MORPHOLOGICAL DEPENDENCE OF MID-INFRARED PROPERTIES OF SDSS GALAXIES IN THE SPITZER SWIRE SURVEY

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ABSTRACT

We explore the correlation between morphological types and mid-infrared (MIR) properties of an optically flux-limited sample of 154 galaxies from the Fourth Data Release (DR4) of the Sloan Digital Sky Survey (SDSS), cross-correlated with Spitzer SWIRE fields of ELAIS-N1, ELAIS-N2, and the Lockman Hole. Aperture photometry is performed on the SDSS and Spitzer images to obtain optical and MIR properties. The morphological classifications are given based on both visual inspection and bulge-disk decomposition in SDSS g- and r-band images. The average bulge-to-total ratio (B/T) is a smooth function over different morphological types. Both the 8 μm (dust) and 24 μm (dust) luminosities and their relative luminosity ratios to 3.6 μm (MIR dust-to-star ratios) present obvious correlations with both the Hubble T-type and B/T. The early-type galaxies notably differ from the late types in the MIR properties, especially in the MIR dust-to-star ratios. It is suggested that the MIR dust-to-star ratio of either νLr/[νLr][3.6 μm] or νLr/[24 μm (dust)]/[νLr][3.6 μm] is an effective way to separate the early-type galaxies from the late-type ones. Based on the tight correlation between the stellar mass and the 3.6 μm luminosity, we have derived a formula to calculate the stellar mass from the latter. We have also investigated the MIR properties of both edge-on galaxies and barred galaxies in our sample. Since they present similar MIR properties to the other sample galaxies, they do not influence the MIR properties obtained for the entire sample.

Key words: galaxies: formation — galaxies: statistics — galaxies: structure — infrared: galaxies

Online material: color figures

1. INTRODUCTION

Ever since Hubble’s famous paper outlined his classification system (Hubble 1926, 1936), morphological classification in conjunction with physical measurement has become an important tool in extragalactic astrophysics. A number of quantitative classifiers have been developed or extended over the years to probe the structure of galaxies. There are parametric classifiers like radial multi-Gaussian deconvolution (Bendinelli 1991) and bulge-disk decomposition (Byun & Freeman 1995), and nonparametric ones such as the C-A system (Abraham et al. 1994, 1996), artificial neural nets trained from visual classification sets (Odehwan et al. 1996), and the Gini coefficient (Lotz et al. 2004). As one of the main quantitative criteria and as a function of the Hubble classification, bulge-disk decomposition has now been widely used as an effective method to examine galaxy structures and morphological properties, (e.g., de Jong 1996; Baggett et al. 1998; Tasca & White 2005; Allen et al. 2006).

The variations of galaxy physical properties with morphology and environment are crucial in our understanding of the evolution of galaxies (Kennicutt 1998; Brinchmann et al. 2004). Numbers of properties such as the integrated birthrate variation (Sandage 1986), the optical and infrared photometric properties (Boselli et al. 2001; Shimasaku et al. 2001; Popescu et al. 2002; Davoobi et al. 2006), the star formation properties of galaxies in clusters (Yuan et al. 2005), the circumnuclear Hα luminosity and bar structures (Shi et al. 2006), and the statistical properties of spiral galaxies (Ma 2000) that have been investigated present regularity or correlation along different morphological types. Through substantial former investigations, it is known that as a result of different stellar populations and the amount of dust and gas for the environment of star forming, the early-type galaxies (ellipticals and lenticulars) exhibit rather different properties compared with the late-type ones (spirals, irregulars, and so on).

As we know, on average one-third of the total luminosity from normal galaxies is absorbed and reradiated by dust (Mathis 1990; Popescu & Tuffs 2002), and an even higher fraction from galaxies with the most star-forming activity (e.g., luminous infrared galaxies [LIGs; Sanders & Mirabel 1996; Wang et al. 2006]). Both the Infrared Space Observatory (ISO; Kessler et al. 1996) and the Spitzer Space Telescope (Werner et al. 2004) continue to explore the importance of dust. Studies of dusty starburst galaxies (Poggianti & Wu 2000; Flores et al. 2004) have shown that most of the activities (e.g., star formation and/or AGN emission) in these galaxies are hidden by dust, and the bolometric luminosities of the active systems are mostly emitted in the infrared. This suggests that the infrared emission is a sensitive tracer of the young stellar population and star formation rates (SFRs), and suffers weaker extinction. The MIR dust emissions mainly consist of polycyclic aromatic hydrocarbon (PAH) emission and the continuum emission feature of the warm dust component. Both of these components have been investigated as reliable measures of the SFRs of galaxies as a whole (Peeters et al. 2004; Wu et al. 2005), whereas studies in the MIR properties will certainly improve our understanding of the galaxies which have been well studied in the optical bands, and give an insight into the details of their star formation histories.

This work tries to explore the relationships between the morphology and the MIR properties for a flux-limited sample of normal galaxies which were selected from the galaxies of SDSS DR4 (Adelman-McCarthy et al. 2006) cross-correlated with the SWIRE (Spitzer Wide-Area Infrared Extragalactic) survey (Lonsdale et al. 2003). Considering that the Spitzer IRAC (Fazio et al. 2004) 8 μm band covers the strongest PAH feature (7.7 μm), and the MIPS (Rieke et al. 2004) 24 μm band covers the continuum emission of very small grains (VSGs) free of PAH features, we tried to employ...
the IRAC bands and MIPS 24 μm band to investigate the MIR dust properties of entire galaxies. We performed elliptical aperture photometric analysis in both the optical and MIR bands. The 8 μm dust and 24 μm dust luminosity and their dust-to-stellar ratios are used to quantitatively investigate the MIR properties of our sample galaxies. Two ways to classify the morphologies of the sample galaxies were adopted: the T-type of the revised Hubble classification system (de Vaucouleurs et al. 1976) by visual inspection, and the quantitative parameter of $B/T$ by bulge-disk decomposition.

