THE CALIBRATION OF STAR FORMATION RATE INDICATORS FOR WISE 22 μm-SELECTED GALAXIES IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We study star formation rate (SFR) indicators for Wide-field Infrared Survey Explorer (WISE) 22 μm-selected, star-forming galaxies at 0.01 < z < 0.3 in the Sloan Digital Sky Survey. Using extinction-corrected Hα luminosities and total infrared luminosities as reference SFR estimates, we calibrate WISE mid-infrared- (MIR-) related SFR indicators. Both the 12 and 22 μm monochromatic luminosities correlate well with the reference the SFR estimates, but tend to underestimate the SFRs of metal-poor galaxies (at lower than solar metallicity), consistent with previous studies. We mitigate this metallicity dependence by using a linear combination of observed Hα and WISE MIR luminosities for our SFR estimates. This combination provides SFR measurements as robust as those applied to Spitzer data by Kennicutt et al. However, we find that the coefficient a in \( L_{\text{H}\alpha(\text{obs})} + aL_{\text{MIR}} \) increases with the SFR, and show that a nonlinear combination of observed Hα and MIR luminosities gives the best SFR estimates with small scatters and with little dependence on physical parameters. Such a combination of Hα and MIR luminosities for SFR estimates is first applied to the WISE data. Using WISE data, we provide several SFR recipes that are applicable to galaxies with 0.1 \( \lesssim \text{SFR} (M_\odot \text{yr}^{-1}) \lesssim 100.

Key words: dust, extinction – galaxies: ISM – galaxies: starburst – infrared: galaxies – stars: formation – surveys

Online-only material: color figures

1. INTRODUCTION

Measuring accurate star formation rates (SFRs) of galaxies is important to understand the formation and evolution of galaxies (see Kennicutt 1998 and Kennicutt & Evans 2012 for a review). Among the many SFR indicators, the ultraviolet (UV) continuum and hydrogen recombination emission lines (e.g., Hα, Paα), which are directly related to the bulk energy of young massive stars, are widely used. However, SFRs based on UV/optical tracers can be very uncertain when galaxies suffer from severe dust extinction, which is difficult to correct. In these dusty galaxies, observation in the infrared (IR), where the dust-reprocessed light emerges, is necessary to measure accurate SFRs.

The monochromatic mid-IR (MIR) luminosities can be useful SFR indicators because they are tightly correlated with the total IR luminosities in normal star-forming galaxies (e.g., Rieke et al. 2009; Elbaz et al. 2011; Goto et al. 2011). However, there are several components contributing to the MIR luminosities, including the thermal continuum emission from heated small grains, polycyclic aromatic hydrocarbon (PAH) features, silicate absorption, molecular hydrogen lines, and fine-structure lines (see Draine & Li 2007). Because of this complication, it is important to examine the reliability of MIR-based SFRs in each observed band. There have been a number of studies that calibrate the SFR indicators based on Spitzer 8 and 24 μm luminosities (e.g., Wu et al. 2005; Alonso-Herrero et al. 2006; Calzetti et al. 2007; Zhu et al. 2008) and on AKARI 9 and 18 μm luminosities (Yuan et al. 2011). Moreover, the energy balance method that combines (M)IR and UV/optical measurements can trace both obscured and unobscured star formation, which is useful for estimating the SFRs of various galaxy populations with small scatters (e.g., Kennicutt et al. 2009; Hao et al. 2011).

The new all-sky infrared survey with the Wide-field Infrared Survey Explorer (WISE) satellite provides photometric data for a large sample of galaxies at 3.4–22 μm with excellent sensitivity (Wright et al. 2010). There are several studies based on WISE data that investigate the correlations between WISE MIR luminosities and other SFR indicators (Donoso et al. 2012; Shi et al. 2012; Jarrett et al. 2013). Donoso et al. (2012) and Shi et al. (2012) use the optical SFR as a reference, derived from the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectra using the aperture correction method of Brinchmann et al. (2004). This aperture correction method assumes that the specific SFR (SFR per unit stellar mass) distribution for a given set of colors inside the fiber is the same as that outside, which can introduce a bias of color-dependent SFR calibration (see Shim et al. 2011; Xiao et al. 2012). On the other hand, Jarrett et al. (2013) adopt the IR luminosity as a reference SFR indicator, but they use only dozens of galaxies with SFR \( \lesssim 4 M_\odot \text{yr}^{-1} \).

