Stellar mass estimation based on IRAC photometry for Spitzer SWIRE-field galaxies *

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Abstract We analyze the feasibility of estimating the stellar mass of galaxies by mid-infrared luminosities based on a large sample of galaxies cross-identified from Spitzer SWIRE fields and the SDSS spectroscopic survey. We derived the formulae to calculate the stellar mass by using IRAC 3.6 $\mu$m and 4.5 $\mu$m luminosities. The mass-to-luminosity ratios of IRAC 3.6 $\mu$m and 4.5 $\mu$m luminosities are more sensitive to the star formation history of galaxies than to other factors, such as the intrinsic extinction, metallicity and star formation rate. To remove the effect of star formation history, we used $g - r$ color to recalibrate the formulae and obtain a better result. Researchers must be more careful when estimating the stellar mass of low metallicity galaxies using our formulae. Due to the emission from dust heated by the hottest young stars, luminous infrared galaxies present higher IRAC 4.5 $\mu$m luminosities compared to IRAC 3.6 $\mu$m luminosities. For most of type-II AGNs, the nuclear activity cannot enhance 3.6 $\mu$m and 4.5 $\mu$m luminosities compared with normal galaxies. Star formation in our AGN-hosting galaxies is also very weak, almost all of which are early-type galaxies.

Key words: galaxies: stellar content — galaxies: active — infrared: galaxies

1 INTRODUCTION

It is important to obtain the mass of galaxies for understanding the evolution of the universe. We know that the dark matter halo contains most of the mass, and it can only be detected using the effect of gravitation. So generally, the total mass of galaxies could only be computed on the basis of kinematics of bright stars, clusters, or even satellite galaxies (e.g., Rogstad & Shostak 1972; Roberts & Rots 1973; Ostriker et al. 1974). However, due to the restriction of low resolution and low sensitivity of telescopes for detecting the motion of celestial bodies in high redshift galaxies, these methods are just used to derive general properties of nearby galaxies. Though the fraction of baryonic

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components in galaxies is relatively small, it could be detected and easily studied. Except for gas-dominant galaxies, stars hold most of the baryonic components in galaxies. Thus, to understand the correlation between the stellar mass and total mass, it is essential to study faint and distant galaxies. Therefore, it is necessary to seek some methods to estimate the stellar mass in galaxies.

If we know the mass-to-luminosity ratio of a galaxy, and assume an initial mass function (IMF), its stellar mass could also be estimated from the luminosity in the corresponding wavelength (e.g., Bell & de Jong 2001; Portinari et al. 2004). Traditionally, mass-to-luminosity ratios could be derived by fitting photometric colors or spectra with models. Most of the baryonic components are trapped in low mass stars, which dominate the output of galaxies in a longer wavelength range compared to the massive ones. At the same time, the short life scale of massive stars and heavy extinction in relatively short wavelength ranges restrict us to using them to detect the bulk of galactic stellar masses. Hence, being less affected by other factors, such as metallicity, star formation rate (SFR) and star formation history (SFH), luminosities in relatively longer wavelengths (for example, the near-infrared (NIR) band) are ideal tracers of the stellar mass (e.g., Cole et al. 2001; Kochanek et al. 2001). The \( K \) band luminosity distribution of distant galaxies was discussed in support of the hierarchical picture by Kauffmann & Charlot (1998). The main uncertainty in the inferred stellar masses arises from the age of the stellar population (Rix & Rieke 1993), similar to the results calculated by optical luminosities (Bell et al. 2005). The discrepancy among stellar masses derived from various methods has been found (e.g., Drory et al. 2004). For example, the uncertainty of the stellar mass estimated by the \( K \)-band luminosity alone has been discussed by Brinchmann et al. (2000). Kannappan & Gawiser (2007) compared many estimation methods for local galaxies and also showed the differences (with factors up to 2) among them.

Except for the above methods, the stellar mass could also be directly calculated using mid-infrared (MIR) luminosities in 3–5 \( \mu \)m, since emissions from the photosphere of old stars dominate the output of galaxies in this wavelength range. At the same time, the extinction and reddening in this range are clearly weak. However, using these emissions to study the universe was prevented because of the absorption of the atmosphere until the advent of space-based infrared observations. The \textit{Spitzer Space Telescope} (Werner et al. 2004) is a very useful facility to help us study the MIR to far-infrared (FIR) emission properties of galaxies. The two detectors in the shorter wavelength bands (3.6 \( \mu \)m and 4.5 \( \mu \)m) of the \textit{Spitzer} Infrared Array Camera (IRAC; Fazio et al. 2004) could be treated as stellar mass tracers of nearby galaxies, although some disturbances may exist, such as the continuum from hot dust or spectral features from polycyclic aromatic hydrocarbons (PAHs; Léger & Puget 1984; Puget & Léger 1989; Draine 2003; Wu et al. 2005). Using about 150 local galaxies, Li et al. (2007) showed that there truly existed tight correlations between the \( K \)-corrected 3.6 \( \mu \)m luminosities and the stellar mass based on Bell et al.’s (2003) formula.

In this paper, we derive the stellar mass formulae using IRAC 3.6 and 4.5 \( \mu \)m luminosities based on the observation of \textit{Spitzer} and the Sloan Digital Sky Survey (SDSS; York et al. 2000). The \textit{Spitzer} Wide-area Infrared Extragalactic Survey (SWIRE; Lonsdale et al. 2003), with a total field of \( \sim 49 \) deg\(^2\), is the largest extragalactic survey program among the six \textit{Spitzer} cycle-1 Legacy Programs, and provides us with the best opportunity to establish such correlations.

