SPITZER 70 μm EMISSION AS A STAR FORMATION RATE INDICATOR FOR SUB-GALACTIC REGIONS

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Received 2010 July 1; accepted 2010 October 2; published 2010 November 19

ABSTRACT

We use Spitzer 24 μm, 70 μm and ground-based Hα data for a sample of 40 SINGS galaxies to establish a star formation rate (SFR) indicator using 70 μm emission for sub-galactic (∼0.05–2 kpc) line-emitting regions and to investigate limits in application. A linear correlation between 70 μm and SFR is found and a star formation indicator SFR(70) is proposed for line-emitting sub-galactic regions as \(\Sigma(\text{SFR}) (M_\odot \text{yr}^{-1} \text{kpc}^{-2}) = 9.4 \times 10^{-44} \Sigma(70) \text{ (erg s}^{-1} \text{kpc}^{-2})\), for regions with \(12 + \log(O/H) \gtrsim 8.4\) and \(\Sigma(\text{SFR}) \gtrsim 10^{-3} (M_\odot \text{yr}^{-1} \text{kpc}^{-2})\), with a 1σ dispersion around the calibration of ∼0.16 dex. We also discuss the influence of metallicity on the scatter of the data. Comparing with the SFR indicator at 70 μm for integrated light from galaxies, we find that there is ∼40% excess 70 μm emission in galaxies, which can be attributed to stellar populations not involved in the current star formation activity.

Key words: galaxies: ISM – H II regions – infrared: galaxies – infrared: ISM – ISM: structure

Online-only material: color figures

1. INTRODUCTION

Interstellar dust absorbs UV and optical light and reradiates it at infrared wavelengths. In dusty systems, the use of UV and Hα emission to trace recent star formation is subject to large uncertainties even when dust attenuation corrections are used, since these corrections have large scatter produced by the large range of possible dust content, distribution, and geometry relative to stars and gas present in galaxies (e.g., Meurer et al. 1999; Calzetti 2001; Kong et al. 2004; Dale et al. 2007; Johnson et al. 2007; Cortese et al. 2008). IR emission then becomes a reliable method to trace star formation rates (SFRs) in galaxies, where the UV light produced by recent star formation is attenuated and reprocessed by dust into the infrared (Kennicutt 1998).

As deep galaxy surveys have often access to limited wavelength information, monochromatic SFR indicators offer advantages over indicators using integrated luminosity over extended wavelength range (e.g., FIR luminosity) by providing “easier to use” recipes. Monochromatic SFR indicators based on infrared emission from both whole galaxies and sub-galactic regions have been investigated in detail, particularly at the wavelength of 8 μm and 24 μm, by many authors (Calzetti et al. 2005, 2007; Wu et al. 2005; Alonso-Herrero et al. 2006; Pérez-González et al. 2006; Relaño et al. 2007; Zhu et al. 2008; Kennicutt et al. 2009; Rieke et al. 2009), thanks to large samples of nearby galaxies observed at these wavelengths with unprecedented resolution and sensitivity by the Spitzer Space Telescope (e.g., Kennicutt et al. 2003; Dale et al. 2009). Monochromatic SFR indicators at the longer Spitzer bands, 70 μm and 160 μm, have also been investigated for the integrated light of galaxies (Calzetti et al. 2010). These longer wavelengths may provide more reliable SFR indicators than either 8 μm or 24 μm as they are close to the peak of dust IR emission (Rieke & Lebofsky 1979; Draine et al. 2007; Lawton et al. 2010). Calzetti et al. (2010) analyze the emission in those two bands as an SFR indicator using a sample of 189 galaxies, showing that reliable SFR indicators could be established above an SFR ∼ 0.1–0.3 M_\odot yr^{-1}. Boquien et al. (2010) also presented SFR calibration of Herschel (Space Telescope) 100 μm and 160 μm bands for spatially resolved regions in M33.

The launch and recent commissioning of the Herschel Space Telescope is providing a sensitive and high angular resolution window into the far-infrared/submillimeter wavelength regime, also tracing the dust peak emission in high redshift galaxies. Upcoming ground facilities at millimeter wavelengths (ALMA and the Large Millimeter Telescope) will also provide increased sensitivity and coverage for deep surveys in the millimeter wavelength regime. Such surveys will probe near the rest-frame dust emission peak (∼60–150 μm), at high redshift, e.g., the Herschel Space Telescope will probe the rest-frame dust emission peak up to z ∼ 2. Thus, it is of significant interest to analyze the behavior of the Spitzer 70 μm band as an SFR indicator in spatially resolved sub-galactic regions, since these regions may resemble actively star-forming and starburst galaxies at high redshift. In this paper, we will investigate the 70 μm as an SFR indicator in star-forming regions, with sizes from ∼0.05 to 2 kpc.

A study of the 70 μm luminosity of H II regions has been already presented by Lawton et al. (2010) for the Magellanic Clouds. Our analysis differs from that of Lawton et al. (2010) in that we probe a large range of galaxies, thus matching the range of properties those studies that have derived SFR(70) for whole galaxies. We also use an unbiased reference SFR indicator proposed by Kennicutt et al. (2007), Calzetti et al. (2007), and Kennicutt et al. (2009), consisting of Hα and 24 μm emissions. As a drawback, our study will generally probe larger physical scales than the Lawton et al. (2010) paper, although our scales are still matched to those of large star formation complexes (∼100 pc; Elmegreen et al. 2006).
The paper is structured as follows: Section 2 explains the data, Section 3 discusses the method for deriving photometry on the sub-galactic regions, Section 4 compares the 70 μm against a reference SFR indicator and then the data are compared with a simple stellar population plus dust model, and Section 5 provides the calibration of 70 μm as an SFR indicator. Discussions are presented in Section 6 and summary in Section 7.