In this work, we calibrate the WISE 12 and 22 μm related SFR indicators for a large sample of star-forming galaxies in the local universe. Using extinction-corrected Hα luminosities and total IR luminosities as reference SFR indicators, we first validate the SFR indicators based on MIR monochromatic luminosities and compare them with previous results. We then show that the combination of MIR and Hα luminosities provides better SFR estimates than MIR monochromatic luminosities. We also suggest several SFR recipes that are applicable to galaxies with a wide range of SFRs. The structure of this paper is as follows. Section 2 describes the observational data and sample selection. Section 3 explains our calibration results. We discuss the results and conclude in Sections 4 and 5, respectively. Throughout, we adopt the flat ΛCDM cosmological parameters \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_\Lambda = 0.7, \text{ and } \Omega_m = 0.3. \)

2. DATA AND SAMPLE

2.1. Observational Data

We use a spectroscopic sample of galaxies from the SDSS data release 7 (Abazajian et al. 2009) that covers \( \sim 8000 \text{ deg}^2 \) of the sky and is nearly complete to \( m_r < 17.77 \) (mag). We
adopt the photometric parameters (e.g., ugriz-band magnitudes) of galaxies from the SDSS pipeline (Stoughton et al. 2002) and the spectroscopic parameters, including optical emission line fluxes, from the MPA/JHU value-added galaxy catalogs (VAGCs; Tremonti et al. 2004).

For the MIR data, we use the WISE all-sky survey catalog (Wright et al. 2010), which contains uniform data for over 563 million objects in four IR bands. The WISE 3.4 μm sensitivity is estimated to be better than 0.05, 0.07, 0.6, and 3.6 mJy at 3.4, 4.6, 12, and 22 μm in unconfused regions on the ecliptic plane (Wright et al. 2010). We identify WISE counterparts of the SDSS galaxies with a matching tolerance of 3′′ (≈0.5 × FWHM of the WISE point-spread function at 3.4 μm). To avoid contamination by nearby sources within the matching tolerance, we select only unique matches; for a given SDSS object, we choose the WISE object closest to the SDSS object and vice versa. We focus on galaxies with WISE 22 μm detection (i.e., signal-to-noise ratio (S/N) ≳ 3) in the spectroscopic sample. All of these galaxies have S/N > 3 at 12 μm.

To obtain the rest-frame (monochromatic) luminosities at the 12 and 22 μm bands (hereafter LW3 and LW4), we compute the K-correction for each galaxy using a set of empirical spectral energy distribution (SED) templates and the fitting code in Assef et al. (2010). Each template spans the wavelength range from 0.03 to 30 μm and represents an old stellar population, a continuously star-forming galaxy, a starburst galaxy, and an active galactic nucleus (AGN). We apply this code to the combined photometry of SDSS and WISE (i.e., nine data points) with varying amounts of reddening and absorption by the intergalactic medium. We use the Petrosian and point-source profile-fitting magnitudes for the SDSS and WISE data, respectively. The amount of K-corrects in the WISE 12 and 22 μm bands is typically ≲0.1 dex for our sample.

2.2. Sample Selection

To construct a reliable sample of star-forming galaxies, we first remove AGN host galaxies in our sample. Among the 22 μm-selected galaxies, we use only galaxies satisfying the selection criteria for pure star-forming galaxies in the emission line ratio diagram of [OIII]λ5007/Hz versus [NII]λ6584/Hz (Kauffmann et al. 2003a) and S/N > 3 for each line flux. Most of these galaxies (>99.9%) have WISE colors of [3.4]−[4.6] < 0.8 (mag in Vega), indicating that the AGN contamination is negligible in our sample (Stern et al. 2012).

We also restrict our analysis to galaxies at 0.01 < z < 0.3. The upper redshift limit ensures that the Hα line is comfortably within the SDSS spectral coverage (≈3800–9200 Å). The SDSS spectra were taken with 3′′ diameter fibers. Thus, the spectra could be dominated by the light from the central regions of galaxies. To avoid this aperture bias, Kewley et al. (2005) recommended using SDSS galaxies at z > 0.04 to capture >20% of the galaxy light. However, Hopkins et al. (2003) demonstrate that their aperture correction method works well even for galaxies at z > 0.01 (see also Figure 13 in Brinchmann et al. 2004). We also find that using the lower limit of z > 0.01 does not introduce any bias into our results (see the next section). By changing the lower redshift limit from 0.04 to 0.01, the number of galaxies increases from 90,523 to 105,753. This also results in the increase of the SFR range for the sample from 1–100 M⊙ yr⁻¹ to 0.1–100 M⊙ yr⁻¹. Therefore, we can calibrate the SFR indicators for a larger number of galaxies and for a wider SFR range.