The structure of the paper is as follows. We describe the construction of our sample and the reference stellar mass in Section 2. The major results of the MIR stellar mass estimations are presented in Section 3. Discussion and summary are given in Sections 4 and 5, respectively. Throughout this paper, we adopt a \( \Lambda \)CDM cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1} \).

2 THE SAMPLE AND REFERENCE STELLAR MASS

The optical spectral sample galaxies are selected from the Sloan Digital Sky Survey’s (SDSS; York et al. 2000) main galaxy sample (Strauss et al. 2002), with \( r \)-band Petrosian magnitudes lower than 17.77 mag. A total 15 deg\(^2\) of SDSS sky matches the three northern \textit{Spitzer} SWIRE fields. The de-
derived data from SDSS DR7, including the stellar mass, was supplied by the Max-Planck-Institute for Astrophysics (MPA) and the Johns Hopkins University (JHU) in their archives.\(^1\) Compared with former data releases, such as DR4, some galaxies were excluded in DR7 due to new restrictions on the detected sources before publication by MPA/JHU. The stellar mass derived from fitting photometries with population synthesis models was treated as a reference. The foreground extinctions in all the five SDSS bands were corrected by subtracting the extinction values presented in the SDSS catalog. The IDL code by Blanton (version tag v4_1.4) was used to calculate the K-correction. The method and the SED used in this code were described in detail by Blanton et al. (2003) and Blanton & Roweis (2007).

The IRAC four band (3.6, 4.5, 5.8 and 8.0 µm) images were mosaiced from the Basic Calibrated Data (BCD; acquired from the Spitzer Science Center) after the flat-field corrections, dark subtraction, linearity and flux calibrations (Fazio et al. 2004; Huang et al. 2004), with the final pixel scale of 0.6″ (Wu et al. 2005; Cao & Wu 2007; Cao et al. 2008). The MIPS 24 µm images were mosaiced in the same way but with a pixel scale of 1.225″ (Wen et al. 2007; Cao & Wu 2007; Wu et al. 2007). Based on the catalogs of the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997; Cutri et al. 2003), we enhanced the accuracy of the astrometric calibration of 0.1″ in all five bands. The final IRAC and MIPS 24 µm flux has calibration uncertainties of less than 10% (Rieke et al. 2004). Then we matched these MIR sources with the above SDSS sample galaxies with a cross radius of 2″. For the purpose of this work, the sources with both IRAC 3.6 µm and 4.5 µm detections were selected. The basic sample contains 1454 objects. For all these sources, a set of Spectral Energy Distributions (SEDs) (Huang et al. 2007) was used to perform K-correction in IRAC 3.6 µm and 4.5 µm bands.

Only part of the galaxies (total is 659) has been mapped by 2MASS. The Extended Source Catalog (XSC) was downloaded from the archives of the Infrared Processing and Analysis Center [IPAC]\(^2\) and matched with the above sample with a cross radius of 2″. The K-correction for 2MASS NIR band flux was also based on the IDL code by Blanton et al. (2003) and Blanton & Roweis (2007). The difference in \(K_s\) band between the Vega magnitude, which was used by 2MASS catalogs and AB magnitude, is 1.84 (Finlator et al. 2000). Also, a factor of 5.12 (Finlator et al. 2000; Binney & Merrifield 1998) was used as the \(K_s\) band solar absolute magnitude.

### 2.1 Spectral Classification

Among all the 1454 galaxies, 68 with positive H\(\alpha\) equivalent widths were classified as absorption line galaxies, while the other 1386 were classified as emission line galaxies. Furthermore, emission line galaxies with detected H\(\alpha\), H\(\beta\), [OIII], and [NII] emission lines were selected, and optical spectral classifications were carried out on these 1152 galaxies, adopting the traditional BPT diagnostic diagram: [NII]/H\(\alpha\) versus [OIII]/H\(\beta\) (Baldwin et al. 1981; Veilleux & Osterbrock 1987), as shown in Figure 1. The dashed curve is from Kauffmann et al. (2003b) and the dotted curve is from Kewley et al. (2001). Objects located below the dashed curve were classified as star-forming galaxies; those between these two lines were classified as composite (starburst + AGN) galaxies (Kewley et al. 2006; Wu et al. 1998); while those above the dotted line were classified as narrow-line AGNs. Therefore, the final sample contains 1220 galaxies, including 561 star-forming galaxies, 292 composites, 299 narrow-line AGNs, and 68 absorption line galaxies; 544 members of this final sample have the 2MASS \(K_s\) band flux.