Units in this paper are erg s⁻¹ for luminosity, erg s⁻¹ kpc⁻² for luminosity surface density (LSD, with symbol Σ), M⊙ yr⁻¹ for SFR, and M⊙ yr⁻¹ kpc⁻² for star formation rate surface density (Σ(SFR) or SFRD), unless otherwise specified. We adopt a Hubble constant, H₀ = 70 km s⁻¹ Mpc⁻¹.

2. DATA

2.1. Sample Selection and Description

Our baseline sample is the SINGS (Spitzer Infrared Nearby Galaxies Survey; Kennicutt et al. 2003) survey, which obtained images in both the mid-IR and far-IR with the Spitzer Space Telescope, plus ancillary images in the optical. For the present work, we are interested in the subset of images obtained at 24 μm, 70 μm (with Spitzer/MIPS) and in Hα (see Figure 1 for example images). Dale et al. (2009) and Calzetti et al. (2010) describe the images, including background subtraction for the Hα images, which were obtained from both the KPNO 2.1 m and the CTIO 1.5 m telescopes. Among the 75 galaxies of SINGS, we exclude all ellipticals, S0 galaxies and some irregular galaxies, which satisfy at least one of the following conditions: (1) only one central source could be selected but the galaxy is identified as hosting an active galactic nucleus (AGN); (2) there are either bright star(s) across the galaxy disk, or other factors causing the quality of the images, when convolved to the resolution of the 70 μm images, to be degraded by spurious artifacts. Thus, we end up with a sample of 40 galaxies; their galaxy types, nuclear types, and adopted distances are listed in Table 1. We do not apply any further selection criterion on galaxy properties, and our 40 galaxies cover almost the full range in Hubble types of spiral galaxies and a few irregular galaxies, with different intensities of star formation, from starburst to normal star-forming galaxies. Some of these galaxies have or may have an AGN in the center, and these central regions will be excluded from our analysis. What we term as “central regions” are usually the central ~1 kpc of the galaxies, because of the angular resolution (~16′′) of the Spitzer 70 μm images. Hence, when discarding AGN-impacted nuclei, we will also be discarding regions outside of the nucleus that may be affected by the AGN. The large range of properties of the regions matches or exceed (especially in SFR surface density) the range of properties of the whole galaxies in our final sample. The Hα images are corrected for [N II] contamination using the [N II]/Hα ratios listed in Kennicutt et al. (2009).

2.2. Oxygen Abundance

Oxygen abundances, which we will term “metallicities” in the rest of the paper, for the galaxies in our sample are from Moustakas et al. (2010). They are listed in Tables 8 and 9 in Moustakas et al. (2010); 16 out of 40 galaxies have metallicity gradient measurements. Two calibrations were used by Moustakas et al. (2010), namely, KK04 (Kobulnicky & Kewley 2004) and PT05 (Pilyugin & Thuan 2005), to derive the metallicity information and we will use the average from these two methods in our analysis. Because of the factor ~5 discrepancy in the metallicity scale resulting from the two methods (Moustakas et al. 2010), we will avoid, to the extent possible, referring to absolute metallicity values and mainly use relative values. For those with gradient information, we calculate the metallicity for each aperture taking into account the distance of the center of the aperture to the center of the galaxy, after correcting for the projection effect using inclination information (Table 1 in Moustakas et al. 2010). For the remaining galaxies, we assign the characteristic metallicity of the whole galaxy to each aperture of this galaxy, while for six of the small/dwarf galaxies metallicity is derived from the B-band luminosity–metallicity (L–Z) relation and may be susceptible to additional systematics biases (Moustakas et al. 2010). Figure 2 shows the distributions of the metallicities and of the metallicity uncertainties for the 597 data points in our sample. The uncertainties are derived from the quoted uncertainties in Moustakas et al. (2010) in the case of galaxies with directly measured metallicity values or gradients; an uncertainty of 0.2 dex is instead assigned to the metallicity value of galaxies derived from the L–Z relation, reflecting the factor 5 difference between the two calibration scales.

We divide our sample into three sub-samples based on the adopted metallicities: a low metallicity sample with 12 + log(O/H) ≤ 8.4 (“sub-solar”, including a total of four galaxies and 41 apertures), an intermediate metallicity sample with 8.4 < 12 + log(O/H) < 8.8 (“solar”, including a total of 25 galaxies and 425 apertures, where two galaxies’ metallicities are from L–Z relation), and a high metallicity sample with 12 + log(O/H) ≥ 8.8 (“super-solar”, including a total of 11 galaxies and 131 apertures, where four galaxies’ metallicities are from L–Z relation). The adopted solar oxygen abundance is 8.69 from Asplund et al. (2009).

3. APERTURE PHOTOMETRY

3.1. Source Selection

For the comparison of multi-wavelength images, all the 24 μm (6′′) and Hα (~1′′–2′′) images have been convolved to the same resolution as 70 μm (16′′) using the convolution kernel and method from Gordon et al. (2008) and registered to the same coordinate system and pixel size (4.5 arcsec pixel⁻¹), after the global background is subtracted, which is determined from the mode of the pixel value distribution of the whole image. The aperture size is chosen to be 16′′ in radius which corresponds to the FWHM of the 70 μm point-spread function (PSF; MIPS handbook⁶) and a physical radius ~50 pc–2000 pc depending on the galaxy distance (Table 1). Sources are selected by manual inspection, at emission peaks of the 70 μm band; the other two images, at 24 μm and in Hα, are then checked for the presence of peaks in correspondence of the 70 μm ones. A candidate within a given aperture is accepted if it appears in all three images (See Figure 1). This will bias our sample by excluding very dust obscured objects (i.e., with completely absorbed Hα) and very transparent objects (with weak IR emission). We do not consider this a major bias in our sample, as Prescott et al. (2007) found that in SINGS galaxies only a small fraction (~3%) of star-forming regions is highly obscured. The exclusion of very transparent objects is also not considered a problem for our analysis, which is centered on the derivation of an SFR calibrator from IR emission, thus requiring the presence of dust emission. Although crowding is present within our apertures, and often