In § 2 we describe the infrared and optical data, the sample construction, and the elliptical aperture photometry. The morphological classifications are presented in § 3. In § 4 we analyze the optical and MIR colors and give the statistical results of the MIR dust properties against galaxy morphological types and the corresponding discussions. The conclusions are presented in § 5. Throughout this paper we assume a Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ in calculating the distance and the luminosity.

2. DATA AND DATA REDUCTION

2.1. The Sample

We used the IRAC 3.6, 4.5, 5.8, and 8.0 μm and the MIPS 24 μm images from the northern SWIRE fields of the Lockman Hole, ELAIS-N1, and ELAIS-N2. The BCD (basic calibrated data) images of the four IRAC bands were obtained from the Spitzer Science Center, which include flat-field corrections, dark subtraction, and linearity and flux calibrations (Fazio et al. 2004). The IRAC images (in all four bands) were mosaicked from the BCD images after pointing refinement, distortion correction, and cosmic-ray removal, with a final pixel scale of 1.225′′.

The MIPS 24 μm images were mosaicked in a similar way with a final pixel scale of 0.6″ as described by Huang et al. (2004) and Wu et al. (2005a); likewise, the MIPS 24 μm images were mosaicked from the SWIRE MIR catalog measured by SExtractor (Bertin & Arnouts 1996) in the four IRAC bands and MIPS 24 μm were matched with Two Micron All Sky Survey (2MASS) sources to achieve astrometric uncertainties of around 0.1″.

The SDSS data provide full coverage of the SWIRE fields of the Lockman Hole and ELAIS-N2 but cover only one-third of the ELAIS-N1 field. The ugriz-selected frames of spectrophotometrically observed galaxies were taken from the SDSS DR4. The pixel scale of SDSS images is 0.4″ (Stoughton et al. 2002). The SDSS DR4 ugriz spectrophotometric catalog was cross-correlated with the SWIRE MIR catalog measured by SExtractor (Bertin & Arnouts 1996) with a radius of 2″. The total survey area of the three northern SWIRE fields is ~24 deg$^2$, of which the overlap with SDSS is ~15 deg$^2$.

To obtain a reliable morphological classification (Fukugita et al. 2004), 163 bright galaxies with Petrosian magnitude $r \leq 15.9$ were selected. Only four SDSS galaxies were not matched with SWIRE MIR sources by 2″, since the SDSS fiber observations mistakenly pointed to the off-nuclear regions rather than the nuclear regions of galaxies. This provided a preliminary sample of 159 galaxies.

We excluded a further five galaxies in our magnitude-limited sample of 159 galaxies, because they failed in either the sky-background subtraction or the bulge-disk decomposition, or were severely contaminated by nearby bright stars. This led to an SDSS r-band flux-limited final sample of 154 galaxies; 142 of this sample have been imaged by the four IRAC bands, and 137 have been imaged by the MIPS 24 μm band. Finally, a subsample of 125 galaxies has images in all five MIR bands and is used for further statistical discussion in § 4.4. All of these objects are local, with redshifts less than 0.13. In our sample, six galaxies had an absolute $B$ magnitude fainter than −18, and were thus classified as dwarf galaxies (Mateo 1998). Here, the $B$ magnitude can be obtained from the SDSS $g$ and $r$ magnitudes (Smith et al. 2002). The distributions of the SDSS r-band Petrosian magnitudes, the redshift, and the $B$-band absolute magnitudes for the 154 sample galaxies, as well as those for the 125 subsample galaxies, are plotted in Figure 1. All these distributions show that the subsample can well represent the flux-limited sample.

Among the 154 sample galaxies, 133 with emission-line detections could be classified with the traditional log (O iii/ Hβ)-log (N ii/Hα) diagnostic diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). The emission-line fluxes were derived from the catalog of Tremonti et al. (2004). The criteria given by Kewley et al. (2001) were adopted to distinguish the potential star-forming galaxies from AGNs, as is shown in Figure 2.

2.2. Photometry

To obtain accurate photometry, sky background fitting and subtraction were done (Zheng et al. 1999; Wu et al. 2002, 2005b) on both the SDSS-corrected frames and the Spitzer images. All objects detected by SExtractor were masked to generate a background-only image, and the fitted sky background was then subtracted. Photometry was performed on the background-subtracted images by the IRAF task e2dipse (Jedrzejewski 1987). To contain almost all the flux of these extended sources in the different bands, an elliptical isophote with a $B$-band surface brightness of 26 mag arcsec$^{-2}$ was adopted as the photometric aperture, based on the SDSS g-band images. With such elliptical apertures, the total fluxes were measured in all the wavelengths including the SDSS ugriz, the four IRAC bands, and the MIPS 24 μm band (see the sample apertures marked in Fig. 3) with the IRAF task polyphot. Note that the point-spread functions (PSFs) of MIPS 24 μm are rather extended; therefore, further aperture corrections were performed on this band. For objects with an equivalent radius of the elliptical apertures smaller than 15″, aperture corrections were applied to calibrate the integrated flux to an equivalent radius of 15″. The photometric accuracies of these different bands are quite small, less than 0.03 mag on average. The flux calibration accuracies of the four IRAC bands (Fazio et al. 2004) and the MIPS 24 μm band (Rieke et al. 2004) are less than 10%. The final errors include both the above errors.