Wu et al. (2007) presented an equation to compute \(d_{\text{AGN}}\), that represents the amount of AGN activity, defined as the distance of an AGN from its position \((x_p, y_p)\) index in the traditional line-diagnostic diagram [OIII]/H\(\beta\) versus [NII]/H\(\alpha\) to the Kewley et al. (2001)’s curve along the parallel of the best linear fitting of 27 AGNs. This is quite similar to the star-forming distance defined by Kewley et al. (2006) in the diagnostic diagram [OIII]/H\(\beta\) versus [OI]/H\(\alpha\) or [SII]/H\(\alpha\). Here, we also

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\(^1\) http://www.mpa-garching.mpg.de/SDSS/DR7
\(^2\) http://irsa.ipac.caltech.edu/
Fig. 1 BPT diagnostic diagram: [NII]/H$\alpha$ vs [OIII]/H$\beta$. The criteria from Kauffmann et al. (2003b) and Kewley et al. (2001) are illustrated as dotted and dashed curves, respectively. The objects below the dotted curve are defined as star-forming galaxies. The triangles between the above two curves are those classified as composite galaxies, while the boxes above the dashed curve denote AGNs. We use the distance $d_{AGN}$, which was defined by Wu et al. (2007), to characterize AGN activity. The two dash-dotted lines mark the boundaries that were used by Wu et al. (2007). An example was shown in this figure with an orange solid line (see electronic version).

use this formula to quantify the amount of AGN activity (see the orange solid line in Fig. 1 as an example). In Figure 1, the two dash-dotted lines above the dotted curve mark the boundaries that were used by Wu et al. (2007). Only sources whose EW(H$\beta$) values were less than –5 were selected by Wu et al. (2007). However, in this work, we did not use this limit to remove those sources with smaller values of EW(H$\beta$), such as LINERs. Therefore, many AGNs appeared outside the right boundary in Figure 1.

2.2 Define Reference Stellar Mass

The thermally pulsing asymptotic giant branch (TP-AGB) could dominate the output of galaxies at some evolutionary phases (Maraston et al. 2006; Bruzual 2007). However, lots of evolutionary tracks used in stellar population synthesis models did not consider the effect from TP-AGB. Hence, there must exist bias for the derived stellar mass when comparing observations with those models. For example, for young template models (with ages less than 2 Gyr), both Maraston et al. (2006) and Bruzual (2007) have concluded that galactic stellar masses calculated with an improved treatment of TP-AGB stars are roughly 50 to 60 percent lower. Hence, due to the lower effective surface temperature of TP-AGB, the reference stellar mass derived from optical observations could avoid the emission of TP-AGB.
The reference stellar mass used in this work was provided by MPA/JHU in their archive\(^3\). They derived stellar masses from fitting photometries (Salim et al. 2007) and spectral features (Gallazzi et al. 2005; Kauffmann et al. 2003a) with a large grid of models from BC03 (Bruzual & Charlot 2003) spanning a large range in SFH. The stellar mass derived using SDSS photometries could avoid the aperture effect which should be considered when fitting spectral features, since only a part of the region of the observed object was covered by SDSS spectral fibers with 3" diameters. For about eighty thousand galaxies randomly selected from the MPA SDSS DR4 Sample, the stellar masses derived from photometries and spectral index fits were compared and shown in Figure 2(a). We found a good correlation between them.

![Fig. 2](image.png)

**Fig. 2** Comparison of the reference stellar mass, which was derived by photometric fitting, with those from spectral feature fitting supplied by MPA/JHU (Panel (a)) for about eighty thousand galaxies randomly selected from SDSS DR4. In Panel (b), the comparison between the reference and the stellar mass computation based on the rest-frame $g-r$ color, $r$-band model magnitude and the equation by Bell et al. (2003) is presented. Please note that a factor of 0.15 was added to the equation of Bell et al. (2003) to correct the ‘diet Salpeter’ IMF to a normal Salpeter (Salpeter 1955) IMF.

If the luminosity in some wavelength ranges could be obtained, we can estimate the stellar mass by assuming the mass-to-luminosity ratio in the corresponding wavelength range. Bell et al. (2003) presented the relationship between various optical colors and mass-to-luminosity ratios. In Figure 2(b), we compared the referenced stellar mass with those computed based on the equation by Bell et al. (2003). Here, to correct the ‘diet Salpeter’ IMFs (Bell et al. 2003) to normal Salpeter (Salpeter 1955) IMFs, we added a factor of 0.15 (Bell et al. 2003) to the stellar mass calculated by using rest-frame $g-r$ color and $r$-band model magnitudes. Also, a factor of 4.67 (Bell et al. 2003) was treated as the $r$-band solar absolute magnitude (note there is a difference of 0.09 in the factor compared to the value used by Blanton et al. 2003). For the stellar mass derived from the equations of Bell et al. (2003), there is a systematic overestimation by a factor of about 0.2–0.6 dex, and such a discrepancy is more obvious for a galaxy with lower stellar mass. This trend is clearer in Figure 3. The disagreement is more obvious for lower stellar mass and bluer galaxies than higher stellar mass and redder ones, which is similar to the results supplied by Kannappan & Gawiser (2007) who found that a large discrepancy existed between their reference stellar mass and the one derived from Bell et al.’s (2003) correlations, with factors in the range of 2 to 5.

\(^3\) http://www.mpa-garching.mpg.de/SDSS/
Fig. 3 Correlations between the stellar mass ratio and the reference stellar mass (a), $g - r$ colors (b) for about eighty thousand galaxies randomly selected from SDSS DR4. The stellar mass ratio represents the discrepancies between the reference stellar mass and the stellar mass estimated based on the rest-frame $g - r$ color, $r$-band model magnitude and the equation by Bell et al. (2003) is presented. Same as in Fig. 2, a factor of 0.15 was added to the equation of Bell et al. (2003) to correct the ‘diet Salpeter’ IMF to a normal Salpeter (Salpeter 1955) IMF.