⁶ http://ssc.spitzer.caltech.edu/mips/mipssinstrumenthandbook/MIPS_Instrument_Handbook.pdf
Table 1
Sample

| Galaxy     | Type   | Nuc. | $D$ (Mpc) | Size (pc/16$''$) | Oxygen Abundance (Information) | No. of Regions | Sub-sample |
|------------|--------|------|-----------|-------------------|---------------------------------|----------------|------------|
| NGC0024    | SAc    | SF   | 8.2       | 636               | 1                               | 3              | M          |
| NGC0337    | SBd    | SF   | 24.7      | 1916              | 1                               | 5              | M          |
| NGC0628    | SAc    | SF   | 11.4      | 884               | 2                               | 40             | M          |
| NGC0925    | SAbd   | AGN  | 10.4      | 807               | 2                               | 23             | M          |
| NGC1097    | SBB    | AGN  | 16.9      | 1311              | 2                               | 20             | M          |
| NGC1512    | SBB    | AGN  | 10.4      | 807               | 1                               | 7              | H          |
| NGC1566    | SABbc  | AGN  | 18        | 1396              | 3                               | 15             | H          |
| NGC1705    | Am     | SF   | 5.8       | 450               | 1                               | 2              | L          |
| NGC2403    | SABcd  | SF   | 3.5       | 271               | 2                               | 41             | M          |
| Ho II      | Im     | SF   | 3.5       | 271               | 1                               | 8              | L          |
| NGC2798    | SBA    | AGN  | 24.7      | 1916              | 1                               | 1              | M          |
| NGC2841    | SAb    | AGN  | 9.8       | 760               | 2                               | 9              | H          |
| NGC2976    | SAc    | SF   | 3.5       | 271               | 1                               | 9              | M          |
| NGC3049    | SBB    | SF   | 19.6      | 1526              | 1                               | 1              | H          |
| NGC3190    | SAp    | AGN  | 17.4      | 1350              | 3                               | 3              | H          |
| NGC3184    | SABcd  | SF   | 8.6       | 667               | 2                               | 27             | H          |
| IC2574     | SABm   | SF   | 3.5       | 271               | 1                               | 10             | L          |
| M83        | Im     | SF   | 21.7      | 1683              | 1                               | 1              | M          |
| NGC3351    | SBB    | SF   | 9.3       | 721               | 2                               | 8              | H          |
| NGC3521    | SABbc  | AGN  | 9         | 698               | 2                               | 22             | M          |
| NGC3627    | SABb   | AGN  | 8.9       | 690               | 1                               | 8              | M          |
| NGC3938    | SAc    | SF   | 12.2      | 946               | 3                               | 22             | M          |
| NGC4254    | SAc    | SF   | 20        | 1551              | 2                               | 20             | M          |
| NGC4321    | SABbc  | AGN  | 20        | 1551              | 2                               | 24             | H          |
| NGC4450    | SAb    | AGN  | 20        | 1551              | 3                               | 5              | H          |
| NGC4536    | SABbc  | SF/AGN | 25       | 1939             | 1                               | 8              | M          |
| NGC4559    | SABcd  | SF   | 11.6      | 900               | 2                               | 17             | M          |
| NGC4579    | SABb   | AGN  | 20        | 1551              | 3                               | 7              | H          |
| NGC4631    | Sbd    | SF   | 9         | 698               | 1                               | 14             | M          |
| NGC4725    | SABbc  | AGN  | 17.1      | 1326              | 1                               | 22             | M          |
| NGC5055    | SAbc   | AGN  | 8.2       | 636               | 2                               | 24             | M          |
| NGC5194    | SABbc  | AGN  | 8.2       | 636               | 2                               | 35             | H          |
| NGC5474    | SAbd   | AGN  | 6.9       | 535               | 1                               | 6              | M          |
| NGC5713    | SABc    | SF   | 26.6      | 2063              | 1                               | 1              | M          |
| IC4710     | SBm    | SF   | 8.5       | 659               | 3                               | 8              | M          |
| NGC6822    | IBm    | SF   | 0.6       | 47                | 1                               | 18             | L          |
| NGC6946    | SABcd  | SF   | 5.5       | 427               | 2                               | 37             | M          |
| NGC7331    | SAb    | AGN  | 15.7      | 1218              | 2                               | 22             | M          |
| NGC7552    | SAc    | SF   | 22.3      | 1730              | 1                               | 3              | M          |
| NGC7793    | SAd    | SF   | 3.2       | 248               | 2                               | 41             | M          |

Notes. Column 1 SINGS galaxy name; Column 2 morphological type; Column 3 adopted nuclear optical spectral classification from Moustakas et al. (2010); type AGN is adopted when it is SF/AGN in Moustakas et al. (2010); Column 4 distance; morphological type and distance are adopted from Kennicutt et al. (2003) and also listed in Moustakas et al. (2010); Column 5 physical size of adopted aperture; Column 6 oxygen abundance information adopted from Moustakas et al. (2010); 1 = characteristic value for the galaxy is adopted; 2 = gradient is adopted and metallicity calculated for each aperture; 3 = $L$–$Z$ relation derived value is adopted; Column 7 the number of apertures selected from each galaxy; Column 8 the sub-sample each galaxy belongs to, but the regions in the galaxy may belong to another sub-sample according to metallicity gradients, if available; L = low metallicity sample; M = intermediate metallicity sample; H = high metallicity sample.