The Galactic extinction in each SDSS filter from the SDSS DR4 catalog was adopted, and then the intrinsic extinction was derived from the Balmer decrement (Calzetti 2001). The photometric K-correction was calculated using the method of Blanton et al. (2003), kcorrect v4_1_4. No extinction correction was performed on the photometric results in the MIR bands, since the extinction effect is rather negligible in the infrared compared with the optical wavelength. Due to the fact that our sample are all low-redshift galaxies and, as of this work, there is no reliable K-correction for these MIR spectral ranges available yet, we applied no K-correction to the MIR photometry. All the measurements were converted to AB magnitudes (Oke & Gunn 1983).

Although PAH and VSG emissions dominate the 8 and 24 μm bands for the majority of our sample, there is still a stellar continuum in these bands, especially for the early-type galaxies. Here with a subtraction of the stellar contribution using the 3.6 μm luminosity was adopted, with a scale factor of 0.232 for the 8 μm band and 0.032 for the 24 μm band (Helou et al. 2004). Hereafter, we use 8 μm (dust) and 24 μm (dust) to represent the dust emissions after subtracting the stellar contribution (Wu et al. 2005a).
3. MORPHOLOGICAL CLASSIFICATION

We conducted the morphological classification by two methods: visual inspection and bulge-disk decomposition with GIM2D (Galaxy Image 2D; Simard 1998; Simard et al. 2002).

3.1. GIM2D Fitting

GIM2D is a two-dimensional photometric-decomposition fitting algorithm which fits each image to a superposition of a bulge component with a Sérsic profile, and a disk component with an exponential profile (Simard 1998; Simard et al. 2002). GIM2D was employed to obtain the structural parameters of galaxies in our sample. The bulge component of the model is a profile of Sérsic form (Sérsic 1968):

\[ \Sigma(r) = \Sigma_e \exp \left\{ -b \left( \frac{r}{r_e} \right)^{1/n} - 1 \right\}, \]  

(1)

where \( \Sigma(r) \) is the surface brightness at radius \( r \) and \( \Sigma_e \) is the characteristic value (i.e., the effective surface brightness), defined as the brightness at the effective radius \( r_e \). Parameter \( b \) is related to the Sérsic index \( n \) and is chosen to equal 1.9992\( n - 0.3271 \) so that \( r_e \) remains the projected radius enclosing half of the light in this...
component (Ciotti 1991). The disk component is an exponential profile of the form

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d),$$

(2)

where $\Sigma_0$ is the central surface brightness and $r_d$ is the disk scale length.

Decomposition was performed based on this model, with a Gaussian PSF. A total of 12 parameters were adjusted in fitting the galaxy image and retrieved as output from our decomposition: the total luminosity $L$, the bulge fraction $B/T$, the bulge effective radius $r_e$, the bulge ellipticity $e$, the bulge position angle $\phi_b$, the disk scale length $r_d$, the disk inclination angle $i$, the disk position angle $\phi_d$, the centroiding offsets $dx$ and $dy$, the Sérsic index $n$, and the Sérsic profile of the bulge.

Fig. 3.—Examples of the science, mask, model, and residual SDSS $r$-band images for our sample for galaxies corresponding to our morphological types: E/S0, Sa, Sb, Sc, Sd, and Irr (top to bottom). Elliptical isophotes for aperture photometry are overlaid in the first column.
and the residual sky background level $db$. The $B/T$ which is defined as the fraction of the total flux in the bulge component has been extracted as a quantitative indicator of morphology, where $B/T = 1$ corresponds to a pure bulge, while $B/T = 0$ corresponds to a pure disk. With all the objects detected by SExtractor flagged except the galaxy of interest, the $g$-band mask images were adopted not only in the $g$ band but also in the $r$ band, throughout the decomposition fitting with GIM2D. Figure 3 shows example (science, mask, model, and residual) images of different morphological types in GIM2D fitting. The returned $\chi^2$ values of the $g$- and $r$-band fitting have mean values of 1.14 and 1.18 with deviations of 0.26 and 0.33, respectively, representing rather convincing fitting results.

To check the results obtained, we compared the parameters $B/T$ of the 154 galaxies estimated from the $g$ and $r$ band in Figure 4. The $B/T$ values obtained from both bands agree well, with a small amount of deviation. Among the three most deviated sources, SDSS J161222.61+525827.9 is an early-type galaxy with a highly centralized surface brightness distribution in the bluer band. SDSS J151723.30+593517.0 is a peculiar galaxy, and UGC 5888 is an irregular. We adopted $B/T$ values derived from $r$-band images throughout the following investigation, since the decomposition results in the two SDSS bands hold quite good agreement.

### 3.2. Visual Classification

The morphological types of the revised Hubble sequence (de Vaucouleurs & de Vaucouleurs 1964) of our sample galaxies were classified by visual inspection based on features like bulge ratios, the presence of spiral arms and/or bars, signs of interaction, and multiple nuclei. All galaxies in our sample were classified into six morphological classes: $T = 0$ (E or S0), 1 (Sa), 3 (Sb), 5 (Sc), 7 (Sd), and 9 (Irr). Notice that we assigned an additional class 10 corresponding to galaxies with peculiar morphology possibly related to galactic interactions, mergers, etc. We performed the visual classification in both the SDSS $g$- and $r$-band images. The classifications were made independently by the four of us, agree in over 90% of the sample. The classifications were verified for 36 of those galaxies whose morphological types were found in the NASA/IPAC Extragalactic Database (NED)\(^4\) and were found to be accurate to $\Delta T = \pm 1$.