2.3 Sample Distribution

The distributions of the SDSS $B$-band absolute magnitude ($M_B$), redshift, reference stellar mass and $r$-band concentration parameters of star-forming galaxies, composite galaxies, AGNs and absorption line galaxies are shown in Figure 4. Here, $M_B$ values were calculated from the SDSS $g$ and $r$-band model magnitudes according to Smith et al. (2002). Most of the galaxies, especially composites, AGNs and absorption line galaxies, have $M_B$ values brighter than $-18$ mag, which is usually regarded as the boundary to distinguish dwarf galaxies (Thuan & Martin 1981). Few galaxies have redshifts larger than 0.15. Hence, most of the galaxies in our sample are local ones. The star-forming galaxies have lower stellar mass than the others in Figure 4(c). The morphology of galaxies was represented by $r$-band concentration parameters ($R_{50}/R_{90}$), which are defined as the ratio of two radii containing 50% and 90% of the Petrosian $r$-band luminosity. The values of $R_{50}/R_{90}$ are smaller for early-type galaxies than those of late-type galaxies. According to the distributions of four different spectral type galaxies in Figure 4(d), we found that the morphologies of the composite galaxies, AGNs and absorption line galaxies are similar, but those of star-forming galaxies are later-type ones. Therefore, on the basis of the above discussions, we find that low luminosity dwarf early-type galaxies are scarce in this sample.

3 RESULT: STELLAR MASS ESTIMATED BY MIR LUMINOSITIES

A lot of factors could effect the stellar mass estimations. Therefore, good stellar mass tracers should be insensitive to these factors. Figure 5 shows the correlations between mass-to-luminosity ratios of the 2MASS $K_s$-band and two MIR bands and various factors. The $K_s$ luminosity was proved to be an ideal stellar mass tracer. Figure 5(a1, a2, a3) presents the effect of EW(Hα) on the mass-to-luminosity ratios. EW(Hα) is Hα equivalent width and could be regarded as the representative of
Fig. 4 Distributions of (a) absolute $B$-band magnitude; (b) redshift; (c) the referenced stellar mass; (d) the concentration parameters ($R_{50}/R_{90}$) for star forming galaxies (solid lines), composites (dashed lines), AGNs (dotted lines) and absorption line galaxies (dash-dotted lines).

SFH (Kennicutt 1998). The concentration parameters ($R_{50}/R_{90}$) in Figure 5(b1, b2, b3) represent the morphology of galaxies. The effect of color excess $E(B-V)$ on the mass-to-luminosity ratios is illustrated in Figure 5(c1, c2, c3). $E(B-V)$ is for the intrinsic extinction and calculated from the Balmer decrement $F_{H\alpha}/F_{H\beta}$ (Calzetti 2001). Thus, only the emission line galaxies are plotted here. In Figure 5(d1, d2, d3), the oxygen abundance is used to represent the metallicity of star-forming galaxies (Kauffmann et al. 2003a). The oxygen abundances of the ISM were provided by Tremonti et al. (2004), which computed the abundances by fitting serial spectral features from SDSS observational spectra to models. The effect of AGN activities is shown in Figure 5(e1, e2, e3) by using $d_{AGN}$ to represent AGN activities in the same way as Wu et al. (2007). Only AGNs located between the two boundaries defined by Wu et al. (2007) were adopted. We should note, except for
Comparing the mass-to-luminosity ratios with various factors, including Hα equivalent width (a1, a2, a3), $R_{50}/R_{90}$ (b1, b2, b3), intrinsic reddening (c1, c2, c3), oxygen metallicity (d1, d2, d3) and the activity of AGN (e1, e2, e3). The 2MASS $K_s$-band luminosity is used in the upper five panels. The 3.6 $\mu$m luminosity is used in the middle five panels. The 4.5 $\mu$m luminosity is used in the bottom five panels.

In order to derive the formulae to estimate stellar masses using these three band luminosities, we first present the correlations between them and stellar masses for all the galaxies in our sample. The $K_s$-band, 3.6 $\mu$m and 4.5 $\mu$m band luminosities are plotted against stellar masses in Figure 6. The stellar masses are the reference ones described in Section 2.2. These galaxies show good correlations between the three band luminosities and stellar masses. The best nonlinear and linear fits are shown as solid and dotted lines in Figure 6, and the fitted parameters are listed in Table 1. Here, the best nonlinear fits are obtained by using two-variable regression. Similar to Li07, we can derive star mass formulae based on the non-linear correlations:

$$\log_{10} M_{\star,\text{ref}} = (-1.60 \pm 0.05) + (1.12 \pm 0.02) \times \log_{10} \nu L_{\nu}[K_s], \quad (1)$$

$$\log_{10} M_{\star,\text{ref}} = (-0.79 \pm 0.03) + (1.19 \pm 0.01) \times \log_{10} \nu L_{\nu}[3.6\mu m], \quad (2)$$

$$\log_{10} M_{\star,\text{ref}} = (-0.25 \pm 0.03) + (1.15 \pm 0.01) \times \log_{10} \nu L_{\nu}[4.5\mu m]. \quad (3)$$
Table 1 Correlation Coefficients between Stellar Mass and $K_s$-Band, 3.6 $\mu$m and 4.5 $\mu$m Luminosities

