vagc/dr7/
The mean value of density of the universe for local SDSS galaxies, \( \bar{\rho} = (0.0223 \pm 0.0005)(\gamma L)_{-20}(h^{-1}{\text{Mpc}})^{-3} \), was adopted, where \((\gamma L)_{-20}\) is the mass of a late-type galaxy with \( M_r = -20 \) (Park et al. 2008).

For high-z GOODS galaxies, we computed the mean mass density \( \bar{\rho} \) using the galaxies at \( z = 0.4-1.2 \) with various absolute magnitude limits varying from \( M_r = -16 \) to \( -20 \). We found that the mean mass density appears to converge when the magnitude cut is fainter than \( M_r = -17.5 \), which means that the contribution of faint galaxies is not significant because of their small masses. In this calculation, each galaxy is weighted by the inverse of completeness according to its apparent magnitude and color (see Fig. 1 of Hwang & Park 2009). We obtain \( \bar{\rho} = 0.017 \) and \( 0.013 (\gamma L)_{-20} \) (Mpc\(^{-3}\)) for GOODS-N and -S, respectively, where \((\gamma L)_{-20}\) is the mass of a late-type galaxy with \( M_r = -20 \). According to our formula the virial radii of galaxies with \( M_r = -20 \) and \( -21 \) are 300 and 400 h\(^{-1}\) kpc for early types, and 240 and 320 h\(^{-1}\) kpc for late types, respectively.

The spectroscopic completeness can affect the identification of the genuine nearest neighbor, and then the nearest neighbor can be seriously misidentified if the completeness is very low. Our previous Monte Carlo experiment shows that the fraction of the misidentified nearest neighbor reaches about 50\% when the sample completeness is 50\% (Hwang & Park 2009). Therefore, it is necessary to have survey data with high completeness so that one does not miss the genuine nearest neighbor. Up to now, GOODS has highest spectroscopic completeness (71-86\% for GOODS galaxies at \( m_r < 23 \)) among several extensive, deep-field surveys with HST images to our knowledge. Therefore, GOODS is the best survey data for our analysis, but it should be noted that our results could be weakened by this incompleteness. The completeness depends on the apparent magnitude and color (see Fig. 1 of Hwang & Park 2009) and also on the distance between galaxies owing to the difficulty in observing galaxies close to each other with the multiobject spectrograph (MOS). We checked the completeness as a function of the projected distance to the target galaxy, and found that it does not change with the projected distance. It might be because we combined spectroscopic data from numerous references, therefore, the difficulty in observing galaxies with small separation using MOS is significantly reduced. Similarly, the redshift information of some SDSS galaxies missed by the SDSS database was complemented by the data in the literature (Hwang et al. 2010a), so there is no bias for local galaxies, either.

Note that the nominal FWHMs of the point spread function (PSF) are 37\"(65 \mu{\text{m}}), 39\"(90 \mu{\text{m}}), 58\"(140 \mu{\text{m}}), and 61\"(160 \mu{\text{m}}) for AKARI bands (Kawada et al. 2007), and 1.4\"(60 \mu{\text{m}}) and 2.94\"(100 \mu{\text{m}}) for IRAS bands (Sanders et al. 2003). The corresponding angular size of one virial radius for typical late- and early-type galaxies with \( M_r = -21 \) and \( z = 0.035 \), is 11.3\' and 14.3\', respectively. Therefore, the galaxies in pairs are selected from galaxy catalogs in optical bands with high spatial resolutions, the measured SFRs of galaxies in close pairs cannot be clearly assigned to the individual galaxies because of the poor spatial resolution of FIR data. For example, local galaxies with \( M_r = -21 \) and \( z = 0.035 \) having neighbors at \( \leq 0.06r_{\text{FWHM}} \) (50.12 r\(_{\text{FWHM}}\)) are not resolved with AKARI 90\mu{\text{m}} (IRAS 60\mu{\text{m}}), because the pair separation is smaller than the FWHM at each band. Consequently, the measured SFRs for these galaxies can indeed indicate SFRs of the whole interacting systems. However, our results on the increased SFRs (or SSFRs) caused by galaxy-galaxy interactions that we present in Sect. 3 are not strongly affected by this effect because the increased SFRs (or SSFRs) are found to be much higher than a factor of two, which could be simply caused by this blending problem of two galaxies in one FIR beam.

