

Star Formation Rate Indicators in Wide-Field Infrared Survey Preliminary Release

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Abstract. With the goal of investigating the degree at which the MIR luminosity in the Wide-field Infrared Survey Explorer (WISE) traces the SFR, we analyse 3.4, 4.6, 12 and 22 μm data in a sample of $\sim 140,000$ star-forming galaxies or star-forming regions *covering a wide range in metallicity* $7.66 < 12 + \log(\text{O}/\text{H}) < 9.46$, *with redshift* $z < 0.4$. These star-forming galaxies or star-forming regions are selected by matching the WISE Preliminary Release Catalog with the star-forming galaxy Catalog in SDSS DR8 provided by JHU/MPA¹. We study the relationship between the luminosity at 3.4, 4.6, 12 and 22 μm from WISE and $\text{H}\alpha$ luminosity in SDSS DR8. From these comparisons, we derive reference SFR indicators for use in our analysis. Linear correlations between SFR and the 3.4, 4.6, 12 and 22 μm luminosity are found, and calibrations of SFRs based on $L(3.4)$, $L(4.6)$, $L(12)$ and $L(22)$ are proposed. The calibrations hold for galaxies with verified spectral observations. The dispersion in the relation between 3.4, 4.6, 12 and 22 μm luminosity and SFR relates to the galaxy's properties, such as 4000 \AA break and galaxy color.

Key words. Galaxies: star formation—galaxies: abundances—methods: data analysis—infrared: galaxies.

¹<http://www.sdss3.org/dr8/spectro/galspec.php>

1. Introduction

The star formation rate (SFR) is a crucial parameter to characterize the star formation history of galaxies. To calculate the SFR reliably, extensive efforts have been made to derive SFR indicators at various wavelengths, including radio, infrared (IR), ultraviolet (UV), optical spectral lines and continuum (Kennicutt 1998). Among these wavelengths, SFR indicators at the infrared (IR) band have attracted more attention in recent years because of the high sensitivity and high angular resolution data provided by the Spitzer Space Telescope. As a result, the general correlation between infrared luminosity and SFR has been found and calibrated (Calzetti *et al.* 2005, 2007, 2009, 2010; Alonso-Herrero *et al.* 2006; Schmitt *et al.* 2006; Kennicutt *et al.* 2007a; Persic & Rephaeli 2007; Rosa-Gonzalez *et al.* 2007; Salim *et al.* 2007; Bigiel *et al.* 2008; Rieke *et al.* 2009).

During the last twenty years, the calibrations of these correlations are mainly focused on the relation between the total luminosity in the IR band (L_{TIR}) and SFR because of dust heating in the wide IR band. As a result, the monochromatic SFR indicators based on a single band measurement from galaxies are ignored to some extent. Calculation of L_{TIR} requires models for the infrared spectral energy distribution (SED) of star-forming galaxies (Chary & Elbaz 2001; Dale & Helou 2002; Lagache *et al.* 2003; Marcillac *et al.* 2006; Noll *et al.* 2009), but these models usually suffer from small galaxy sample size and limited sensitivities from surveys such as Infrared Astronomical Satellite (IRAS) and Infrared Space Observatory (ISO).

Because of the shortcomings of the L_{TIR} , studies of monochromatic SFR indicators based on the single band measurement from galaxies have experienced a new resurgence, such as the emission detected in the 8 μm and 24 μm Spitzer bands. This emission has been analysed by a number of authors (Calzetti *et al.* 2005, 2007, 2010; Alonso-Herrero *et al.* 2006; Perez-Gonzalez *et al.* 2006; Relaño *et al.* 2007; Salim *et al.* 2007; Rieke *et al.* 2009), but the sample size of Spitzer is small and the sensitivity is also limited.

In other words, the calibrations based on the relation between the total luminosity and SFR are still problematic because of the limitation of sensitivity and size of the sample. This dearth of infrared data for normal star-forming galaxies is largely a consequence of prior instrumental limitations.