|   | $y$ | $x$ | $a$  | $b$  | $s$  | $r$   | $c$  | $N$ |
|---|-----|-----|------|------|------|-------|------|-----|
| $M_\ast$ $\nu L_\nu [K_s]$ | $-1.60\pm0.05$ | $1.12\pm0.02$ | $0.10$ | $0.94$ | $0.28\pm0.11$ | $544$ |
| $M_\ast$ $\nu L_\nu [3.6\mu m]$ | $-0.79\pm0.03$ | $1.19\pm0.01$ | $0.11$ | $0.96$ | $0.99\pm0.14$ | $1220$ |
| $M_\ast$ $\nu L_\nu [4.5\mu m]$ | $-0.25\pm0.03$ | $1.15\pm0.01$ | $0.12$ | $0.95$ | $1.17\pm0.14$ | $1220$ |

Col.(1): the reference stellar mass in solar units; Col.(2): names of luminosities; Cols.(3)–(4): the coefficients $a$ and $b$ of the nonlinear fit: $\log_{10}(y) = a + b \log_{10}(x)$; Col.(5): the standard deviation $s$ of the fitted residuals; Col.(6): the coefficient $r$ of the Spearman Rank-order correlation analysis; Col.(7): the coefficient $c$ of the linear fit: $\log_{10}(y) = c + \log_{10}(x)$; Col.(8): the number of sample galaxies used for the fitting procedures.

Fig. 6 Correlations between reference stellar mass and the 2MASS $K_s$-band, and the two IRAC band luminosities for all the galaxies. The best nonlinear and linear fits are illustrated as solid and dotted lines. The dashed lines shown in Panel (b) represent the nonlinear fits for more than one hundred luminous SWIRE-field galaxies by Li et al. (2007).

The correlations between two IRAC band luminosities and reference stellar mass are as tight as that between the $K_s$-band luminosities and referenced stellar masses. The fitted residuals’ standard deviations and the Spearman Rank-order correlation analysis coefficients of the correlations of 3.6 $\mu$m and 4.5 $\mu$m luminosities with stellar masses are 0.11 and 0.12, and 0.96 and 0.95, respectively. The dashed line shown in Figure 6(b) represents the non-linear fits for local luminous galaxies in the northern Spitzer SWIRE fields obtained by Li et al. (2007). Comparing the best non-linear fits in this work with that of Li et al. (2007), an obvious downward shift exists, especially for the non-luminous ones. For example, for galaxies with 3.6 $\mu$m luminosity of $10^9 L_\odot$, the stellar mass estimated from formula (2) would be about 0.5 dex lower than the result from the corresponding formula in Li et al. (2007). The shift could be due to the fact that different stellar mass references (Fig. 2) are used in these two works.

The above analysis ignored the effect by different SFH. In fact, there is such an effect, at least for star-forming galaxies illustrated in Figure 5(a1, a2, a3), which showed the correlations between the EW(Hα) and mass-to-luminosity ratios of the $K_s$-band, 3.6 $\mu$m and 4.5 $\mu$m luminosities. The SFH could also be represented with the $g-r$ color indicated by both Bell & de Jong (2001) and Kauffmann et al. (2003a), which was also proved to be an effective method to estimate the stellar mass by
Correlations between $EW(H\alpha)$ and $g - r$ color for all the galaxies. Due to the relatively low sensitivity in the 2MASS $K_s$-band observation, only 544 galaxies were detected and presented in Panel (b). The solid lines represent the best nonlinear fits. The dash-dotted line in Panel (a) is the respective line by Bell et al. (2003). Figure 7 shows the correlation between $g - r$ color and the $EW(H\alpha)$ of our sample galaxies. There exists an obvious anti-correlation between the $-EW(H\alpha)$ and $g - r$ color. Therefore, we calibrate the correlations between mass-to-luminosity ratios and $g - r$ color. Panels in Figure 8 show the correlations between various mass-to-luminosity ratios and $g - r$ color. Here, SDSS model magnitudes are used, and the foreground extinction and redshift have been corrected. These mass-to-luminosity ratios that are shown in Figure 8 do not constantly follow the changes in color. From these four panels, we find that redder galaxies tend to have larger mass-to-luminosity...
ratios. Using the two-variable regression, we obtain the best non-linear fits illustrated as solid lines in the four panels of Figure 8 and the fitted parameters are listed in Table 2. According to these correlations, we derive the formulae to estimate the stellar mass:

\[
\log_{10} M_{\star, ref} / L_{\nu} (r) = (-0.81 \pm 0.01) + (1.47 \pm 0.01) \times (g - r),
\]

\[
\log_{10} M_{\star, ref} / L_{\nu} (K_s) = (-1.29 \pm 0.05) + (1.42 \pm 0.06) \times (g - r),
\]

\[
\log_{10} M_{\star, ref} / L_{\nu} (3.6) = (0.23 \pm 0.01) + (1.14 \pm 0.01) \times (g - r),
\]

\[
\log_{10} M_{\star, ref} / L_{\nu} (4.5) = (0.39 \pm 0.01) + (1.17 \pm 0.02) \times (g - r).
\]