For high-z galaxies, the PSF FWHMs are 6.0\" (Spitzer 24\mu{\text{m}}), 6.7\" (Herschel 100\mu{\text{m}}), 11.0\" (160\mu{\text{m}}), 18.1\" (250\mu{\text{m}}), 24.9\" (350\mu{\text{m}}), and 36.6\" (500\mu{\text{m}}). The angular size of one virial radius for typical late- and early-type galaxies with \( M_r = -21 \) would be, respectively, 70.8\' and 88.6\' at \( z = 0.6 \), and 59.1\' and 73.5\' at \( z = 1.0 \). Similar to the case of local galaxies, high-z galaxies having neighbors at \( \leq 0.07r_{\text{FWHM}} \) (50.09r\(_{\text{FWHM}}\)) are not resolved with Spitzer 24\mu{\text{m}} (source extraction on Herschel images was performed at the prior positions of Spitzer 24\mu{\text{m}}-selected sources; Elbaz et al. 2011). However, this has no effect on our conclusions.

### 3. Results

#### 3.1. Change in SSFRs as a function of pair separation

In Fig. 3 we plot several FIR properties of local (left) and high-z (right) late-type galaxies as a function of the projected distance to the nearest neighbor galaxy normalized by the virial radius of the neighbor (\( r_{\text{vir}}/r_{\text{FWHM}} \)). Note that we only plot IRAS or AKARI-selected (left) and Herschel-selected (right) late-type galaxies, but their nearest neighbors are selected among the spectroscopic samples of SDSS and GOODS galaxies regardless of FIR detections. To remain complete in terms of neighbor galaxies and remove the effect of mass on the SFA, we restrict our analysis to the late-type galaxies with \( \sim 20 \sim M_r \) and \( 10^{10} \sim M_{\ast} (M_{\odot}) \sim 10^{11} \). Therefore, even if we use the physical distance for the pair separation without using a normalization by the virial radius, the observed trends in this figure do not change.

For high-z samples, we only plot GOODS galaxies that have at most one neighbor within 6\'\prime (the full width half maximum, FWHM, of the Spitzer beam at 24\mu{\text{m}}) with \( S_{24} > 50\% \) of the central 24\mu{\text{m}} source (i.e. \( N_{\text{neigh,24\mu{\text{m}}} \leq 1} \). This criterion is introduced to reduce the contamination of neighboring sources, but to allow for the possibility of having one close neighbor to study the effects of galaxy proximity. In practice, this criterion results in the removal of only four galaxies among 330 GOODS galaxies in Fig. 3, which has no effect on our conclusions.

Assuming a Salpeter IMF, we converted the IR luminosity into SFR\(_{\text{IR}}\) using the relation in Kennicutt (1998): SFR\(_{\text{IR}}\)

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\(^{5}\) We correct a typo for \( \Omega_m(z) \) in Hwang & Park (2009), but all the related values in that paper are correct.
Because the SFR is strongly correlated with the mass (Brinchmann et al. 2004; Elbaz et al. 2007; Daddi et al. 2007; Magdis et al. 2010c), it is important to check the effects of galaxy mass on the change of SFR. Therefore we plot the distributions of stellar masses and specific SFRs (SFR$_{IR}$/M$_{star}$, SSFRs) in panels (c–f). Panels (c, d) show no significant change of masses as a function of $R_n$, but panels (e, f) suggest that a difference in SSFRs between early- and late-type neighbor galaxies is still prominent at $R_n \leq 0.5R_{\text{vir,nei}}$. We also checked the redshift distributions as a function of $R_n$ (not shown), which again shows no significant dependence on $R_n$ and the morphology of the neighbor. We used a Kolmogorov-Smirnov (K-S) test to determine whether the SSFR distributions of interacting and non-interacting galaxies with late-type neighbors are drawn from the same distribution. We tested two cases of interacting galaxies with late-type neighbors: 1) strongly interacting ($R_n \leq 0.1R_{\text{vir,nei}}$) galaxies versus non-interacting galaxies ($R_n > R_{\text{vir,nei}}$); and 2) relatively weakly interacting ($R_n \leq 0.5R_{\text{vir,nei}}$) galaxies versus non-interacting galaxies. The hypothesis that the two distributions are extracted from the same parent population can be rejected at a confidence level of $>99\%$ for both cases in the local universe. In the high-$z$ universe, the hypothesis can be rejected at a confidence level of $>99$ and $90\%$ for strongly and weakly interacting galaxies, respectively. To help the understanding of the difference in SSFRs for several subsamples, we plot in Fig. 4 the distribution of SSFRs for interacting and non-interacting galaxies in SDSS and GOODS.