The Wide-field Infrared Survey Explorer (WISE, Wright *et al.* 2010) will map the entire sky with 5σ point source sensitivities better than 0.08, 0.11, 1 and 6 mJy at wavelengths of 3.4, 4.6, 12 and 22 μm , which is 3 to 6 orders of magnitude more sensitive than previous surveys. For example, WISE is achieving 100 times better sensitivity than IRAS in the 12 μm band. As an all-sky survey, WISE will finally return data of about over 500 million objects, so it provides us a large sample of star-forming galaxies. The improved sensitivity and large sample size make it suitable for studying the evolution of galaxies.

The WISE Preliminary Release has been available to the astronomical community since April 14, 2011 and contains the attributes for 257,310,278 objects observed during the first 105 days of the survey. The data presented here were processed with initial calibrations and reduction algorithms of the WISE pipeline derived from early survey data (Cutri *et al.* 2011).

This paper is organized as follows. Based on the WISE Preliminary Data Release, we present a sample to derive our SFR index calibration (§2). In §3, we study the

correlation between SFR and the luminosity at 3.4, 4.6, 12 and 22 μm and calibrate the 3.4, 4.6, 12 and 22 μm SFR index. In §4, we study the origin of dispersion between SFR and the luminosity at 3.4, 4.6, 12 and 22 μm . In §5, we summarize the calibration result and conclude this paper. Throughout the paper, we adopt a value of the $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$.

2. Data sample

The preferred method for determining SFR in star-forming galaxies is obtained from the luminosity at some wavelengths. WISE is surveying the entire sky at wavelengths of 3.4, 4.6, 12 and 22 μm (W1 through W4, respectively), so we will study the correlation between the SFR and the luminosity at 3.4, 4.6, 12 and 22 μm and calibrate them. In this paper, the adopted SFR values are provided by JHU/MPA, determined from the method in Brinchmann *et al.* (2004) which combines emission line measurements from within the fibre where possible and aperture corrections are done by fitting models of Gallazzi *et al.* (2005) and Salim *et al.* (2007) to the photometry outside the fibre. The luminosities L at 3.4, 4.6, 12 and 22 μm are calculated based on redshift and the ‘raw’ source flux measured in the profile-fit photometry:

$$\text{Flux} = \frac{L}{4\pi \times D^2},$$

where D is the luminosity distance derived from the redshift.

We match the WISE Preliminary Release Catalog with the star-forming galaxy catalog in SDSS DR 8 provided by JHU/MPA. The star-forming galaxy is selected by requiring the rigorous great circle arc distances between the galaxy of SDSS and WISE Preliminary Release Catalog to be less than the 6.1”, which is the angular resolution of wavelength 1 (W1). After converting digital numbers to Jy using the PSF-fit photometry (Cutri *et al.* 2011), we made the internal reddening correction for the flux of all the emission lines, using the two strongest Balmer lines, $H\alpha/H\beta$ and the effective absorption curve $\tau_\lambda = \tau_V(\lambda/5500 \text{ \AA})^{-0.7}$, which was introduced by Charlot & Fall (2000). Then, we made use of the spectral diagnostic diagrams from Kauffmann *et al.* (2003) to classify galaxies as star-forming galaxies, active galactic nuclei (AGN), or unclassified. To reduce systematic and random errors, our galaxy samples are limited by the requirement that the ‘raw’ source flux measured photometry is always larger than three times of the uncertainty in the ‘raw’ source flux measurement in profile-fit photometry.

In total, $\sim 140,000$ star-forming galaxies are adopted in our sample.

3. Star formation rates calibrator

Hydrogen recombination line fluxes have been used very extensively to estimate the SFR, since they are proportional to the number of photons produced by the hot stars, which is in turn proportional to their birthrate. Most applications of this method have been based on measurements of luminosity from the $H\alpha$ line (Kong 2004; Gao *et al.* 2010).

Star-forming regions tend to be dusty and the dust absorption cross-section peaks in the UV, and then is reprocessed by dust and emerges beyond a few μm . As a result, the luminosity at a few μm are reliable SFR indicators. This process is restricted by

the complex physical conditions, such as not all of the luminous energy produced by recently formed stars being re-processed by dust in the infrared depending on dust amount and evolved non-star-forming stellar populations also heating the dust that then emits in the FIR, etc. (Calzetti *et al.* 2010, and references therein). So it is necessary to check whether the IR luminosity can be reliable SFR indicators.