3. CALIBRATION OF STAR FORMATION RATE INDICATORS

3.1. Hα Luminosity as a Reference SFR Indicator

We use the Hα luminosity of a galaxy as a reference SFR indicator to calibrate the WISE-based SFR indicators. To estimate the Hα luminosities of SDSS galaxies, it is necessary to convert the Hα flux measured from a fiber spectrum into the flux covering the entire galaxy. We perform this aperture correction using the difference between r-band Petrosian and fiber magnitudes following Hopkins et al. (2003). This method assumes that the radial profile of line emission is the same as that for stellar light, which is supported by the observational results in Koopmann et al. (2001, 2006).

The observed Hα emission suffers from dust extinction from both the Milky Way and the host galaxy. The foreground Galactic extinction is corrected using the Cardelli et al. (1989) extinction curve (Rv = 3.1) and the Schlegel et al. (1998) maps. To correct the internal extinction of star-forming galaxies, we use the Calzetti et al. (2000) extinction curve (Rv = 4.05) and the Balmer decrement with the assumption of intrinsic Hα/Hβ = 2.86 (case B recombination for T_e = 10,000 K and n_e = 100 cm⁻³; Osterbrock & Ferland 2006). If the observed Hα/Hβ ratio is smaller than 2.86, then we do not apply this correction. The emission line fluxes including Hα and Hβ are measured after subtracting the stellar population models of S. Charlot & G. Bruzual (2013, in preparation) from the spectra, meaning that the stellar absorption in emission lines is properly corrected (but see also Groves et al. 2012).

To convert the corrected Hα luminosity into an SFR, we adopt the relation in Kennicutt (1998): SFRHα(M⊙ yr⁻¹) = 7.9 × 10⁻⁴LHα (erg s⁻¹). This relation assumes a Salpeter initial mass function (IMF; mass range at 0.1–100 M⊙) and solar abundances with continuous star formation over timescales of 100 Myr. The SFRs based on the Salpeter IMF are known to be larger than those based on other IMFs, such as Kroupa and Chabrier, by a factor of 1.4–1.6 (e.g., Calzetti et al. 2007; Kennicutt et al. 2009; Rieke et al. 2009). Therefore, it is necessary to take into account these offsets when comparing the calibration results with different IMFs. Detailed discussions on the effect of different assumptions can be found in Kennicutt (1998) and Kennicutt & Evans (2012).

In Figure 1, we compare the Hα-based SFR estimates for our sample galaxies with those from the total IR (8–1000 μm) luminosities. Among the 105,753 galaxies in our sample, there are 5995 galaxies with IRAS 60 μm detection (Moshir et al. 1992). For these galaxies, we compute the total IR luminosities using the SED templates of Charý & Elbaz (2001). We also use 100 μm data for the computation when it is available (see Hwang et al. 2010a for more details). We convert the IR luminosities into SFRs using the relation of Kennicutt (1998): SFRIR(M⊙ yr⁻¹) = 1.72 × 10⁻⁴LIR/(L⊙).

The left panel of Figure 1 shows that SFRHα and SFRIR agree well. The Calzetti reddening curve seems to work well for the internal extinction correction, at least in our sample. If we use the Cardelli reddening curve instead, then SFRHα tends to be smaller than SFRIR for high SFR galaxies (see also Figure 3 in Hwang et al. 2010a).
When using the SFRs in the MPA/JHU VAGC derived from the SDSS optical spectra (hereafter SFR\textsubscript{Opt}) rather than SFR\textsubscript{Hα}, SFR\textsubscript{Opt} deviates from SFR\textsubscript{Hα}, as seen in the right panel. This offset originates primarily from the aperture correction method of Brinchmann et al. (2004); if we compare SFR\textsubscript{Hα} and SFR\textsubscript{Opt} directly measured from the fiber spectra without aperture correction, then the two measurements are similar.

For the SFR\textsubscript{Opt} aperture correction, Brinchmann et al. assume that the specific SFRs can be estimated from galaxy colors. However, red galaxies show a very wide range of specific SFRs because of the degeneracy between age, metallicity, and extinction (see Brinchmann et al. 2004). Xiao et al. (2012) indeed show that in a given set of colors, the specific SFR inside the fiber increases with the Balmer decrement. This implies that the color-dependent aperture correction method can result in the underestimation of the specific SFRs outside galaxies, particularly for dusty galaxies. On the other hand, Salim et al. (2007) found that the UV-based SFRs agree well with SFR\textsubscript{Opt} for the sample of \textit{GALEX}-selected SDSS galaxies. This may suggest that the aperture correction of Brinchmann et al. introduces no bias, at least for less dusty galaxies. Similarly, if we compare SFR\textsubscript{Opt} with our SFR\textsubscript{Hα} for the entire sample of star-forming galaxies regardless of (M)IR detection, then the systematic difference is negligible. Therefore, these results suggest that the effect of the different aperture corrections is significant only for dusty galaxies; the aperture correction of Hopkins et al. (2003) and Jarrett et al. (2013) show small offsets from ours, but these are not statistically significant.