### 3.3. Comparison

A comparison between Hubble $T$-type and the bulge-to-total ratio $B/T$ has been carried out, as shown in Figure 5. Except for the peculiar galaxies, which exhibit a diversity of $B/T$, there is a smooth inclination $B/T$ along the Hubble sequence from $T = 9$ to $T = 0$; i.e., for normal galaxies, except for the peculiar, the late types exhibit lower $B/T$ than the early types. Hence $B/T$ does act as a reliable measure of morphological type for normal galaxies in our sample. In order to statistically examine the properties of our sample, the galaxies have been divided into two morphological types: the early type ($E/S0$) with $T = 0$ and the late type ($Sa$, $Sb$, $Sc$, $Sd$, and $Irr$) with $T$ from 1 to 9. Consequently, according to Simien & de Vaucouleurs (1986), such a classification roughly corresponds to the division of $B/T = 0.4$. Out of the 144 normal sample objects, 128 coincide with their morphological types classified with $T$. The divisions are shown in Figure 5. Since as a whole divisions with the two methods agree with each other, considering the possible effects that inclinations and bar structures may cause, we further divided the sample galaxies into three types: barred galaxies, edge-on galaxies, and the rest defined as general galaxies for further consideration. Note that when defining edge-on galaxies, we adopted a standard GIM2D fitted disk inclination angle $i > 70^\circ$. Table 1 shows the numbers and corresponding fractions of different morphological types in our sample. In Table 2 we present the numbers of galaxies observed by different MIR bands in each morphological type. It can be drawn from Table 2 that the morphological fractions $E/S0 : S(Sa-Sd)$: Irr of the optical – 8 $\mu$m and optical – 24 $\mu$m samples are 0.47:0.51:0.014 and 0.44:0.54:0.016, respectively. Both are consistent with an E($E/S0-S0$): S($S0a-Sdm$): Im of 0.40:0.57:0.014 obtained from an optically selected sample of SDSS galaxies (Fukugita et al. 2007).

### Table 1

| Type      | E/S0 | Sa | Sb | Sc | Sd | Irr | Normal | Pec |
|-----------|------|----|----|----|----|-----|--------|-----|
| General   | 53   | 13 | 13 | 11 | 1  | 2   | 93     | 7   |
| Barred    | 6    | 6  | 8  | 7  | 1  | 0   | 28     | 2   |
| Edge-on   | 7    | 6  | 5  | 4  | 1  | 0   | 23     | 1   |
| Total     | 66   | 25 | 26 | 22 | 3  | 2   | 144    | 10  |
| Percent   | 42.9 | 16.2 | 16.9 | 14.3 | 1.9 | 1.3 | 93.5   | 6.5 |

Notes.—shown are the respective numbers and fractions of different morphological types and the classes of 154 sample galaxies. Note that throughout the discussion in this paper, unless particularly stated, general, barred and edge-on types are referred to as normal galaxies (from $T = 0$ to $T = 9$), while peculiar galaxies are an independent class.

### Table 2

| Band ($\mu$m) | E/S0 | Sa | Sb | Sc | Sd | Irr | Total |
|--------------|------|----|----|----|----|-----|-------|
| 3.6........... | 61   | 22 | 26 | 21 | 3  | 2   | 145   |
| 4.5........... | 66   | 24 | 25 | 21 | 2  | 2   | 150   |
| 5.8........... | 61   | 22 | 26 | 21 | 3  | 2   | 145   |
| 8.0........... | 66   | 24 | 25 | 21 | 2  | 2   | 150   |
| 24............ | 57   | 22 | 23 | 22 | 3  | 2   | 137   |
| All bands..... | 53   | 19 | 20 | 21 | 2  | 2   | 125   |

Notes.—The table shows the respective numbers of different morphological types in each of the four IRAC bands and the MIPS 24 $\mu$m band, and also in the subsample whose 125 galaxies have images in all MIR bands.

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\(^4\) See http://nedwww.ipac.caltech.edu/index.html.
we have adopted the T-type to divide the sample galaxies into either early type or late type in the following statistics.

4. RESULT AND DISCUSSION

4.1. Color-Color Diagram

The optical-MIR color-color diagrams are shown in the left panels of Figure 6, and there are anticorrelations between the optical and MIR colors, which is consistent with the result of Hogg et al. (2005). Such a trend can be explained rather naturally: the optically blue color is related to the recent star formation, indicating the existence of a notable amount of dust, and the MIR dust emission can be shown in both the 8 and 24 μm bands. On the other hand, optically red galaxies are always too old to contain plenty of dust, and hence present weak MIR dust emission.