To check whether the luminosities at 3.4, 4.6, 12 and 22 μm are reliable SFR indicators, we show the relation between $\text{H}\alpha$ luminosity and the luminosity at 3.4, 4.6, 12 and 22 μm for our data sample in Figure 1. Apart from a few outliers in the sample, all the objects merge into a relatively tight, linear and steep sequence, which gives strong evidence that the luminosities at 3.4, 4.6, 12 and 22 μm are good SFR indicators just like the $\text{H}\alpha$ line.

From the relation between SFR and the luminosity at 3.4, 4.6, 12 and 22 μm for our data sample in Figure 2, we can define a new SFR calibration. The observed distribution of all the points in this figure is linear least-square-fitted by the expression given as the dashed line in Fig. 2.

It should be noted that our SFR calibration holds only for the galaxies with authentic spectral observation. Only galaxies which have reasonable values of oxygen abundance can be used in Fig. 2 ($\sim 70,000$ galaxies). All these galaxies have high quality spectral observations. If we plot the whole sample in Fig. 2, the dependencies of SFR on the luminosity at 3.4, 4.6, 12 and 22 μm will worsen. In the next section, these fit residuals will be discussed.

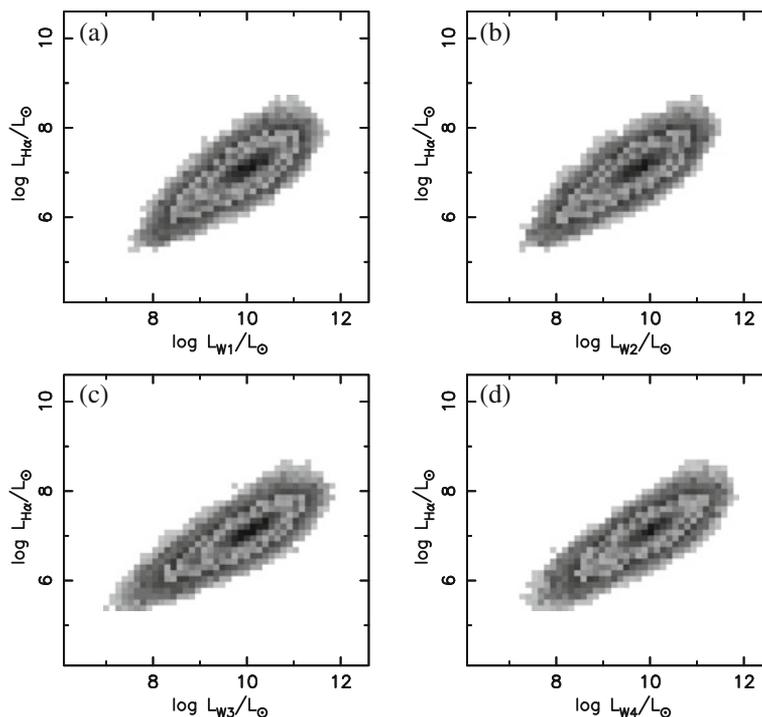


Figure 1. The relation between $\text{H}\alpha$ luminosity and the luminosity at W1 through W4, respectively, for our data sample. The luminosity is in units of solar luminosity.