We choose a fitting range of $\text{SFR} > 3 M_\odot \text{yr}^{-1}$ where the slope converges within the fitting error. If we fix the slope to be unity, then the resulting relations (blue solid lines) are $\text{SFR}_{W3}(M_\odot \text{yr}^{-1}) = (1.64 \pm 0.11) \times 10^{-9} L_{W3}(L_\odot)$ and $\text{SFR}_{W4}(M_\odot \text{yr}^{-1}) = (1.59 \pm 0.11) \times 10^{-9} L_{W4}(L_\odot)$.

The top panels suggest that 12 and 22 $\mu$m monochromatic luminosities can be good SFR indicators, considering the tightness of the correlations (Spearman rank correlation coefficients $= \sim 0.8$ and dispersions of the fitting residuals $= \sim 0.2$ dex). The scatters in the correlations are not fully explained by the expectations from measurement errors (typically 0.01, 0.02, and 0.07 dex for Hα fluxes, 12 $\mu$m and 22 $\mu$m flux densities, respectively). These scatters mainly result from uncertainties in the corrections for Hα luminosities (i.e., $\sim 0.18$ and $\sim 0.08$ dex for extinction and aperture corrections, respectively). Note also that the relation for 12 $\mu$m luminosity is meaningful only for galaxies with SFR $\gtrsim 1 M_\odot \text{yr}^{-1}$ because galaxies with SFR $\lesssim 1 M_\odot \text{yr}^{-1}$ deviate more than 1σ from the relation for high SFR galaxies.

We summarize the relations between SFRs and 12/22 $\mu$m luminosities in Table 1, together with those in the literature at similar wavelengths. To directly compare our results with those in the literature, we plot several relations based only on \textit{WISE} data in the bottom panels of Figure 2. The figure shows that the results in this study and in Donoso et al. (2012) are in excellent agreement. The results of Jarrett et al. (2013) show small offsets from ours, but these are not statistically significant. However, the results of Shi et al. (2012) clearly deviate from other relations, especially in high SFR galaxies. The exact cause for this difference is not fully understood. However, we suspect that the offset mainly results from the difference in computing the MIR luminosities. It is because the MIR luminosity range in their sample is much larger than for the samples in this study and in Donoso et al. (2012), even though all of the studies use similar \textit{WISE}-selected SDSS galaxies. For example, it is not clearly explained in their paper whether or not they perform the K-corrections to compute the rest-frame MIR luminosities.

Our calibration of SFR indicators based on \textit{WISE} MIR luminosities is consistent with those in Donoso et al. (2012) and Jarrett et al. (2013). However, our calibration is based on a large sample of galaxies with a wide SFR range, and we provide the relations for both the 12 and 22 $\mu$m luminosities, suggesting that our results can supplant previous results. Moreover, due to our large sample, we further show in the next section that the SFRs based on MIR luminosities suffer from metallicity bias.
Figure 2. Top: Hα-based SFRs vs. 12 μm (left) and 22 μm (right) luminosities. The data points are indicated as gray-scale density maps for better visibility. The red solid lines are the best fits to the galaxies with SFR > 3 M⊙ yr⁻¹. The blue solid lines are the same, but by fixing the slope to be unity. The dashed lines are extensions of the solid lines. Bottom: SFR calibrations based on 12 μm (left) and 22 μm (right) luminosities of Donoso et al. (2012, green line), Shi et al. (2012, cyan line), Jarrett et al. (2013, black line), and this study (red and blue lines). The solid lines indicate the SFR ranges used for deriving the relations (see Table 1), and the dashed lines extend these relations.

(A color version of this figure is available in the online journal.)