The statistical significance of the increased SSFRs of interacting galaxies with late-type neighbors compared to non-interacting galaxies was also tested with a Monte Carlo (MC) test. We constructed two subsamples (with the same number of galaxies as in the actual samples) by randomly drawing the SSFRs from the whole galaxy sample and computed the median of each subsample. The resulting two subsamples will have the same medians on average. These random subsamples will tell us whether or not the difference in SSFRs between interacting and non-interacting galaxies with late-type neighbors is statistically significant. We constructed 1000 trial data sets and computed the fraction of simulated data sets in which the difference of the SSFRs is larger than or equal to that based on the real data ($f_{\text{sim2obs}}$). The significance levels of the difference defined by $100(1-f_{\text{sim2obs}})$ (%). This test also confirms the increased SSFRs of interacting galaxies with late-type neighbors compared to non-interacting galaxies with a significance level of $>99\%$ for both strongly and weakly interacting galaxies in local and high-$z$ universe.

Similarly, the statistical significance of different SSFR distributions of interacting galaxies with early- and late-type neighbors at $R_n \leq 0.5R_{\text{vir,nei}}$ is examined with the K-S and MC tests. The difference is confirmed with a significance level of 98 and
>99% from the K-S and MC tests, respectively, in the local universe, and of 98% from both K-S and MC tests in high-z universe.

To study the evolution of SSFRs depending on the morphology of the nearest neighbor, we plot in Fig. 5 the median SSFRs of strongly and weakly interacting galaxies with stellar masses similar to target galaxies, respectively. Interacting galaxies (i.e. $R_n \leq 0.5r_{\text{vir},\text{nei}}$) with early- and late-type neighbors are denoted by hatched histograms with orientation of $45^\circ$ (\ with red color) and of $315^\circ$ (\ \ with blue color) relative to horizontal, respectively.

For the early-type neighbor case (left panel in Fig. 5), the SSFRs of interacting galaxies are similar to or slightly smaller than those of non-interacting galaxies in all redshift bins. However, for the late-type neighbor case (right panel), obviously the increased SSFRs for weakly and strongly interacting galaxies are systematically higher than those for non-interacting galaxies in all redshift bins. The SSFRs of strongly and weakly interacting galaxies are, on average, higher than those of non-interacting galaxies by factors of about 4.0 and 1.2 and 1.8, respectively. If these increased SSFRs are simply caused by the blending of two galaxies with similar masses in one FIR beam without any enhanced SFA, the SSFRs are expected to increase by a factor of only two. Indeed, the neighbor-separation scale of $R_n \sim 0.05r_{\text{vir},\text{nei}}$ ($=15h^{-1}$ kpc for galaxies at $M_r = -21$) is important because the galaxies in pairs start to merge at this separation, so the SFA starts to change abruptly (Park & Choi 2009). Thus the increased SFR for strongly interacting galaxies ($R_n \leq 0.1r_{\text{vir},\text{nei}}$ $\approx 30h^{-1}$ kpc for $M_r = -21$) by a factor of four really reflects the enhancement of SFA caused by a merger.

### 3.2. Change in dust temperature as a function of pair separation

In Fig. 6 we show the dependence of dust temperature on the distance to and the morphology of the nearest neighbor galaxy. For local SDSS galaxies in (a), we plot the dust temperature derived from the flux density ratio ($S_{60}/S_{250}$) using Eq. (1) to increase the statistics. For high-z GOODS galaxies in (b), we do not use the dust temperature derived from the FIR flux density ratio because the large scatter in the correlation between Herschel flux density ratios and dust temperature makes statistics worse.

The dust temperature of both local and high-z late-type galaxies appears to increase as they approach late-type neighbors, which is clearly seen at $R_n \leq 0.1r_{\text{vir},\text{nei}}$. We also show the distribution of dust temperature in Fig. 4 for interacting and non-interacting galaxies in SDSS and GOODS. The MC test supports this different $T_{\text{dust}}$ distribution between strongly interacting and non-interacting galaxies with late-type neighbors with a significance level of 96 and >99% for local and high-z galaxies, respectively. However, there are only two GOODS galaxies at $R_n \leq 0.1r_{\text{vir},\text{nei}}$, so this trend needs to be checked with more extended data sets in future studies. On the other hand, the dust temperature of local late-type galaxies with early-type neighbors at $R_n \leq 0.1r_{\text{vir},\text{nei}}$ seems to be lower than or marginally similar to that of non-interacting galaxies. Therefore, the difference in the dust temperature of strongly interacting galaxies with late- and early-type neighbors seems to be significant, which is supported by the MC test with a significance level of 98%. For high-z galaxies, there are few late-type galaxies with close early-type neighbors at $R_n \leq 0.1r_{\text{vir},\text{nei}}$ with $T_{\text{dust}}$ measurements, so we cannot study the trend.