References. (1) Kennicutt et al. 2003; (2) Moustakas et al. 2010.

more than one H II knot is included in them, we usually can identify peaks in each aperture that are brighter than any other in the same aperture. We keep the overlap between apertures to no more than 4% of the aperture area. Some apertures in crowded environments need to be off-centered because of the overlap criterion and also because of the presence of multiple emission peaks within a given aperture. The central regions of these galaxies, which are classified as having or possibly having an AGN by Moustakas et al. (2010), listed in Table 1, are not included. With these criteria, we obtain 597 regions out of our sample of 40 galaxies.

3.2. Local Background Subtraction

Due to crowding, background annuli are difficult to determine for each aperture, without the influence of a neighboring aperture. Thus, we adopt the method of Calzetti et al. (2005) to remove the local background from each aperture. Each galaxy in our sample is divided into several local regions usually identified as having a common environment, e.g., within the same spiral arm, after verifying that no sharp decrement of background, caused by either mosaicing problems, other data processing artifacts, or changes in the galaxy’s environment, exists within...
one local background region. Then, the local background for
each aperture is determined using the mode of the pixel value
distribution of the background region. For some more distant
galaxies, only a few emission knots are resolved and are quite
isolated. Although for these galaxies annuli around photometric
apertures would be applicable to remove the background, we
still apply our method of local background mode removal,
for consistency with other galaxies. A comparison between
our method and the standard background annuli method using
these isolated regions shows that our method works within
1% accuracy in removing the background of each aperture.
For extremely crowded regions, especially the central regions
of most large spiral galaxies, the local background of the
region is hard to determine. So, higher uncertainty should be
expected in those central regions, and extreme caution has
been applied in those regions when determining the local

background. Although the necessity of performing a local
different than a photometric measurement performed with an
advanced annuli background to better characterize both the sky
background and diffuse emission. We present in Appendix A
evidence that local background subtraction is necessary in order
to maintain a consistent behavior between low-luminosity and
high-luminosity data, which is essential for performing a reliable
analysis.

3.3. Empirically Established Aperture Correction

We then need to define aperture corrections in order to
recover the lost flux outside our apertures due to the significant
portion of flux contained in the 70 μm PSF wings. However,
the aperture correction value provided by the MIPS handbook
is not applicable to our photometry, for several reasons: (1) we
adopt a local background subtraction derived from the mode
of local regions rather than annuli around apertures, (2) there
is usually more than one emission peak within each aperture,
and (3) there is crowding in the aperture. Thus, we have to
establish an aperture correction for our case. The use of a
PSF at 70 μm to derive “custom” aperture corrections is also
not applicable, since, within each aperture, usually there are
several emission peaks as can be seen from the high-resolution
images (see Figure 1), and any aperture correction will need to
account for the “extended” nature of our sources. Finally, each
aperture suffers from contamination of the PSF wings from
neighboring apertures because of crowding. All these make it
difficult to establish the aperture correction simply from the
theoretical PSF, as it is hard to build a reasonable model of PSF
distribution both within and outside the aperture. We thus derive
empirical aperture corrections using the original unconvolved
high-resolution Hα images, which we consider to represent
the true flux distribution within the aperture we choose; this
applies since the aperture size is much larger than the FWHM
of the PSF of the original Hα images (typically 1″–2″). We can
then compare the original Hα images and the convolved Hα

![Figure 1](image1)

Figure 1. Aperture and region selection of NGC5194 and NGC3627 on original Hα and 24 μm images (left and right panels) and NGC5194 on convolved Hα and 24 μm images (middle panel). The sizes are 7′05 × 11′25 (280 × 447 pc) for left and middle panels and 3′83 × 6′15 (165 × 265 pc) for the right panel. Circles are selected apertures and boxes are regions for local background subtraction. Central regions of both galaxies are not included as both are classified as having an AGN type nucleus. Red: 70 μm; green: 24 μm; blue: Hα. North is up and east is left. The two galaxies are chosen to show one example of a nearby extended galaxy with multiple resolved features and one example of a farther away, smaller galaxy with a smaller number of identified regions.

![Figure 2](image2)

Figure 2. Distribution of metallicity values for our data on the left panel and metallicity uncertainty on the right panel. The majority are in the intermediate metallicity sub-sample (8.4 < 12 + log(O/H) < 8.8) and have an uncertainty less than 0.15 dex.
images to establish median aperture corrections for our aperture photometry (see Appendix A).

3.4. Other Corrections and Error Terms

After the aperture correction (established in Appendix A), the Hα photometry is also corrected for [N ii] contamination (Section 2.1) and Galactic extinction correction (Schlegel et al. 1998; O’Donnell 1994), while the Galactic extinction for 24 μm and 70 μm is considered negligible (Draine 2003, and references therein). We do not correct the Hα emissions for internal extinction, as we use a combination of Hα and 24 μm in our analysis (Kennicutt et al. 2007; Calzetti et al. 2007). The Hα fluxes in this paper are the observed Hα fluxes as specified in these articles.

In addition to the uncertainties from global and local backgrounds (<2%), calibration uncertainties (2% for 24 μm, 5% for 70 μm, and 10% for Hα, SINGS data release guide⁷), and aperture correction uncertainties (~22%), we have performed other tests to determine the presence of possible uncertainties introduced by the single convolution kernel temperature used (<1%) and misalignment or misplacing of apertures (~1.5%). The convolution of 24 μm and Hα images to the 70 μm images resolution uses a convolution kernel, which assumes a blackbody temperature of 50 K. Since Calzetti et al. (2000) show that there are two components of dust, cool (~20 K) and warm (~50 K), we also use kernels of 25 K and 75 K to perform the convolution and find that less than 1% error in measured flux is shown between those two convolution temperatures and the 50 K we use. We also shift our apertures by half-pixel (4.5 arcsec pixel⁻¹) to see how much the photometry is changed to estimate the error introduced by possible misalignment or misplacing of apertures; this introduces at worst a ~1.5% difference in measured flux.