Table 1

| Band    | m      | n       | c           | σ     | Reference | SFR Range |
|---------|--------|---------|-------------|-------|-----------|-----------|
| Spitzer 8 | 1.09 ± 0.06 | -10.03 ± 0.16 | -9.20 ± 0.19 | 0.18 | 1         | 0.2–20    |
| Spitzer 8 | 0.93 ± 0.03 | -8.59 ± 0.08 | -9.19 ± 0.19 | 0.18 | 4         | 0.1–30    |
| AKARI 9  | 0.99 ± 0.03 | -8.84 ± 0.32 | 0.18 | 6         | 0.2–150   |
| WISE 12  | 1.01 ± 0.01 | -8.85 ± 0.01 | 7     | 0.1–100   |
| WISE 12  | 0.67     | -6.45    | 8     | 0.01–100  |
| WISE 12  | 1.03 ± 0.01 | -9.02 ± 0.02 | -8.78 ± 0.03 | 0.20 | 10        | 3–100     |
| Spitzer 24 | 0.89 ± 0.06 | -7.82 ± 0.17 | -8.81 ± 0.19 | 0.30 | 1         | 0.2–20    |
| Spitzer 24 | 0.87     | -7.82    | 2     | 0.01–50   |
| Spitzer 24 | 0.89 ± 0.03 | -7.97 ± 0.97 | 0.16 | 4         | 0.1–30    |
| Spitzer 24 | 0.85 ± 0.02 | -7.47 ± 0.06 | -8.85 ± 0.17 | 0.30 | 3         | 0.01–50   |
| Spitzer 24 | 0.85 ± 0.02 | -7.47 ± 0.06 | -8.85 ± 0.17 | 0.30 | 3         | 0.01–50   |
| Spitzer 24 | 0.89 ± 0.03 | -7.85 ± 0.30 | 5     | 1–10      |
| AKARI 18 | 0.90 ± 0.03 | -7.85 ± 0.30 | 0.20 | 6         | 0.2–150   |
| WISE 22  | 0.70     | -6.75    | 8     | 0.01–100  |
| WISE 22  | 0.96 ± 0.01 | -8.94 ± 0.01 | 0.21 | 10        | 3–100     |
| WISE 22  | 0.96 ± 0.01 | -8.37 ± 0.02 | -8.80 ± 0.03 | 0.21 | 10        | 3–100     |

Notes. m and n are the coefficients for the fit with log SFR_MIR = m log L_MIR + n, and c is for log SFR_MIR = log L_MIR + c. σ is the standard deviation of the fitting residuals. Each calibration is derived in a given SFR range and is matched to the Salpeter IMF. Here the SFR and luminosity are expressed in units of M⊙ yr⁻¹ and L⊙, respectively.

References. (1) Wu et al. 2005; (2) Alonso-Herrero et al. 2006; (3) Calzetti et al. 2007; (4) Zhu et al. 2008; (5) Ricke et al. 2009; (6) Yuan et al. 2011; (7) Donoso et al. 2012; (8) Shi et al. 2012; (9) Jarrett et al. 2013; (10) this study.
3.2.2. Dependence of SFR Calibration on Physical Parameters

To study what makes the slope for the relation between SFR$_{\text{H}\alpha}$ and $L_{\text{W3}}$ change, we plot the ratio of SFR$_{\text{W3}}$ (Equation (1)) to SFR$_{\text{H}\alpha}$ as a function of several physical parameters in Figure 3. These parameters include (gas-phase) metallicity, stellar mass, mean stellar age, and the amount of dust extinction. We use the oxygen abundance ($12 + \log(O/H)$) based on optical nebular lines; Tremonti et al. (2004), stellar mass ($M_{\text{star}}$ from the SED fit of the SDSS photometry; see also Kauffmann et al. 2003b), and light-weighted age (from the stellar absorption features; Gallazzi et al. 2005) in the SDSS MPA/JHU DR7 VAGCs. The UV continuum slope ($\beta$, defined as $f_\lambda \propto \lambda^\beta$) is a good proxy for the amount of dust extinction, similar to the Balmer decrement (e.g., Meurer et al. 1999). However, the UV continuum slope can also be substantially influenced by the stellar population age (Mao et al. 2012). Following Overzier et al. (2011), we compute the UV continuum slope ($\beta_{\text{GALEX}}$) from the difference between far- and near-UV magnitudes in the GALEX database.\footnote{We use GALEX general release 6, which provides the cross-matched table against SDSS DR7 (http://galex.stsci.edu/GR6).}

The top left panel shows a strong dependence of SFR$_{\text{W3}}$/SFR$_{\text{H\alpha}}$ on metallicity; metal-poor galaxies have much lower SFR$_{\text{W3}}$ than SFR$_{\text{H\alpha}}$. This probably results from the low dust-to-gas ratios of metal-poor galaxies, and thus they are inefficient in the reprocessing of UV light by dust (e.g., Schuerer et al. 2009; Hwang et al. 2012; see also the discussion in Section 4.2). Metallicity also plays a role in the abundance of PAH molecules relative to the total dust content (e.g., Rosenberg et al. 2006; Marble et al. 2010); the metallicity effect is more prominent in the IR bands containing strong PAH features, such as WISE $12\,\mu m$. However, the physical mechanisms for the correlation between the metallicity and the PAH feature are still inconclusive. These could be due to the delayed production of PAHs in low-metallicity galaxies or to PAH destruction mechanisms in harder radiation fields of low-metallicity environments (see Veilleux et al. 2009; Calzetti 2011).