The right panels of Figure 6 show the relationship between MIR colors. It can be seen that the [3.6] - [4.5] colors in our sample are quite blue, with an average of around 0.52, indicating that there are no extremely active galactic nuclei (QSOs, etc.) in our sample, because the emissions at both 3.6 and 4.5 μm of the normal galaxies are dominated by the decreasing stellar continuum of the old stellar population. Yet these two bands of very active galaxies such as quasars are dominated by the power-law spectra of

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**Fig. 5.** — Correlation between the bulge-to-total ratio B/T and T-type. The mean values of each type (including barred, edge-on, and general types) are overlaid in black diamonds, with the standard deviation shown. Dwarf galaxies are overlaid with gray diamonds. Divisions of normal galaxies by early type and late type are plotted, using T and B/T = 0.4, with peculiar galaxies excluded. The typical errors of sample galaxies are plotted in the upper right corner. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 6.** — Color-color diagrams of our sample. The left panels show the dereddened g - r color against MIR colors, while the right show the MIR color-color diagram. The symbols are defined as in Fig. 5. The typical errors are plotted in the lower right corners. [See the electronic edition of the Journal for a color version of this figure.]
4.2. Estimation of the Stellar Mass

The luminosity of the 3.6 μm band is often treated as a tracer of the stellar component (Wu et al. 2005a; Davoodi et al. 2006; etc.), as well as a test of the validity of the mass determination (Hancock et al. 2007). Furthermore, Hancock et al. (2007) have compared the mass of clumps in Arp 82 derived from R-band fluxes and broadband colors against luminosities at 3.6 μm, and have found a strong correlation between them. Here the relationship between the stellar masses and the 3.6 μm luminosities of our sample galaxies is examined. Based on the optical photometries as described in § 2.2, we calculated the stellar mass of our sample, following Bell et al. (2003):

\[
\log \left( \frac{M_*}{M_\odot} \right) = -0.4(M_r,\text{AB} - 4.67) + [a_r + b_r(g - r)_{\text{AB}} + 0.15],
\]

where \(M_r,\text{AB}\) is the r-band absolute magnitude and \((g - r)_{\text{AB}}\) is the rest-frame color in the AB magnitude system. The coefficients \(a_r\) and \(b_r\) come from Table 7 of Bell et al. (2003). A Salpeter (1955) stellar initial mass function has been adopted with \(\alpha = 2.35\) and 0.1 \(M_* < M < 100 M_\odot\). The distribution of the stellar mass for our sample galaxies is presented in Figure 1, in a range between \(10^9\) and \(10^{12} M_\odot\), with the average mass around \(10^{11} M_\odot\) for intermediate-mass galaxies.

A tight correlation of the stellar mass against the luminosity at 3.6 μm is detected for our sample, as shown in Figure 7. Our result is consistent with that found by Hancock et al. (2007) but with smaller scatter; thus, it confirms the capability of the 3.6 μm luminosity of measuring the stellar mass of galaxies. Based on our 145 galaxies and 24 clumps in Arp 82 (Hancock et al. 2007), we fit the relation between the stellar mass and the 3.6 μm luminosity and obtain a nearly linear correlation:

\[
\log \left( \frac{M_*}{M_\odot} \right) = (1.34 \pm 0.09) + (1.00 \pm 0.01) \log \left( \frac{\nu L_\nu[3.6 \mu m]}{L_\odot} \right).
\]

As is pointed out by Charlot (1996) and Madau et al. (1998), the mass-to-infrared light ratio is relatively insensitive to the star formation history, and remains very close to unity, independent of either galaxy color or Hubble type. This relation is probably due to the fact that in the near-infrared, older stellar populations may dominate both the galaxy luminosities and the stellar masses. Therefore, such a correlation provides a proxy way to estimate the stellar mass of galaxies directly from the integrated 3.6 μm luminosity.

4.3. MIR Properties and Morphology

Figure 8 shows the 8 and 24 μm dust luminosities as functions of the different morphological types in our sample. For normal galaxies, except the dwarfs, along either the Hubble T-type or the B/T ratio there exist obvious declinations of the MIR luminosities from the late-type to the early-type galaxies, especially showing a steep change around the division of the late-type and the early-type galaxies. All the peculiar galaxies show relatively higher MIR luminosities, independent of their B/T ratios. This phenomenon could be attributed to the fact that early-type galaxies are dominated by an older population and are deficient of dust, resulting in lower MIR dust luminosities, while the late type contain a larger amount of young stars and more dust, and thus present stronger MIR emission. Peculiar galaxies, which are undergoing strong star-forming activities, contain a great amount of dust and therefore show high MIR luminosities on average. As Wu et al. (2005a) have pointed out, both the 8 and 24 μm dust luminosities can be used as measures of the SFRs of entire galaxies; therefore, the correlations between the MIR dust luminosities and morphological types reflect a consequent relationship between the galactic SFRs and morphological types. This also confirms the previous results of Sandage (1986), Kennicutt (1998), etc. As for the six dwarf galaxies, because they all have a low mass of around \(10^9 M_\odot\) (from the previous mass determination), they contain less dust and thus show lower MIR dust emission (Hogg et al. 2005).

The MIR dust-to-star ratios are also plotted against different morphological types, in Figure 9. Prominent correlations are also detected between the MIR dust-to-star ratios and both the Hubble T-types and the B/T ratios. Furthermore, such correlations seem to be more obvious than those between the MIR luminosities and morphological types. Since both the 8 and 24 μm dust luminosities possess correlations with SFRs for normal galaxies, and the 3.6 μm luminosity is a reliable tracer of the stellar component, such ratios can be treated like the dust-to-star ratios. The correlations between the MIR dust-to-star ratios and the morphological types could represent the distribution of SFRs per unit stellar mass.
Wen et al. (2007) over different morphologies. Contrary to the behavior in Figure 8, the dwarf galaxies are roughly consistent with the other late-type galaxies within the error bars, but still present a little lower dust-to-star ratios. This could be explained with the fact that the gravitational potentials of these low-mass galaxies may not be strong enough to retain as much dust and gas against the radiation fields as those of the normal-mass galaxies, and therefore all the dwarf galaxies show slightly lower MIR dust-to-star ratios. Almost all the peculiar galaxies present higher MIR dust-to-star ratios.