### 4. Discussion

The increase of SSFR for galaxies in pairs found in this study is consistent with results in previous studies at low redshifts (e.g., Kennicutt et al. 1987; Barton et al. 2000; Lambas et al. 2003; Nikolic et al. 2004; Woods & Geller 2007; Huang & Hwang 2011) and high redshifts (e.g., Lin et al. 2007; Wong et al. 2011). However, note that the amount of increased SSFR compared to isolated galaxies is different depending on the studies because the definition of interacting galaxies and the observational selection effects are different. The increase of dust temperature in local late-type galaxies that strongly interact with other late-type neighbors is also consistent with previous studies in the sense that the contribution of warm dust compared to cold dust increases with the merging sequence (Telesco et al. 1988; Xilouris et al. 2004). However, we found the hint of this trend for high-z galaxies at $0.4 \leq z \leq 1.2$ for the first time. It is also interesting to see that the dust temperature of local, late-type galaxies does not seem to increase when they are strongly interacting with early-type neighbors (see Fig. 6). Note also that the distance to the nearest neighbor might not be a direct measure of the merging sequence because galaxies in pairs would merge after several encounters and their orbital geometry is complicated.

We wish to emphasize that our analysis represents a major improvement compared to previous studies because we 1) have robust SFR measurements of galaxies with well-constrained FIR SEDs thanks to Herschel and AKARI; 2) have galaxy samples with high spectroscopic completeness (i.e. >85% for SDSS galaxies at $m_i < 17.77$ and 71–86% for GOODS galaxies at $m_i < 23$); 3) study only the galaxies that are complete in terms of neighbor galaxies with stellar masses similar to target galaxies ($M_{r,\text{nei}} \leq M_{r,\text{target}} + 0.5$); 4) distinguish the morphology...
SSFRs of interacting galaxies normalized by SSFRs of non-interacting galaxies (i.e. $R_n > r_{\text{vir,nei}}$, in Fig. 3) as a function of redshift for a) early-type and b) late-type neighbor case. Filled and open circles are median values for strongly (i.e. $R_n \leq 0.1 r_{\text{vir,nei}}$), and weakly interacting (i.e. $R_n \leq 0.5 r_{\text{vir,nei}}$) galaxies, respectively, at each redshift bin ($0.005 \leq z \leq 0.0656$, $0.4 \leq z \leq 0.8$, and $0.8 \leq z \leq 1.2$).

The dependence of SFR (or SSFR) on the morphology of the neighbor at $R_n \approx 0.5 r_{\text{vir,nei}}$ seen in Fig. 3 may imply that the hydrodynamic interactions with the nearest neighbor play critical roles in triggering the SFA of galaxies in addition to the tidal interactions. This dependence is also observed for local normal galaxies (Park & Choi 2009; Xu et al. 2010) and local LIRGs and ULIRGs (Hwang et al. 2010a), and can be explained as follows. If a late-type galaxy approaches a late-type neighbor within half of the virial radius of the neighbor, the cold gas inflow into the central region of the target galaxy from the neighbor galaxy as well as from the disk of the target galaxy increases, which results in the enhanced SFA of the target galaxy. Because of this starburst mode of compact star formation, the SSFR and the dust temperature are expected to increase as we observed (Elbaz et al. 2011; see also Chanial et al. 2007). Then when two galaxies finish merging, the end product of the merger will be bright because of the very recent SFA, and the new nearest neighbor galaxy of the merger product will be far away. This may explain the existence of some non-interacting galaxies at $R_n > r_{\text{vir,nei}}$ with high SSFRs and $T_{\text{dust}}$ as seen in Figs. 3 and 6.