In the top right panel, SFR$_{\text{W3}}$/SFR$_{\text{H\alpha}}$ also changes significantly with stellar mass. However, when we use only galaxies with a narrow range of metallicities, the stellar mass dependence disappears. This suggests that the dependence of SFR$_{\text{W3}}$/SFR$_{\text{H\alpha}}$ on stellar mass originates simply from the well-known mass–metallicity relation (e.g., Tremonti et al. 2004; Zahid et al. 2012).

The bottom left panel shows that SFR$_{\text{W3}}$/SFR$_{\text{H\alpha}}$ does not depend on the mean stellar age. The MIR emission at $12\,\mu m$ could be attributed to the circumstellar dust around evolved stars in the asymptotic giant branch (AGB, e.g., Piovan et al. 2003; Ko et al. 2012; Hwang et al. 2012). The AGB dust emission decreases with increasing age but remains for several Gyrs. Therefore, in galaxies dominated by old stellar populations, the MIR emission from the AGB dust could be as important as the dust emission related to the current star formation. However, this figure suggests that the contribution from the AGB dust is insignificant in dusty, star-forming galaxies.

The bottom right panel shows that there is no significant dependence of SFR$_{\text{W3}}$/SFR$_{\text{H\alpha}}$ on $\beta_{\text{GALEX}}$. On the other hand, if we replace $\beta_{\text{GALEX}}$ with the Balmer decrement, then the SFR ratio decreases systematically by $\sim0.2$ dex, which is consistent with previous studies (e.g., Kennicutt et al. 2009; Xiao et al. 2012). Because $\beta_{\text{GALEX}}$ and the Balmer decrement are related to the different parts of dust extinction (i.e., star versus gas), it would be interesting to investigate this difference with careful modeling in future studies.

3.3. SFR Indicators Based on the Combination of Hα and MIR Luminosities

As shown in the previous section, the MIR-based SFRs can be uncertain in galaxies where dust reprocesses only a small fraction of the light of young stars, such as metal-poor galaxies. In this section, we mitigate this problem by combining the MIR luminosities and observed (i.e., extinction-uncorrected) Hα luminosities (see Kennicutt et al. 2009). When we combine $L_{\text{H\alpha(\text{obs})}}$ and $L_{\text{MIR}}$ as $L_{\text{H\alpha(\text{obs})}} + a L_{\text{MIR}}$, the...
combination coefficient $a$ is determined from the ratio of the $H\alpha$ luminosity difference before/after extinction correction to the MIR luminosity, as shown in the top panels of Figure 4. By taking median values of the ratios (horizontal dotted lines), we determine the coefficient $a$ for $H\alpha + W3$ and $H\alpha + W4$ as 0.036 ± 0.001 and 0.034 ± 0.001, respectively.

As a sanity check, we plot the extinction-corrected $H\alpha$ luminosity versus a combination of observed $H\alpha$ and MIR luminosities in Table 2. For comparison, we also list the results for the combination of $H\alpha$ and MIR luminosities in Table 2. For comparison, we also list the results for the combination of $H\alpha$ and $Spitzer$ 8/24 $\mu$m luminosities in previous studies.

We then reexamine the dependence of the ratio between SFR$_{H\alpha+W3}$ (Equation (3)) and SFR$_{H\alpha}$ on several physical parameters in Figure 5. The ratio of SFR$_{H\alpha+W3}$/SFR$_{H\alpha}$ depends very weakly on the metallicity (top left panel), different from SFR$_{W3}$/SFR$_{H\alpha}$ (top left panel in Figure 3). The scatter is also small. The median values for the ratio (red solid curve) above the solar metallicity ($12 + \log(O/H) = 8.69$) are similar to those in Figures 3 and 5, but their dependence on mean stellar age and UV slope is negligible.

The results based on the 22 $\mu$m luminosities (not shown here) are similar to those in Figures 3 and 5, but their dependence on metallicity and on stellar mass is much weaker than for 12 $\mu$m.