The ratio of the 8 μm dust luminosity to the 24 μm dust luminosity is compared with different morphological types in Figure 10. Considering that the 8 μm dust emission mainly represents emission from PAHs heated by B-type stars, while the 24 μm dust emission is from hot dust mostly heated by O-type stars (Peeters et al. 2004), this ratio can be treated as the estimation of the ratio between these two components. In general, 8 μm (dust) to 24 μm (dust) ratios remain constant on average along the Hubble sequence, while the larger scatter in distribution of the early type probably arises from the existence of nuclear AGNs, which destroy PAH emission, presumably due to photodestruction of the PAH molecules by extreme-UV/X-ray photons (Genzel et al. 1998; Siebenmorgen et al. 2004), or the outer diffuse PAH emissions heated by the older stars (Sauvage et al. 2005). This can also be seen below in Figure 12, where AGNs present lower 8 μm (dust) luminosities. It should be noted that the two dwarf irregular galaxies exhibit lower 8 μm (dust) to 24 μm (dust) ratios than most of the late type do, possibly due to their low metallicities (Engelbracht et al. 2005).

The above result indicates that for the normal galaxies, except for the dwarfs, the ratio of these two dust components does not vary much against morphology. Therefore, the 8 μm (dust) luminosities are as capable of tracing the galaxy SFRs as the 24 μm (dust) luminosities, as Wu et al. (2005a) have pointed out.

4.4. Statistics of MIR Properties

In order to compare the statistical MIR properties of different types of sample galaxies, we performed all the following statistics on the subsample of 125 galaxies which have photometric information for all the optical and MIR bands. Since from Figure 1 and K-S test results this subsample does not exhibit notable differences from the 154 galaxy sample, we suggest that the following statistical discussions are representative of all the sample galaxies.

Distributions of the MIR luminosities and dust-to-star ratios for both the early-type and the late-type galaxies in the subsample are presented in Figure 11. It is clear that, in general, the late-type galaxies exhibit quite different MIR properties from the early-type ones, presenting distinct and statistically higher MIR luminosities and dust-to-star ratios. The Gaussian fitting is performed on

\[ \text{With metallicity } 12 + \log (O/H) = 8.55 \text{ and } 8.35, \text{ respectively, about } 3/4 \text{ and } 1/2 \text{ the solar value (Asplund et al. 2004).} \]
each distribution, and the line-intersection points of the two Gaussian distributions are presented as the division of the two morphological types. In Table 3 the median values and the mean values together with scatters of distributions of the early-type and the late-type galaxies are listed. Probabilities that the distributions of these two types can match are all smaller than $8 \times 10^{-5}$, indicating that they present quite distinct properties. Therefore, both the MIR luminosities and dust-to-star ratios can be used to separate the early-type galaxies from the late-type ones. Table 7 displays specific values of divisions and the reliability of such classifications. We define the reliability of classification as the fraction of galaxies from the subsample that are selected by Hubble $T$-types.

For example, out of the 117 normal galaxies which have images in all IRAC bands, the $T$-type criterion selects 64 late-type galaxies and 53 early types. Also, 47 of the 64 late-type galaxies have $\log [\nu L_\nu(8 \mu m)/L_\odot] > 8.91$, and thus are consistently classified as late type, while 47 of the 53 early types have $\log [\nu L_\nu(8 \mu m)/L_\odot] \leq 8.91$, and thus are classified as early type. Therefore, the $\log [\nu L_\nu(8 \mu m)/L_\odot] = 8.91$ maintains a reliability of 73% for selecting late-type galaxies and 89% for early types. Correspondingly, $\log [\nu L_\nu(24 \mu m)/L_\odot] = 8.30$ gives a reliability of 70% for the late types and 77% for the early types; $\log [\nu L_\nu(8 \mu m)/\nu L_\nu(3.6 \mu m)] = -1.15$ can give 88% for the late types and 83% for the early types; and $\log [\nu L_\nu(24 \mu m)/\nu L_\nu(3.6 \mu m)] = -1.45$ can give 84% for the late types and 85% for the early types. Therefore, the MIR dust luminosities, especially the MIR dust-to-star ratios, can be effective tools for dividing the early-type galaxies from the late-type ones.

The comparisons between MIR properties of star-forming galaxies and AGNs (see § 2.1) are shown in Figure 12. Generally, star-forming galaxies present stronger MIR emission than those possessing AGN activity. From Table 4 the star-forming galaxies and AGNs show a probability of matching each other in the 8 and 24 $\mu$m dust luminosities and dust-to-star ratios of less than $2.1 \times 10^{-3}$, indicating quite different MIR properties, although not as distinct as those between the early-type and late-type ones.