The dash-dotted line in Figure 8(a) is the respective line by Bell et al. (2003) (see their table 7, fig. 6 and fig. 20). The slope of our fit of M/L(r) vs. g – r color is much deeper than that of Bell et al. (2003). Gallazzi & Bell (2009) also found a similar discrepancy. One possible explanation is that different evolutionary population synthesis models have been used to derive the standard stellar mass. The correlation between M/L(r) and the g – r color is the tightest one, with the Spearman Rank-order correlation analysis coefficient of 0.97 and the fitted residuals’ standard deviations of 0.03. The correlations of M/L(3.6 µm) and M/L(4.5 µm) with g – r color are also tight, with fitted residuals’ standard deviations of 0.05 and 0.06, and the Spearman Rank-order correlation analysis coefficients of 0.83 and 0.80, respectively. The scatter in Figure 8(a) is apparently much smaller than those in other panels, but the slope of the correlation between M/L(r) and g – r color for red galaxies is slightly shallower than the slope for blue ones. This variation is also suggested in Kauffmann et al. (2003a) based on about 100 000 SDSS galaxies. Besides SFH, some other factors could also possibly account for this slope variation. This variation cannot be found in other panels in Figure 8. If variations exist in Figure 8(b, c, d), we cannot clearly see them due to large scatters. The distribution of mass ratios of derived stellar mass and the reference one in Figure 9 show that the stellar masses derived by using Equations (6) and (7) are much tighter than the respective ones from Equations (2) and (3).

### Table 2 Correlations of M/L and Colors

| y | x | a | b | s | r | N |
|---|---|---|---|---|---|---|
| M_{\star} / L_{\nu} (r) | g – r | -0.81±0.01 | 1.47±0.01 | 0.03 | 0.97 | 1215 |
| M_{\star} / L_{\nu} (K_s) | g – r | -1.29±0.05 | 1.42±0.06 | 0.08 | 0.54 | 410 |
| M_{\star} / L_{\nu} (3.6) | g – r | 0.23±0.01 | 1.14±0.01 | 0.05 | 0.83 | 1210 |
| M_{\star} / L_{\nu} (4.5) | g – r | 0.39±0.01 | 1.17±0.02 | 0.06 | 0.80 | 1208 |

Col.(1): various mass-to-luminosity ratios in solar units; Col.(2): g – r color; Cols.(3)–(4): the coefficients a and b of the nonlinear fit: \[ \log_{10}(g) = a + b \log_{10}(x) \]; Col.(5): the standard deviation s of the fitted residuals; Col.(6): the coefficient r of the Spearman Rank-order correlation analysis; Col.(7): the number of galaxies used in the fitting procedures.

## 4 DISCUSSION

### 4.1 Comparison with \( K_s \)-Band

\( K_s \)-band luminosity was often used to derive stellar masses of galaxies. From Figures 5, 6 and 8, we find that IRAC 3.6 µm and 4.5 µm luminosities are also good stellar mass tracers compared
with $K_s$-band luminosity, because the radiation in all these bands was dominated by old stellar populations. Additionally, for the same sky area, the effect of extinctions in IRAC 3.6 $\mu$m and 4.5 $\mu$m photometries is absolutely weaker than that in the 2MASS $K_s$-band (e.g., Gao et al. 2009). There have been very few calibrations between stellar masses and 3 $\mu$m to 5 $\mu$m emissions. One major reason is the limit of the weak transmissions of earth’s atmosphere in this wavelength range. Now, progress in space astronomy gives us the capability to observe the MIR sky directly.

Bell et al. (2003) indicated that the dispersion of blue galaxies was diffused in the $M/L(K_s)$ vs. $B$-$R$ plane (their figure 20). The fitted slope was shallower for red galaxies compared to the blue ones. Using the modified broad band Johnson photometry correlation, Kannappan & Gawiser (2007) also found similar variation in the slope. The transformation point of the slope of Kannappan & Gawiser (2007) was 1.2 in the Johnson optical color $B-R$, which corresponded to an SDSS $g-r$ color of 0.55 based on the transformation methods supplied by Fukugita et al. (1996). In their work, the slope of the correlation of $M/L(K_s)$ vs. $B-R$ was 0.5 for blue galaxies with $B-R$ color less than 1.2, while for the red galaxies with the same selection criterium, the corresponding slope was 0.34. Bell et al. (2003) found that the reason for diffused dispersion and transformation of the slope was the difference in metallicity of the blue galaxies. For two galaxies with the same value of $M/L(K_s)$, the one with lower metallicity must be bluer than the higher metallicity one in optical colors. However, we do not find such phenomena in the other three panels (Fig. 8(b,c,d)), because of the lack of low metallicity galaxies in this sample, or the larger dispersion. Therefore, we must be more careful when estimating stellar masses of low metallicity galaxies using NIR or MIR luminosities. We will investigate their properties in more detail in the future.

4.2 Effect of Star Formation

Besides the EW(H$\alpha$), the mass-to-luminosity ratios of two MIR luminosities are also sensitive to the concentration parameters which could be seen in Figure 5. Figure 10 shows the correlations between
Fig. 10 Correlations between concentration parameters and the stellar mass ratios, which are the discrepancies between the stellar mass derived from our calibrated formulae and the reference. The derived stellar mass by using Eqs. (2), (3), (6), and (7) is shown in Panels (a), (b), (c), and (d), respectively.