These six error terms combined together produce our error estimate, typically ~24%, for the aperture photometry; we can easily see that the aperture correction uncertainty at ~22% (Appendix A) is the dominant source of uncertainty.

4. RESULTS AND ANALYSIS

In order to establish the calibration of SFR(70), we first investigate the correlation between 70 μm emission and SFR and then compare the correlation with a simple model for dust absorption and emission of stellar light.

4.1. Correlation Between 70 μm and SFR

In order to determine whether the 70 μm luminosity of sub-galactic line-emitting regions can be used as an SFR indicator and what its limitations may be, we first need a reference unbiased SFR indicator for spatially resolved regions. We intentionally avoid total infrared (TIR) luminosity as the reference SFR indicator because 70 μm is a major contributor to TIR for most galaxies, since 70 μm is near the peak of dust emission (Rieke & Lebofsky 1979; Draine et al. 2007; Lawton et al. 2010). As proposed by Kennicutt et al. (2007), Calzetti et al. (2007), and Kennicutt et al. (2009), a mixed SFR indicator, involving the combination of an optical and an infrared tracer of SF, can provide an unbiased SFR estimate. In this paper, we take the combination, L(Hα)+0.031L(24), from Calzetti et al. (2007), as our reference SFR indicator. Calzetti et al. (2007) derive the coefficient 0.031 from H II regions. The analogous coefficient for the integrated light of whole galaxies, from Kennicutt et al. (2009), is 0.020; the difference between the two is possibly due to the presence of diffuse 24 μm emission in galaxies (Kennicutt et al. 2009). Although our regions span nearly 2 orders of magnitude in size, the majority of regions are dominated in luminosity by H II regions or clusters of H II regions, also on account of the fact that we remove the local background. The Calzetti et al. (2007) calibration is suitable for a continuous star formation history up to 100 Myr (Calzetti et al. 2010), and our apertures are estimated to have a median crossing timescale ~100 Myr and at most ~400 Myr (see the next section). The potential nonlinearity at Σ(SFR) > 0.17 M⊙ yr⁻¹ kpc⁻² is an important caveat for the application of this calibration (Calzetti et al. 2007), but the SFRs of our apertures reach that high LSD regime only in 2% of the sample. Thus, the combination from Calzetti et al. (2007) is expected to be an appropriate SFR indicator in our case, although we still use in some cases the calibration of Kennicutt et al. (2009) for comparison. Calzetti et al. (2007) used Pa emission as reference SFR to calibrate the unbiased SFR indicator, with 33 galaxies chosen from the SINGS sample, based on the availability of Hubble Space Telescope Pa observations. Their sample and our sample have 19 galaxies in common, and their sample mostly consists of late-type spiral and irregular galaxies, very similar to the morphology distribution of our sample. Galaxies in the Calzetti et al. (2007) sample that are not included in our sample usually show centrally concentrated (e.g., rings, etc.) star formation, and we had to discard them because of the lower angular resolution of our study coupled with the presence of central AGNs in those galaxies. One galaxy, NGC0024, in our sample, is discarded by these authors due to the quality of Pa image (Calzetti et al. 2007).

The conversion used to derive SFR is then SFR(M⊙ yr⁻¹) = 5.45 × 10⁻⁴²L_{intrinsic}(Hα) = 5.45 × 10⁻⁴² L_{obs}(Hα) + 0.031L(24)(erg s⁻¹) (with the stellar initial mass function (IMF) from Kroupa 2001; Calzetti et al. 2010), and L(λ) = νL_ν for 24 μm and 70 μm following the common definition of monochromatic flux. Adopting a Salpeter (1955) IMF in the stellar mass range 0.1–100 M⊙ would increase the calibration coefficient by a factor 1.51. We use LSDs to eliminate the influence of the galaxy distance uncertainties, similarly to the use of LSDs in establishing the aperture correction.

The relation between 70 μm and the reference SFR indicator is shown in Figure 3. The linear fit in log–log space gives the correlation between 70 μm and the reference SFR indicator as

\[ \log[\Sigma(70)] = (0.342 ± 0.504) + (1.036 ± 0.013) \times \log[\Sigma(Hα) + 0.031\Sigma(24)]. \]  

The error term in Equation (1) is dominated by the dispersion of the data rather than the uncertainty in each data point. Although there are intrinsic differences between whole galaxies and sub-galactic regions, we also fit for the correlation between 70 μm and the calibration derived by Kennicutt et al. (2009), for the integrated light of galaxies, as a comparison:

\[ \log[\Sigma(70)] = (0.184 ± 0.526) + (1.042 ± 0.013) \times \log[\Sigma(Hα) + 0.020\Sigma(24)]. \]

This correlation is consistent with the fit in Equation (1) within 1σ uncertainties and both are within ~3σ of a linear correlation with a slope of unity between the two quantities.
The slightly steeper-than-unity trend between 70 μm emission and SFR is a consequence of the increased transparency of the interstellar medium at low SFR (Calzetti et al. 2010). At low SFR or low metallicity, the dust has lower opacity which results in a lower IR emission. If the fitting is constrained to high SFR, the slope asymptotically decreases to unity. For example, the slope is 1.004(±0.014) if fitting is constrained to log[Σ(70)] > 40.3 (log[Σ(Hα) + 0.031Σ(24)] ≥ 38.9 or SFRD ≥ 0.004 M⊙ yr⁻¹ kpc⁻²), which is consistent with unity. From the 70 μm/SFR versus SFR plot (Figure 4), the ratio of 70 μm over SFR distributes almost evenly around a constant value; the 1σ dispersion for the whole data set is ~0.18 dex, and this value decreases to ~0.16 dex if the low metallicity galaxies (12 + log(O/H) ≤ 8.4) are removed from the fit. In Figure 5, residuals in the 70 μm/SFR ratio show the expected correlation with metallicity (i.e., dust content) and weak or no correlation with L(24)/L(70) ratio (i.e., dust temperature), suggesting that dust content is the major contributor to the systematic scatter around the mean trend although other factors may still produce a small effect. We will compare our data to a simple model in the next section to investigate the cause of the scatter in the data.