Some of the sample galaxies are edge-on galaxies and some are barred galaxies. Will the galaxies in edge-on view or with bars present different MIR properties? We compare the distributions
### Table 3
**MIR Properties Distribution and Statistics for Early- and Late-Type Samples**

| Parameters | Median | Mean (Scatter) | Number | D | P  |
|------------|--------|----------------|--------|---|----|
| $\log \nu L_\nu(8 \mu m)/L_\odot$ | Early (2) | Late (3) | Early (4) | Late (5) | Early (6) | Late (7) | (8) | (9) |
|          | 8.30 | 9.30 | 8.28(0.09) | 9.13(0.10) | 53 | 64 | 0.72 | $2.9 \times 10^{-6}$ |
| $\log \nu L_\nu(24 \mu m)/L_\odot$ |          |         | 7.76 | 8.67 | 7.77(0.09) | 8.55(0.10) | 53 | 64 | 0.63 | $8.8 \times 10^{-3}$ |
| $\log \nu L_\nu(8 \mu m)/\nu L_\nu(3.6 \mu m)$ |          |         | -1.55 | -0.22 | -1.49(0.07) | -0.33(0.07) | 53 | 64 | 0.83 | $4.7 \times 10^{-8}$ |
| $\log \nu L_\nu(24 \mu m)/\nu L_\nu(3.6 \mu m)$ |          |         | -2.06 | -0.81 | -2.00(0.08) | -0.92(0.07) | 53 | 64 | 0.77 | $6.9 \times 10^{-7}$ |

**Notes.**—Cols. (2) and (3): Median values of the two compared types of sample galaxies. Cols. (4) and (5): Mean values with scatters. Cols. (6) and (7): Respective numbers in statistics. Col. (8): K-S test discrepancy $D$. Col. (9) K-S probability $P$ that the two distributions match.

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**Fig. 11.**—Distributions of MIR luminosities and dust-to-star ratios for early-type and late-type galaxies of the 125 subsample. (a) Distribution of 8 µm (dust) luminosities; (b) 24 µm (dust) luminosities; (c) 8 µm dust-to-star ratios; (d) 24 µm dust-to-star ratios. The black histogram represents the distribution of early types, and the gray is for the late types. The fitted Gaussian profile of each distribution is overlaid, with dividing lines through the intersection points of the Gaussian profiles marked. [See the electronic edition of the Journal for a color version of this figure.]
### Table 4: MIR Properties Distribution and Statistics for Star-forming and AGN Samples

| Parameters | Median | Mean (Scatter) | Number |
|------------|--------|----------------|--------|
|            | Star-forming | AGN | Star-forming | AGN | Star-forming | AGN | D | P   |
| $\log \nu L_\nu(8 \, \mu m)/L_\odot$ | 9.31 | 8.78 | 8.99(0.14) | 8.72(0.10) | 51 | 46 | 0.38 | $1.8 \times 10^{-3}$ |
| $\log \nu L_\nu(24 \, \mu m)/L_\odot$ | 8.75 | 8.27 | 8.49(0.13) | 8.16(0.10) | 51 | 46 | 0.38 | $2.1 \times 10^{-3}$ |
| $\log \nu L_\nu(8 \, \mu m)/\nu L_\nu(3.6 \, \mu m)$ | $-0.13$ | $-1.16$ | $-0.37(0.10)$ | $-1.04(0.09)$ | 51 | 46 | 0.38 | $1.8 \times 10^{-3}$ |
| $\log \nu L_\nu(24 \, \mu m)/\nu L_\nu(3.6 \, \mu m)$ | $-0.70$ | $-1.65$ | $-0.87(0.09)$ | $-1.60(0.10)$ | 51 | 46 | 0.38 | $2.1 \times 10^{-3}$ |

**Notes.**—Cols. (2) and (3): Median values of the two compared types of sample galaxies. Cols. (4) and (5): Mean values with scatters. Cols. (6) and (7): Respective numbers in statistics. Col. (8): K-S test discrepancy $D$. Col. (9) K-S probability $P$ that the two distributions match.

Fig. 12.—Distributions of MIR luminosities and dust-to-star ratios in star-forming galaxies and galaxies with AGN activity (as in Fig. 11). The gray histogram represents the distribution of star-forming galaxies, and the black is for AGNs. The division lines are the same as in Fig. 11. [See the electronic edition of the Journal for a color version of this figure.]
of the MIR dust luminosities and the MIR dust-to-star ratios between edge-on galaxies, barred galaxies, and normal galaxies in Figures 13 and 14. The statistical results are listed in Tables 5 and 6, with the probabilities of matching each of a few to a tenth of a percent, indicating rather similar distributions. Thus, neither galaxies in edge-on view nor galaxies with bars present statistical differences from the other normal galaxies in both MIR properties. Furthermore, although based on limited data points, one can still see from Figure 13 that the edge-on galaxies can also be classified into early types and late types with the division criteria described in Table 7. Therefore, the inclination of galaxies and the existence of bars do not affect our previous results.

We have also checked the distributions of the total sample of 154 galaxies in the above parameters and type comparisons, and yielded quite similar results. Therefore, the selection of this subsample does not affect the reliability of our statistical results.

5. SUMMARY

We investigated the correlations between the morphological types and the MIR properties of a local optical-flux-limited sample of galaxies selected from the spectroscopic catalog in SDSS DR4, cross-correlated with the Lockman Hole, ELAIS-N1, and ELAIS-N2 of the Spitzer SWIRE survey. Aperture photometry has been performed on all these galaxies in all optical and MIR bands. Morphological classifications have been performed by both visual inspection and bulge-disk decomposition with GIM2D. Our major results are as follows:

1. The presented analysis clearly shows that the bulge-to-total ratio \( B/T \) obtained by bulge-disk decomposition proves to be a qualified quantitative measure of the Hubble \( T \)-types. Galaxies with earlier morphological types possess larger bulge ratios, while later types have more dominant disk structures.

2. The 3.6 \( \mu m \) luminosity presents a tight correlation with the stellar mass, and this provides us a new tool to estimate the stellar mass. The empirical formula to calculate the stellar mass by the 3.6 \( \mu m \) luminosity is given in equation (4).