Fig. 11 Similar to Fig. 10, but the concentration parameters were 24 µm luminosities instead. The crosses represent the three scatters, and they were designated with numbers.
stellar mass ratios (the stellar mass derived from the above formulae divided by the reference stellar mass) and morphology (R50/R90). The derived stellar masses in Figure 10(a, b) are based on nonlinear fits of 3.6 $\mu$m and 4.5 $\mu$m luminosities (with superscript ‘A’) vs. reference stellar masses (Eqs. (2) and (3)); while those in Figure 10(c, d) are based on nonlinear fits of M/L(3.6 $\mu$m) and M/L(4.5 $\mu$m) vs. $g - r$ color (Eqs. (6) and (7)) (with superscript ‘B’). We find that the obvious discrepancies of derived stellar masses of galaxies with different morphologies in Figure 10(a, b) would overestimate the stellar masses of the late-type galaxies compared to the early-type ones; while the ratios keep nearly constant values in Figure 10(c, d). SFH could account for the discrepancies in Figure 10(a, b) when comparing the slopes of the two upper panels and two lower panels. Besides SFH, SFR may be another factor resulting in overestimations of stellar masses for late-type galaxies. Galaxies with different morphologies have different SFRs. There are more new stars born in late-type galaxies than in early-type ones (Li et al. 2007). SFR could relate to the values of intrinsic extinction and metallicity as shown in Figure 5. Hence, it is necessary to check SFR in our stellar mass formulae.

Panels in Figure 11 are similar to those in Figure 10, just replacing r-band concentration parameters by 24 $\mu$m luminosities of galaxies. Same as Figure 10, stellar masses in the two upper panels (Fig. 11(a, b)) are derived by nonlinear fits of 3.6 $\mu$m and 4.5 $\mu$m luminosities (Eqs. (2) and (3)), while those in the bottom panels (Fig. 11(c, d)) are based on the nonlinear fits of M/L(3.6 $\mu$m) and M/L(4.5 $\mu$m) vs. $g - r$ color (Eqs. (6) and (7)). A template SED of a normal HII galaxy NGC 3351 (from SINGS; (Kennicutt et al. 2003)) was used to perform K-correction for the 24 $\mu$m band for all the sample galaxies with 24 $\mu$m detection. Figure 11 shows that Equations (2) and (3) would overestimate the stellar mass for galaxies with higher 24 $\mu$m luminosities. The 24 $\mu$m luminosity was demonstrated to be a good SFR tracer by Spitzer observations (Wu et al. 2005; Calzetti et al. 2005, 2007; Zhu et al. 2008). Therefore, Equations (2) and (3) are available for galaxies with lower star-forming activities, while Figure 11(c, d) is almost flat. Thus, Equations (6) and (7) are not quite as sensitive to SFR or morphology (Fig. 10).

In Figure 11, there are three outliers which are marked with crosses. The one with number ‘3’ is an AGN, which will be discussed in the next subsection. Another two sources are star-forming galaxies with apparent features of interactions or mergers in SDSS images. The one with number ‘1’ is a dwarf star-forming galaxy, with a low metallicity of 7.93 and very large 24 $\mu$m-to-3.6 $\mu$m flux ratio. The one with number ‘2’ is a luminous star-forming galaxy with strong PAH emissions in the IRAC 8 $\mu$m band. Both of them have very blue $g - r$ color. Actually, they are the only two galaxies with $g - r$ color less than 0.1 in Figure 8. Additionally, the stellar mass of ‘2’ derived by using SDSS photometries and that by spectral indices are apparently different. Therefore, it is hard to define which one is the best estimator. The stellar mass estimated using photometries is about 1 dex less than the one estimated by spectral indices. For ‘1’ and ‘3,’ there are no stellar mass values derived by spectral indices.

Apart from emission directly from the photosphere of old red stars, the continuum from very small dust heated by hot stars, even some broad emission features (Gillett et al. 1973; Willner et al. 1977) which were indicated to be from PAHs (Wen et al. 2007; Cao & Wu 2007), could increase the MIR luminosity of a galaxy. The dust emission dominates radiation of star-forming galaxies in the wavelength range beyond 5 $\mu$m, but could also enhance the 4.5 $\mu$m flux (Helou et al. 2004; Smith & Hancock 2009). To evaluate such an effect, the 4.5 $\mu$m-to-3.6 $\mu$m flux ratio is plotted against the 24 $\mu$m luminosity in Figure 12. The three outliers in Figure 11 were marked with crosses. The circles are the AGNs. There are some AGNs with very high 4.5 $\mu$m-to-3.6 $\mu$m luminosity ratios marked with solid circles. Except for these outliers, we find a correlation between the 4.5 $\mu$m-to-3.6 $\mu$m luminosity ratio and star formation for most of the sources. Because the 24 $\mu$m luminosity is the tracer of SFR, this correlation may be due to the dust emissions in the 4.5 $\mu$m band. With the assumption that the entire IRAC 3.6 $\mu$m band luminosity is from the stellar emission, a factor of 0.596 (Helou et al. 2004) was used to scale the stellar continuum of 3.6 $\mu$m to that of 4.5 $\mu$m based on the Starburst99 synthesis model (Leitherer et al. 1999) with the solar metallicity and a Salpeter
Fig. 12 Correlations between the 24 \( \mu m \) luminosity and the flux ratio between 3.6 \( \mu m \) and 4.5 \( \mu m \) for all the galaxies. The circles represent AGNs. The solid circles represent AGNs with 3.6 \( \mu m \)-to-4.5 \( \mu m \) ratios larger than 0.9. The black dots represent star-forming galaxies, composite galaxies and absorption line galaxies. The three outliers in Fig. 11 were denoted with crosses. The dashed line represents the factor of 0.596 which is the ratio between the 4.5 \( \mu m \) and 3.6 \( \mu m \) flux by Helou et al. (2004) with the assumption that the entire IRAC 3.6 \( \mu m \) and 4.5 \( \mu m \) band luminosities are from the stellar emission.