On the other hand, if a galaxy approaches an early-type neighbor within the virial radius of the neighbor, the hot gas of the early-type neighbor prevents the galaxy from forming stars with cold gas, and/or there is no inflow of cold gas from its early-type neighbor, so the SFA of the galaxy is not boosted even if it does have a close companion. This may explain why not all mergers are in a starburst mode. The SF quenching mechanisms of hot gas in early-type neighbors could be similar to those of a hot intracluster medium of galaxy clusters acting on late-type galaxies in it, which are hydrodynamic processes such as thermal evaporation, strangulation, ram pressure stripping, or viscous stripping (Park & Choi 2009; Park & Hwang 2009). Indeed, the X-ray observations of galaxies in pairs with mixed morphology show evidence for extended X-ray halos of the early type that surround the late type, which supports our interpretation (Grützbauch et al. 2007). In addition, that the SSFRs in Fig. 5 are increased by similar factors in all redshift bins suggests that similar physical mechanisms (such as hydrodynamic interactions plus tidal interactions described above) have affected the SFA over at least 8 billion years.
The SFRs of galaxies are known to depend strongly on the local density in the sense that spatially averaged SFRs of galaxies or star-forming galaxy fractions decrease as the background density increases in the local universe (e.g., Lewis et al. 2002; Gómez et al. 2003; Park et al. 2007; Lee et al. 2010; Hwang et al. 2010a). In the high-z universe, some studies found similar results (e.g., Patel et al. 2009; Ferruglio et al. 2010), but there are also hints for an opposite trend (i.e., increasing SFRs or star-forming galaxy fractions with increasing the background density) known as the reversal of SFR-density relation (e.g., Elbaz et al. 2007; Popesso et al. 2011a,b). When we consider the morphology-density relation (Dressler 1980), early-(late)-type neighbors could be preferentially selected in high-(low)-density regions, and the pair separation is correlated with the local density. Therefore, the SFRs appear to depend on both large- and small-scale (attributed to the nearest neighbor) environments. One might expect that the difference in FIR properties depending on the morphology of and the distance to the nearest neighbor is simply caused by the statistical correlation between the local density and the properties of nearest neighbor. Thus, it is necessary to separate the effects of both environments.

In previous studies we have examined the effects of both large- and small-scale environments on the SFA and the morphological transformation of SDSS galaxies (Park et al. 2008; Park & Choi 2009; Hwang et al. 2010a), and on the morphological transformation of GOODS galaxies (Hwang & Park 2009). We found that the SFA of local galaxies is still strongly affected by the nearest neighbors differently depending on the morphology even at fixed large-scale background density (see Fig. 14 in Hwang et al. 2010a and Fig. 7 in Park & Choi 2009). The morphological transformation of high-z galaxies shows a similar trend (see Fig. 6 in Hwang & Park 2009). Therefore, it is expected that the role of the large-scale environment in the SFA for high-z galaxies to be weak. We tried to investigate the change in SFRs of GOODS galaxies depending on both large- and small-scale environments, and found that galaxies with early (late)-type neighbors are not preferentially selected in high (low)-density regions. This implies that there is no bias in our results introduced by the difference in the large-scale environment (see also Fig. 6 in Hwang & Park 2009). However, we could not draw meaningful conclusions on the distinction of the effects of large- and small-scale environments on the SFA because of the small number statistics, which needs to be investigated with a more comprehensive data set of IR-detected galaxies in future studies. On the other hand, a detailed analysis focusing on the effects of large-scale environment on the SFA of high-z galaxies can be found in other studies based on similar GOODS data (Elbaz et al. 2007; Popesso et al. 2011a,b).

### 5. Conclusions

Using the Herschel-selected galaxies in the GOODS fields and the IRAS plus AKARI-selected galaxies in the field of SDSS DR7, we studied the impact of galaxy-galaxy interactions on the FIR properties of galaxies and its evolution at 0 < z < 1.2. Our main results follow.

1. We found that the SFRs and SSFRs of galaxies, on average, depend on the morphology of and the distance to the nearest neighbor galaxy for all redshifts, within 0 < z < 1.2. When a late-type galaxy has a close neighbor galaxy, the SFR and SSFR increase as it approaches a late-type neighbor, which is supported by K-S and MC tests with a significance level of >99%. However, the SFR and SSFR decrease or do not change much as it approaches an early-type neighbor. The bifurcations of SFRs and SSFRs depending on the neighbor’s morphology are seen at $R_n = 0.5 r_{\text{vir}}$, which is also supported by K-S and MC tests with a significance level of >98%.

2. For the redshift range 0 < z < 1.2, the SSFRs of late-type galaxies with late-type neighbors are increased by factors of about 1.8 ± 0.7 and 4.0 ± 1.2, respectively, for the cases of weakly ($R_n \leq 0.5 r_{\text{vir}}$) and strongly interacting ($R_n \leq 0.1 r_{\text{vir}}$) galaxies compared to those of non-interacting galaxies.

3. The dust temperature of both local and high-z late-type galaxies strongly interacting with late-type neighbors appears to be higher than that of non-interacting galaxies with a significance level of 96–99%. However, the dust temperature of local late-type galaxies strongly interacting with early-type neighbors seems to be lower than or similar to that of non-interacting galaxies.

Our results suggest that galaxy-galaxy interactions and mergers have been strongly affecting the SFA and the dust properties of star-forming galaxies over at least 8 billion years.

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