3. Except for dwarf galaxies and a few peculiar objects, the MIR dust luminosities of 8 and 24 \( \mu m \) exhibit correlations with either Hubble \( T \)-type or the bulge-to-total ratio \( B/T \). Such correlations are much more obvious if we use the MIR dust-to-star ratio (either \( \nu L_\nu[8 \, \mu m \, (dust)]/\nu L_\nu[3.6 \, \mu m] \) or \( \nu L_\nu[24 \, \mu m \, (dust)]/\nu L_\nu[3.6 \, \mu m] \)) instead of the MIR luminosity.

4. The MIR dust luminosity ratio of \( \nu L_\nu[8 \, \mu m \, (dust)]/\nu L_\nu[24 \, \mu m \, (dust)] \) turns out to be roughly constant against morphological type, especially for the late-type galaxies. Therefore,
TABLE 6

| Parameters | Median (1) | Mean (Scatter) | Number |
|------------|------------|----------------|--------|
|            |            | (2)            | (3)    |
|            | (4)        | (5)            | (6)    |
|            | (7)        | (8)            | (9)    |
| log $\nu L_{\nu}(8 \mu m)/L_\odot$ | 8.14 | 8.81 | 8.52(0.22) | 8.80(0.08) | 21 | 96 | 0.33 | 0.05 |
| log $\nu L_{\nu}(24 \mu m)/L_\odot$ | 7.82 | 8.31 | 7.96(0.22) | 8.21(0.09) | 21 | 96 | 0.31 | 0.08 |
| log $\nu L_{\nu}(8 \mu m)/\nu L_{\nu}(3.6 \mu m)$ | -1.26 | -0.75 | -0.94(0.19) | -0.83(0.08) | 21 | 96 | 0.25 | 0.25 |
| log $\nu L_{\nu}(24 \mu m)/\nu L_{\nu}(3.6 \mu m)$ | -1.83 | -1.37 | -1.51(0.18) | -1.42(0.09) | 21 | 96 | 0.22 | 0.40 |

Notes.—Cols. (2) and (3): Median values of the two compared types of sample galaxies. Cols. (4) and (5): Mean values with scatters. Cols. (6) and (7): Respective numbers in statistics. Col. (8): K-S test discrepancy $D$. Col. (9) K-S probability $P$ that the two distributions match.

TABLE 5

| Parameters | Median (1) | Mean (Scatter) | Number |
|------------|------------|----------------|--------|
|            |            | (2)            | (3)    |
|            | (4)        | (5)            | (6)    |
|            | (7)        | (8)            | (9)    |
| log $\nu L_{\nu}(8 \mu m)/L_\odot$ | 8.14 | 8.81 | 8.52(0.22) | 8.80(0.08) | 21 | 96 | 0.33 | 0.05 |
| log $\nu L_{\nu}(24 \mu m)/L_\odot$ | 7.82 | 8.31 | 7.96(0.22) | 8.21(0.09) | 21 | 96 | 0.31 | 0.08 |
| log $\nu L_{\nu}(8 \mu m)/\nu L_{\nu}(3.6 \mu m)$ | -1.26 | -0.75 | -0.94(0.19) | -0.83(0.08) | 21 | 96 | 0.25 | 0.25 |
| log $\nu L_{\nu}(24 \mu m)/\nu L_{\nu}(3.6 \mu m)$ | -1.83 | -1.37 | -1.51(0.18) | -1.42(0.09) | 21 | 96 | 0.22 | 0.40 |

Notes.—Cols. (2) and (3): Median values of the two compared types of sample galaxies. Cols. (4) and (5): Mean values with scatters. Cols. (6) and (7): Respective numbers in statistics. Col. (8): K-S test discrepancy $D$. Col. (9) K-S probability $P$ that the two distributions match.

Fig. 14.—Distributions of MIR luminosities and dust-to-star ratios in barred and unbarred galaxies (as in Fig. 11). The gray histogram represents the distribution of barred spirals, and the black is for the unbarred. The division lines are the same as in Fig. 11. [See the electronic edition of the Journal for a color version of this figure.]
on average, the 8 \( \mu m \) (dust) luminosity can measure the global SFRs of normal galaxies as reliably as the 24 \( \mu m \) (dust) luminosity can, regardless of the morphological type.

5. The distributions of the MIR dust luminosities and the MIR dust-to-star ratios of both the early-type and the late-type galaxies are very different. The late-type galaxies present higher MIR dust-to-star ratios of both the early-type and the late-type galaxies can, regardless of the morphological type.

6. The distributions of the MIR dust luminosities and the MIR dust-to-star ratios. The statistical results show that either galaxies in edge-on view or galaxies with bars do not present very different MIR properties from other sample galaxies.

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| Parameters                  | Divisions (2) | Reliability (L) (3) | Reliability (E) (4) |
|-----------------------------|--------------|---------------------|---------------------|
| log \( \nu L_\nu (8 \mu m) / L_B \) | 8.91         | 73                  | 89                  |
| log \( \nu L_\nu (24 \mu m) / L_B \) | 8.30         | 70                  | 77                  |
| log \( \nu L_\nu (8 \mu m) / L_\nu (3.6 \mu m) \) | −1.15        | 88                  | 83                  |
| log \( \nu L_\nu (24 \mu m) / L_\nu (3.6 \mu m) \) | −1.45        | 84                  | 85                  |

Notes.—Col. (2): Values corresponding to the division of the two types. Col. (3): Reliability for selecting late-type galaxies. Col. (4): Reliability for selecting early types.
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