4.2. A Simple Model Analysis

As can be seen from the left panel in Figure 5, changes in metallicity produce a trend in the 70 μm/SFR ratio, with higher metallicity points displaying higher 70 μm emission in fixed SFR than lower metallicity ones. We can also see that the low metallicity sample data points, with 12 + log(O/H) ≤ 8.4 or Z ≤ 0.5 Z⊙, show a broader dispersion than the higher metallicity ones in Figure 3. At low metallicity, the 70 μm luminosity could be lower since there is not enough dust to provide the opacity to absorb UV/optical light and reradiate in the IR. However, other factors, such as stellar population age, dust temperature, and others could also contribute to the dispersion. Thus, in order to further investigate the nature of the distribution and dispersion of the data, we construct a simple model for dust absorption and emission based on the model of Calzetti et al. (2007). Details of the model construction are in Appendix B, where we use Z⊙ = 0.0134 or 12 + log(O/H) = 8.69 (Asplund et al. 2009).

With the model, we can produce predicted 70 μm versus Hα+24 μm lines for each given metallicity and age. We compare the data with three models of different ages at fixed metallicity and vice versa, and find that the age contribution to the dispersion of data is almost negligible compared to the influence of metallicity.

In Figure 6, three models with ages 0.01 (dotted), 0.1, and 1 Gyr (dashed), and about solar (~0.134 Z⊙) metallicity, are overlaid on the data points, the older the redder. If we consider the star formation activity within the region as triggered by a single event, the time required for this perturbation to propagate throughout the entire region is comparable to the crossing time (~100 Myr typically for the median 700 pc physical size and from ~10 Myr to 400 Myr for all the possible physical sizes, ~50 pc to 2 kpc, of our apertures), thus we consider our three age models as bracketing the likely age range of the regions in our sample. The difference between the three models is negligible at the low SFRD end and increases toward high SFRD, but remains small at all SFRs. The small change with age is driven by the fact that, for constant star formation, the amount of dust and ionizing photons (the main contribution to the measured quantities) change negligibly for ages of 10 Myr or longer. Although it is not drawn on the plot, a 10 Gyr model does not show a significant difference from a 1 Gyr model but a 2 Myr model does show a significant difference from 10 Myr model at the high SFRD end, as the ionizing population is still growing from 2 Myr to 10 Myr. However, we do not expect the 2 Myr model to be physically applicable in our sample as it is too short compared to the typical crossing time.

In Figure 7, we keep the age fixed at 100 Myr, of the order of a typical crossing time, and overlay three models with different metallicities, 3.7 Z⊙, 1.4 Z⊙, and 0.3 Z⊙, corresponding to the high metallicity, intermediate metallicity, and low metallicity samples separately as the values are close to the median of these three sub-samples, on the data. The first three panels of the data are constructed as a simple model for dust absorption and emission based on the model of Calzetti et al. (2007). Details of the model construction are in Appendix B, where we use Z⊙ = 0.0134 or 12 + log(O/H) = 8.69 (Asplund et al. 2009).

With the model, we can produce predicted 70 μm versus Hα+24 μm lines for each given metallicity and age. We compare the data with three models of different ages at fixed metallicity and vice versa, and find that the age contribution to the dispersion of data is almost negligible compared to the influence of metallicity.
Figure 5. Residual as a function of metallicity (left-hand side) and $L_{24}/L_{70}$ ratio (right-hand side, see the caption of Figure 3 for color-code and symbol-code information). The trend is clearly stronger for the residual as a function of metallicity, indicating that variations in the temperature of the warm dust (as traced by $L_{24}/L_{70}$) are not the dominant contributor to the scatter around the mean trend. The apparent correlation on the upper right part of the data on the right panel is due to the fact that the plot is actually $1/x$ vs. $x$ once IR emission dominates. Three short lines above the data points in the left panel show the mean metallicity uncertainties of each sample separately. The units are erg s$^{-1}$ kpc$^{-2}$ for LSDs.

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

Figure 6. Models of three different ages, 10 Myr, 100 Myr, and 1 Gyr (blue dotted, green solid, and red dashed, respectively), with solar metallicity, overlaid on data (see the caption of Figure 3 for color-code and symbol-code information). Typical 1σ error is shown as the plus on upper left. Different ages of model do not show significant difference from each other. The units are erg s$^{-1}$ kpc$^{-2}$ for LSDs.

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

show the individual sub-sample overlaid with the corresponding metallicity model line; the models fit the average trend of data pretty well except that there is significant scatter in the low metallicity sample. In the last panel, these three models span a broad range in $\Sigma(70)$ at fixed $\Sigma(SFR)$, accounting at least in part for the dispersion of the data. This supports our argument that metallicity is the major contributor to the dispersion of the data. The models deviate from a linear relation; this is caused by systematic variations of the average stellar radiation field strength, $(U)$, see Appendix B), which increases with increasing luminosity and moves the dust emission peak to shorter wave-lengths than 70 $\mu$m. The convergence of three model lines at the high-luminosity end is caused by the assumption of a scaling between SFR and region opacity, in the sense that more active regions also contain more dust; thus at high luminosity our models simply probe the proportionality between $L_{70}$ and $L_{24}$, and no longer the scaling with metallicity. Nevertheless, each model is still very close to a linear relationship with unity slope. For decreasing metallicity, the dust infrared emission changes in several ways, which could possibly cause the large scatter in the low metallicity sample. First, a decrease in metallicity will directly reduce the dust opacity, which reduces the extinction and thus the total amount of emission absorbed from stellar UV light. Second, as the metallicity decreases, the effective temperature of dust emission increases (Calzetti et al. 2000; Engelbracht et al. 2008), and thus the trend will start to flatten sooner. However, lacking a sufficient number of low metallicity data could also be an important factor of the data behavior.