4.3 Effect of AGNs

Due to the powerful UV emissions from AGNs, the dust surrounding them could be heated by central monsters and then re-radiated in the IR range (see, e.g, Bell et al. 2005; Pérez-González et al. 2006; Elbaz et al. 2007; Daddi et al. 2007). Higher MIR-to-H\( \alpha \)/MIR-to-UV luminosity ratios were found by previous works based on Spitzer observations (Wu et al. 2007; Li et al. 2007; Zhu et al. 2008). So, we want to know whether the energy from AGNs could strengthen the 3.6 \( \mu m \) and 4.5 \( \mu m \) emissions.

Figure 13 shows the correlations between stellar mass ratios and AGN activities. Here, just the AGNs located inside the two boundaries defined by Wu et al. (2007) are adopted. Kauffmann et al. (2003b) found that the contribution from AGN light to the optical continuum was much weaker compared to that from starburst. Thus, ignoring the effect of AGN emission on the estimation of
Fig. 13  Correlations between AGN activity and stellar mass ratios, which are the discrepancies between the stellar mass derived from our calibrated formulae and the reference. Here, the distance \( d_{\text{AGN}} \), which was defined by Wu et al. (2007), characterizes AGN activity. The derived stellar mass by using Eqs. (2), (3), (6) and (7) is shown in Panels (a), (b), (c) and (d), respectively. The solid circles represent the respective AGNs in Fig. 12 with higher 4.5 \( \mu m \)-to-3.6 \( \mu m \) flux ratios (larger than 0.9).

Fig. 14  Correlations between the distance \( d_{\text{AGN}} \), which represents AGN activity, and the flux ratios between 3.6 \( \mu m \) and 4.5 \( \mu m \) for AGNs. The solid circles represent the sources with 4.5 \( \mu m \)-to-3.6 \( \mu m \) flux ratios larger than 0.9. The dashed line represents the factor of 0.596 as plotted in Fig. 12.
referenced stellar mass would be reasonable. Solid circles represent the respective AGNs in Figure 12 with 4.5 $\mu$m-to-3.6 $\mu$m flux ratio larger than 0.9. According to Wen et al. (2007), we know that AGNs with very high 4.5 $\mu$m-to-3.6 $\mu$m ratios may be QSOs. In Figure 13, except for those scatters, the stellar mass derived from MIR luminosities stays constant with increasing $d_{\text{AGN}}$, while Figure 5(e2, e3) shows that AGN activities cannot disturb the mass-to-luminosity ratio for AGN-hosting galaxies, even at 4.5 $\mu$m (Fig. 14). Therefore, there seem to be no confirmed non-thermal radiations or dust emissions heated by AGNs in IRAC 3.6 $\mu$m and 4.5 $\mu$m detections. Because all the sources here are type-II AGNs, the powerful intrinsic extinction of the dust torus of narrow line AGNs could be another explanation for non-detection of AGNs in 3.6 $\mu$m and 4.5 $\mu$m in our sample. The absence of AGN emissions at 3.6 $\mu$m and 4.5 $\mu$m also indicates that the stellar mass formulae based on 3.6 $\mu$m and 4.5 $\mu$m luminosities are applicable to most AGN-hosting galaxies.

Figure 4 presents the distributions of absolute $B$-band magnitudes, reference stellar masses and $r$-band concentration parameters. The distributions in Figure 4 of composite galaxies and AGNs are strikingly different from those of star-forming galaxies, but similar to absorption line galaxies. These results indicate that AGNs in our sample tend to be hosted in early-type galaxies (Kauffmann et al. 2003b; Zhu et al. 2008). Based on these results and the discussions about the effect of star formation in Section 4.2, we find star formation rates in our AGN-hosting galaxies are lower.

5 SUMMARY

Based on the sample cross-identified from the Spitzer SWIRE field and SDSS spectrographic survey, we derived the formulae to calculate the stellar mass using non-linear correlations with IRAC 3.6 $\mu$m and 4.5 $\mu$m luminosities. The mass-to-luminosity ratios of these two MIR luminosities are sensitive to the EW(H$\alpha$), morphology and metallicity of galaxies, especially for the former one, while the value of the EW(H$\alpha$) represents the SFH for normal galaxies. Using the $g-r$ color to represent SFH, we re-calibrate the stellar mass formulae for various galaxies. We find these formulae are better than those which ignore the effects of SFH. We could not conclude that the applicability to low metallicity galaxies is due to a lack of such objects in our sample; thus one must be really careful when adopting our formulae to estimate stellar masses of those galaxies. Additionally, we found that dust emission heated by the hottest young stars could enhance the IRAC 4.5 $\mu$m luminosity, especially for luminous infrared galaxies. So, the formulae we derived are not applicable to these galaxies. These formulae are also not applicable to the stronger AGNs, such as QSOs, although almost all the AGN-hosting galaxies in our sample present similar properties to absorption line galaxies (early-type), with low SFRs.

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