4. DISCUSSION

4.1. Total Infrared Luminosity as a Reference SFR Indicator

Figure 6 shows the comparison of IR-based SFRs with other SFR estimates in this study (Equations (1)–(4)). The top panels show that SFR$_{IR}$ and MIR-based SFRs correlate well for galaxies with SFR $\gtrsim 1 M_\odot$ yr$^{-1}$. We show the best fit to

$y = 1.06 \times -0.52$
Table 2

| Band        | a       | i       | j       | σ       | Reference | SFR Range |
|-------------|---------|---------|---------|---------|-----------|-----------|
| Spitzer 8   | 0.010   | 1.12 ± 0.01 | -8.49 ± 0.04 | 0.14 | 2 | 0.1–30 |
| Spitzer 8   | 0.011 ± 0.003 | 0.11 | 3 | 0.004–100 |
| WISE 12     | 0.036 ± 0.001 | 1.07 ± 0.01 | -8.12 ± 0.02 | 0.17 | 4 | 0.1–100 |
| Spitzer 24  | 0.031 ± 0.006 | 0.30 | 1 | 0.01–50 |
| Spitzer 24  | 0.022 | 1.04 ± 0.01 | -7.82 ± 0.04 | 0.14 | 2 | 0.1–30 |
| Spitzer 24  | 0.029 ± 0.005 | 0.12 | 3 | 0.004–100 |
| WISE 22     | 0.034 ± 0.001 | 1.06 ± 0.01 | -8.04 ± 0.02 | 0.18 | 4 | 0.1–100 |

Notes. a is the coefficient for the fit with $L_{\text{Hα}}(\text{corr}) = L_{\text{Hα}}(\text{obs}) + aL_{\text{MIR}}$, and i and j are for $\log \text{SFR}_{H\alpha+\text{MIR}} = i \log (L_{\text{Hα}}(\text{obs}) + aL_{\text{MIR}}) + j$. σ is the standard deviation of the fitting residuals. Each calibration is derived in a given SFR range, and is matched to the Salpeter IMF. Here the SFR and luminosity are expressed in units of $M_\odot \text{yr}^{-1}$ and $L_\odot$, respectively.

References. (1) Calzetti et al. 2007; (2) Zhu et al. 2008; (3) Kennicutt et al. 2009; (4) this study.

4.2. Limitations of Our Calibration

In this study, we use SFRs converted from observed quantities (i.e., extinction-corrected Hα luminosities and total infrared luminosities), using the relations in Kennicutt (1998) as references for the calibration. Therefore, our SFR recipes are only valid under the assumptions for the SFR conversion relations (see Kennicutt 1998 for details). For example, the strong dependence of $\text{SFR}_{24}/\text{SFR}_{H\alpha}$ on metallicity in Figure 3 could be affected by the assumption in the SFR conversion relation. When we convert the Hα luminosity into $\text{SFR}_{H\alpha}$, we use a constant conversion factor from Kennicutt (1998) that is based on the assumption of solar metallicity. However, the conversion factor could be smaller in metal-poor galaxies. Brinchmann et al. (2004) indeed showed that the Kennicutt conversion factor is a very good typical value, but can change by $\lesssim 0.4$ dex depending on the metallicity. However, although we use the SFROpt of Brinchmann et al., which takes into account the variation of conversion factor, the metallicity dependence of the SFR ratio still remains. This trend is also confirmed by Domínguez Sánchez et al. (2012), who found that the SFR ratio between $\text{SFR}_{IR}$ and $\text{SFR}_{H\alpha}$ still depends on metallicity even if they use the recipes of Brinchmann et al. to derive $\text{SFR}_{H\alpha}$.

We also assume that all of the MIR emission of galaxies is attributed to the current star formation. Therefore, the SFRs based on our calibration could overestimate the true SFRs of galaxies if the MIR emission is significantly contaminated by other components such as dust emission from AGNs (see the next section for details).
Figure 6. Comparison between SFRs based on total IR luminosity and on 12 μm luminosity (top left), 22 μm luminosity (top right), combination of Hα and 12 μm luminosities (bottom left), and combination of Hα and 22 μm luminosities (bottom right). The red solid line is the best fit to the data, and the blue dotted line is the one-to-one relation. In the top panels, we use only galaxies with SFR > 3 M⊙ yr⁻¹ for the fit, and the red dashed lines are extensions of the solid line. (A color version of this figure is available in the online journal.)

The SFR indicators in this study are calibrated with normal star-forming galaxies in the local universe. Thus, the SFR recipes may not be applicable to the galaxies not covered in this study. For example, our sample does not contain galaxies with very low SFRs (i.e., SFR ≲ 0.1 M⊙ yr⁻¹) or with very high SFRs (i.e., SFR ≳ 100 M⊙ yr⁻¹). It is also necessary to examine whether the SFR recipes determined with low-z galaxies are still applicable to high-z star-forming galaxies (e.g., Magdis et al. 2010); high-z galaxies may experience star formation under different physical conditions from the low-z galaxies (e.g., Hwang et al. 2010b; Kawara et al. 2011; Elbaz et al. 2011).