To see how the characteristics of the dust emission change as a function of SFRD, we plot the $L_{24}/L_{70}$ ratio against SFRD, (Figure 8), for both data and models. As can be seen from the plot, the data show a trend that is similar to that of the models, a similarity made even more evident when the comparison is performed with the binned data (filled symbols). The similarity holds at all SFR values, except for the high SFRD bin of the low metallicity sample which suffers from low number statistics; this is in contrast with the results of Calzetti et al. (2010) who find that the $L_{24}/L_{70}$ ratio flattens at high SFRD. We attribute the difference to the fact that the high SFRD data of Calzetti et al. (2010) consist mainly of LIRGs, whose dust opacity is sufficiently large that effects of self-shielding of the dust become important and the effective dust temperature no longer increases for increasing SFRD. In our case, regions at high SFRD may still display analogous properties of dust geometry as the low SFRD regions.

From the comparison between the data and models, and an investigation of the $L_{24}/L_{70}$ ratio as a function of SFR, we conclude that the observed infrared trends of the H II knots
Figure 7. Three models with different metallicities, $3.7Z_\odot$ (red dashed lines), $1.4Z_\odot$ (green solid line), and $0.3Z_\odot$ (blue dotted line), with an age of 100 Myr, overlaid on data with corresponding metallicity sample (see the caption of Figure 3 for color-code and symbol-code information) separately on each panel and the merged plot on the bottom right panel. The models reproduce the average trend of the data once the different metallicities are taken into account. Combined together, the data show the scatter which we attribute mainly to differences in metallicity. Typical $1\sigma$ error is shown as the black plus on the upper left cornel. The units are erg s$^{-1}$ kpc$^{-2}$ for LSDs.

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

Figure 8. Luminosity ratio $L(24)/L(70)$ as a function of the star formation rate density (SFRD) for our sample regions (see the caption of Figure 3 for color-code and symbol-code information). Three models with different metallicity (see the caption of Figure 7 for line style information) are overlaid on data. The big filled symbols (blue circles for low metallicity sample, green diamonds for intermediate metallicity sample, and red squares for high metallicity sample) represent the binned average (bins separated by vertical dashed lines) for each metallicity sample and the model lines follow reasonably well the average trend of the data. The units are $M_\odot$ s$^{-1}$ kpc$^{-2}$ for SFRDs and erg s$^{-1}$ kpc$^{-2}$ for LSDs separately.

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

are similar to those of whole galaxies (Calzetti et al. 2010), except for the most luminous galaxies. The differences among different H II knots appear to be mainly due to a luminosity scaling, with the more luminous 70 $\mu$m regions being more luminous in all other bands, while the systematic scatter is mostly due to differences in metallicity. This supports a mostly linear dependence between the 70 $\mu$m luminosity and SFR. Because the low metallicity sample shows significantly larger dispersion and deviation from the mean trend, we will exclude the low metallicity sample to derive an SFR(70) calibration.

5. 70 $\mu$m AS AN SFR INDICATOR

We now derive a relation between $\Sigma(70)$ and $\Sigma$(SFR) using only data with oxygen abundance greater than 8.4, to reduce the scatter due to the increased transparency of the interstellar medium. The metallicity cut excludes only 4 galaxies and 41 regions, which changes the relation by $\sim7.5\%$. For the remaining 556 regions, spanning almost 5 orders of magnitude in SFRD, we can approximate the trend with a unity slope relation (Figure 9),

$$\frac{\Sigma(\text{SFR})}{M_\odot \text{ yr}^{-1} \text{kpc}^{-2}} = \frac{\Sigma(70)}{1.067(\pm 0.017) \times 10^{43} \text{ erg s}^{-1} \text{kpc}^{-2}}$$

(3)

for $2 \times 10^{40} \lesssim \Sigma_{70} \lesssim 5 \times 10^{42}$. This translates into an SFR calibration,

$$\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} = \frac{L(70)}{1.067(\pm 0.017) \times 10^{43} \text{ erg s}^{-1}}$$

(4)

for $5 \times 10^{40} \lesssim L(70) \lesssim 5 \times 10^{43}$. However, the relation between luminosity and LSD has large dispersion due to the uncertainty in the distances. The uncertainty of the calibration coefficient is from the fitting and the dispersion of the data about the mean trend in Equations (3) and (4) is $\sim0.16$ dex (dashed lines in Figure 9).

Comparing our results with those of Calzetti et al. (2010), we find that our calibration coefficient for the SFR--L(70) relation is 60\% larger than theirs, which means for the same 70 $\mu$m luminosity our calibration will give 60\% higher SFR than the calibration of Calzetti et al. (2010). The difference can be due to the fraction of diffuse emission included in the measurements of whole galaxies, while we probe H II-dominated regions.
Since we are only investigating active, star-forming regions, and we remove the local background, we expect a minimal level of contamination from diffuse, non-star-forming stellar populations in our own analysis.

6. DISCUSSION

The results and analysis in Sections 4 and 5 give a reliable mean calibration of SFR(70), which can be used under certain luminosity ranges and metallicity limitation (Equations (3) and (4)). The origin and impact of the scatter around the mean correlation and the comparison between this calibration with other monochromatic IR SFR calibrations are interesting and important issues themselves and we further discuss these issues in this section.