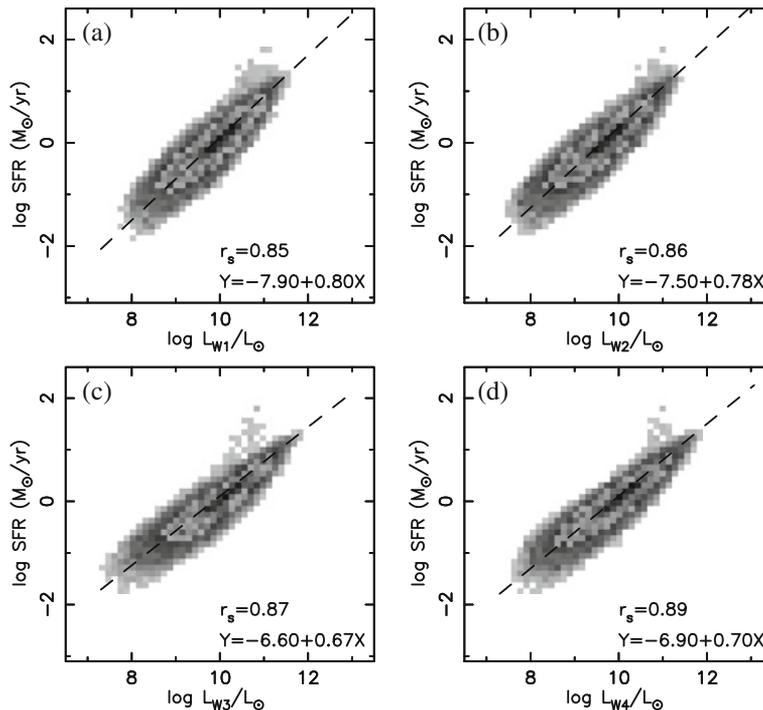


Figure 2. The relation between SFR and the luminosity at 3.4, 4.6, 12 and 22 μm for our data sample. The dashed lines denote the best-fit function. X and Y are luminosity and SFR, respectively. The SFR is in units of M_{\odot}/yr . The luminosity is in units of solar luminosity, L_{\odot} . r_s is the Spearman's rank correlation coefficient of the fit.

4. The origin of the dispersion

This close correlation between SFR and the luminosity can be understood by the knowledge of the domination of the young star at wavelengths of 12 and 22 μm . The contribution from the evolved non-star-forming stellar populations at wavelengths of 12 and 22 μm are negligible for most star-forming galaxies in our sample. But for the wavelengths of 3.4 and 4.6 μm , it is established that the contribution by the old star populations can be non-negligible in these wavelengths. The strong correlation for the wavelengths of 3.4 and 4.6 μm in our data sample gives strong evidence that the contribution of young stellar populations are still dominant at wavelengths of 3.4 and 4.6 μm .

Although the SFR is closely related to the luminosity at 3.4, 4.6, 12 and 22 μm , the dispersion of the relation is significant. Furthermore, the scatter does not show significant change in increasing wavelength, but appears to increase for increasing luminosity (Fig. 2).

4.1 Metallicity and concentration index

To further investigate these trends, we subdivide the sample into sub-samples with different oxygen abundances (Figure 3a). The luminosity-SFR relation at low

oxygen abundance is displaced to lower SFR and lower luminosity. We can explain this because majority of low oxygen abundance galaxies have less star forming events, and therefore they have relatively lower SFR.

The behavior that the higher oxygen abundance galaxies tends to have higher luminosity (mass) has been studied by many authors (Shi *et al.* 2005, and references therein). With the luminosity and metallicity correlation, the most straightforward interpretation is that more massive galaxies form fractionally more stars in a Hubble time (higher luminosity) than low-mass galaxies, and then have higher metallicity.

The galaxies with the concentration value $C > 2.6$ are mostly early type galaxies whereas late type galaxies have $C < 2.6$ (Kauffmann *et al.* 2003). It is well known that early type galaxies are dominated by old/small mass stars, but late type galaxies are dominated by young/massive stars. In Fig. 3b, we subdivide the sample into sub-samples with different C . It is clear that the concentration value does not contribute to the dispersion.

4.2 4000 Å Break

To show the contribution of the star formation history to the dispersion in the relation between SFR and the luminosity at 3.4, 4.6, 12 and 22 μm , we divided the data sample into sub-samples with different 4000 Å breaks (Fig. 3c).

We caution that because these 4000 Å break quantities are derived within the fiber aperture, they may not be representative of the galaxy as a whole, whereas the SFR