In heavily obscured galaxies, the Hα luminosities could be underestimated if the Balmer decrement is used for the extinction correction. This is because the correction is not meaningful at V-band optical depths ≳ 5 (e.g., Veilleux et al. 1999; Moustakas et al. 2006). This problem could be solved if we use Hα-based SFRs with extinction corrections based on emission lines at longer wavelengths (e.g., Paα/Hα) or other SFRs not severely affected by dust emission (e.g., radio 20 cm continuum; see Kennicutt et al. 2009).

The SFR recipes in this study are not applicable to individual H II regions or star-forming complexes because our calibration is based on the integrated properties of galaxies. The comparison of spatially resolved Hα and MIR images of star-forming galaxies suggests that there is a diffuse MIR emission other than the MIR and Hα emissions from point-like sources (e.g., Prescott et al. 2007; Kennicutt et al. 2009; Kennicutt & Evans 2012). This diffuse component comes from the cool interstellar dust (i.e., IR cirrus emission), and can contribute to the MIR emission of galaxies up to several tens of percent (e.g., Bell 2003; Dale et al. 2007). Therefore, the calibration of SFR indicators can be different between galaxies and H II regions depending on the amount of diffuse MIR emission (see Zhu et al. 2008).

4.3. Contamination of AGNs and Stellar Continuum to the MIR Emission

The MIR emission in star-forming galaxies is mainly dominated by dust continuum and PAH features, which are associated with current star formation. However, there could be other components contributing to the MIR emission: dust emission from AGB stars and AGNs, and the remaining stellar continuum. The AGB dust emission is already considered in the bottom left panels of Figures 3 and 5; its contribution is insignificant in our sample of galaxies with SFR ≳ 0.1 M⊙ yr⁻¹.

The dust emission from AGNs can be significant in IR luminous galaxies (e.g., Mullaney et al. 2011; Lee et al. 2012). However, the AGN contribution in our sample is expected to be ≲ 10% because we use only star-forming galaxies classified on the emission-line ratio diagram (Donoso et al. 2012; Lee 2012). Therefore, the effect of AGNs on our calibration of SFR indicators is very small.

The stellar continuum of galaxies peaks around the near-IR, but can remain even in the MIR. If we assume that the WISE 3.4 μm flux density is dust-free, then we can compute the
contribution of the stellar continuum to the 12 μm flux density by properly scaling the 3.4 μm flux density (see Helou et al. 2004; Wu et al. 2005). Using the WISE-selected SDSS galaxies without optical emission lines (i.e., no star formation and nuclear activity), we find that the scaling factor is 0.1 from the ratio between the WISE 12 and 3.4 μm flux densities. This scaling factor is comparable to that in Jarrett et al. (2013: ~0.15). The corresponding contribution of stellar continuum to the 12 μm flux density in our sample is then only a few percent. We find that the dependence of the ratio between SFR estimates on physical parameters and its scatter do not change even if we use stellar-continuum-subtracted MIR luminosities for the calibration of the SFR indicators.

5. CONCLUSIONS

We use WISE 22 μm-selected, star-forming galaxies at 0.01 < z < 0.3 in the SDSS to calibrate the SFR indicators based on 12 and 22 μm monochromatic luminosities and on the combination of MIR and Hα luminosities. We adopt extinction-corrected Hα luminosities and total IR luminosities as reference SFR indicators. We then investigate how the calibration depends on physical parameters including metallicity, stellar mass, mean stellar age, and dust extinction. Our main results are as follows.

1. Both 12 and 22 μm monochromatic luminosities correlate well with reference SFR estimates (Equations (1) and (2)). However, these MIR luminosities, especially for 12 μm, tend to underestimate the SFRs of galaxies with SFR $< 1 M_{\odot}$ yr$^{-1}$. This discrepancy seems to mainly result from a low-metallicity effect.

2. We confirm that the metallicity dependence of MIR-based SFRs can be reduced by using a linear combination of observed Hα and MIR luminosities ($L_{H\alpha,\text{obs}} + aL_{MIR}$).

3. We find that the combination coefficient (a) increases with SFRs. To take into account this variation, we use a non-linear combination of observed Hα and MIR luminosities (Equations (3) and (4)). This method provides the best SFR estimates with small scatters and with little dependence on physical parameters.

We confirm that WISE MIR monochromatic luminosities can be good SFR indicators of dusty galaxies, but suffer from metallicity bias. To mitigate this metallicity dependence, we applied the energy balance method, which combines (M)IR and UV/optical measurements to WISE data for the first time, providing robust SFR estimates with small scatters and with little dependence on physical parameters. Our calibration is robust because it is based on a large sample of galaxies with a wide SFR range and on reliable reference SFR estimates; it is applicable to the galaxies with 0.1–100 $M_{\odot}$ yr$^{-1}$. The proposed SFR recipes will be useful for studying the star formation activity for a large sample of WISE-selected galaxies.

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