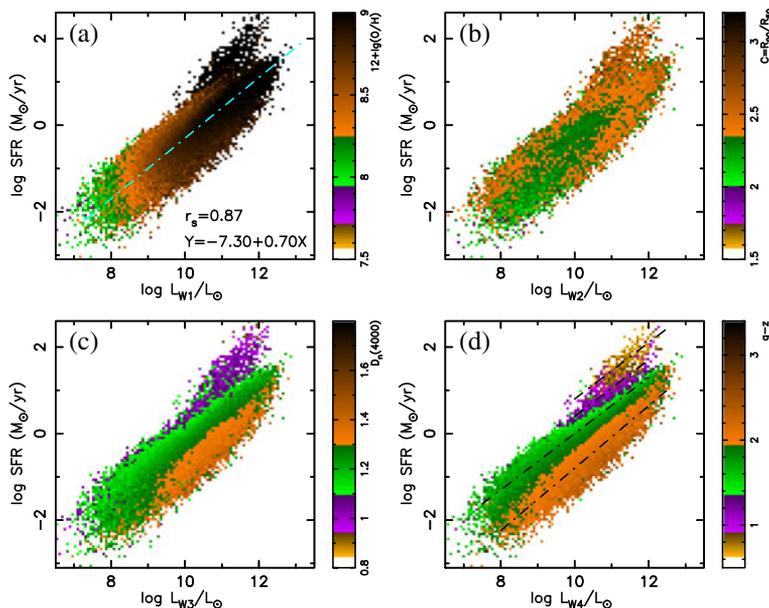


Figure 3. The relation between SFR and the luminosity for our data sample. (a) The sample is subdivided into different oxygen abundances. X and Y are luminosity and SFR, respectively. r_s is the Spearman's rank correlation coefficient of the fit. (b) The sample is subdivided into different concentration values. (c) The sample is subdivided into different 4000 Å breaks. (d) The sample is subdivided into different $g - z$ colors. The luminosity is in units of solar luminosity.

estimates are for the entire galaxy. If we make the same plot using SFR within the fibre aperture, we still recover a similar behavior as Fig. 3c which use the SFR of the entire galaxy. From that, we can conclude that the influence of the fibre aperture effect on this relation is negligible.

It shows that the luminosity-SFR relation at a low 4000 Å break is displaced to higher SFR and lower luminosity. Brinchmann *et al.* (2004) showed that most of the star formation takes place in galaxies with a low 4000 Å break. It can explain the behavior of the low 4000 Å break displaced to higher SFR, where galaxies with a low 4000 Å break have a younger stellar population, and therefore higher SFR values than high 4000 Å break galaxies of the same SFR. The selection effects also contribute to the effect that high 4000 Å break galaxies tend to be excluded from our data sample because these galaxies usually have old stellar populations and seldom show evident emission lines. If one high 4000 Å break galaxy indeed shows an evident emission line, it will tend to have less starbursts, hence lower SFR.

4.3 $g - z$ Color

It is interesting to study whether color relates to SFR or not. To show this view clearly, we divided the data sample into sub-samples with different $g - z$ colors (Fig. 3d).

It shows that the luminosity-SFR relation at the bluer end is displaced to higher SFR and lower luminosity. We can explain this trend like the 4000 Å break where the galaxies with bluer colors are younger, and therefore have a lower 4000 Å break. The observed distribution of the points in each $g - z$ color bin is linear least-square-fitted by the following expression, given as the dashed line in Fig. 3d.

$$\log \text{SFR} = -5.70 + 0.65 \log L_{W4} \quad (g - z \leq 0.95), \quad (1)$$

$$\log \text{SFR} = -6.10 + 0.65 \log L_{W4} \quad (0.95 < g - z \leq 1.35), \quad (2)$$

$$\log \text{SFR} = -6.50 + 0.65 \log L_{W4} \quad (1.35 < g - z \leq 1.95), \quad (3)$$

$$\log \text{SFR} = -8.00 + 0.72 \log L_{W4} \quad (g - z > 1.95). \quad (4)$$

5. Conclusions

We have collected from Wide-field Infrared Survey Explorer (WISE), a large sample of star-forming galaxies covering a wide range in metallicity $7.66 < 12 + \log(\text{O}/\text{H}) < 9.46$, with redshift less than 0.4, and matched the data with a sample of SDSS DR8 data. We have found the existence of the correlation between 3.4, 4.6, 12 and 22 μm luminosity and SFR and have obtained a calibration that can be used as a method for determining SFR for star-forming galaxies. The calibrations hold for galaxies with high quality spectral observations. The dispersion and non-linearity between 3.4, 4.6, 12 and 22 μm luminosity and SFR is related to the galaxy's properties, such as the 4000 Å break and galaxy color.

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