6.1. Scatters in the Correlation

From the analysis of the data and the comparison with the models, we infer that the systematic dispersion in the data around the mean trend is mainly due to variations in metallicity; variations in the age and dust temperature can also produce some scatter, but at a much smaller level. Since metallicity and dust attenuation are correlated in first approximation, we should expect a relation between scatter and dust attenuation as well. The upper panel of Figure 10 shows the attenuation of Hα as a function of metallicity: higher metallicity regions do tend indeed to have higher attenuation on average. The attenuation at Hα is calculated as the ratio between \( L_{\text{obs}}(\text{H} \alpha) \) and \( L_{\text{intrinsic}}(\text{H} \alpha) = L_{\text{obs}}(\text{H} \alpha) + 0.031L(24) \), \( A(\text{H} \alpha) = 2.5 \log \frac{L_{\text{intrinsic}}(\text{H} \alpha)}{L_{\text{obs}}(\text{H} \alpha)} \) (Kennicutt et al. 2009). Higher extinction results in more TIR emission, hence more 70 μm emission; in fact, the lower panel of Figure 10 shows that the attenuation (red squares, \( A(\text{H} \alpha) > 1 \); green pluses, \( 0.25 < A(\text{H} \alpha) < 1 \); blue circles, \( A(\text{H} \alpha) < 0.25 \)) trace the scatter similar to that of metallicity. However, there may be objects with low extinction that have been excluded from the sample, due to our source selection criterion.

As the metallicity systematically introduces a scatter around the mean trend, we should expect that the calibration will change for different metallicity samples and the higher the sample metallicity the larger the calibration coefficient. We attempt to quantify this by dividing our entire sample into six different (but overlapping) sub-samples with different metallicity ranges and deriving the calibration for each sub-sample. The result is shown in Figure 11. The error bar on the calibration coefficient shows the dispersion in data of each sub-sample. From the linear fit in the figure, we could propose a metallicity-dependent SFR calibration as

\[
\frac{\text{SFR}}{M_\odot \text{yr}^{-1}} = \frac{L(70)}{A(Z) \times 10^{43} \text{ erg s}^{-1}},
\]

where \( A(Z) = (-8.727 \pm 9.186) + (1.124 \pm 1.063)(12 + \log(O/H))_{\text{mean}} \) in terms of mean metallicity of each sub-sample. Our caveat for this calibration is the current unknown nature of the systematic discrepancy in the metallicity values obtained from the KK04 and PT05 (Moustakas et al. 2010) calibration scales; any change to these scales will change Equation (5) accordingly.

As a comparison, we plot in Figure 11 the calibration constant derived by Lawton et al. (2010) for the Magellanic Clouds (with dashed line error bar). The error bar for the Magellanic Clouds calibration is from the dispersion of the 70 μm/TIR ratio in their work. Even though our mean calibration is consistent with Lawton et al.’s (2010) result, the two results are slightly inconsistent once the appropriate dependency on metallicity is taken into account. The discrepancy may be due to the reference SFR indicator used by Lawton et al. (2010). These authors use the TR emission, i.e., the dust-absorbed starlight, and the calibration of Kennicutt (1998) to derive SFRs for the H II regions of the Magellanic Clouds. However, the SFR(TIR) as derived by Lawton et al. (2010) likely underestimates the true SFR in the relatively low-opacity H II regions of the Magellanic Clouds as it only takes account of the obscured SFR and misses the unobscured SFR, thus yielding an overestimated calibration constant for SFR(70). Our test showing a (albeit weak) dependency of the calibration constant on the sub-sample mean metallicity further confirms that metallicity differences do introduce a systematic scatter in the data.

6.2. Excess 70 μm Emission in Galaxies

From the calibration in Calzetti et al. (2010), a galaxy with an SFR of 1 \( M_\odot \text{ yr}^{-1} \) implies a 70 μm luminosity of 1.725 \times 10^{33} \text{ erg s}^{-1}. The calibration in this paper shows that resolved H II regions or sub-galactic star-forming regions with the same total SFR of 1 \( M_\odot \text{ yr}^{-1} \) have a total 70 μm luminosity of only 1.067 \times 10^{33} \text{ erg s}^{-1}. The difference in these two calibrations reveals an average of ~40% excess 70 μm emission in the galaxies. Both calibrations use the Hα emission in their “reference” SFR, and in Calzetti et al. (2010) both the Hα emission and the IR emission are measured across the whole galaxy, including any contribution from both the clustered (H II) regions and the diffuse component. Thus, the SFR(70) calibration of Calzetti et al. (2010) includes contributions from both components. Conversely, our measurements are local, and explicitly exclude any diffuse contribution, to the extent possible with the angular resolution of MIPS/70; our calibration of SFR(70) thus also excludes any diffuse component from the galaxies. If the heating of the 70 μm emission in galaxies simply scaled with the Hα emission (either clustered or diffuse), then our calibration constant should be the same as that from Calzetti et al. (2010) for the same metallicity value. The presence of a significant difference between the two calibration constants (in the sense of “excess” 70 μm emission in the whole galaxies)
suggests that a portion of the 70 μm emission from whole galaxies is in excess of what can be accounted for from a simple scaling of the Hα emission. Hence, we suggest that the excess 70 μm emission is likely due to stellar populations that are different from those that can ionize hydrogen, i.e., likely to be evolved populations older than about 10 Myr. The only other option is that the photons that ionize the diffuse ionized gas can heat the dust more efficiently than in HII regions; we consider this scenario unlikely, as it would require a higher density of such photons than found in HII regions, and this is not observed. Thus, the excess 70 μm emission should be coming from some “older” or “diffuse” populations.

Dust heated by older (>5–10 Myr), diffuse stellar populations, which are no longer producing ionizing photons and are not related to the most recent star formation activity, are still capable of heating the dust to sufficiently high temperatures that significant emission at 70 μm can be expected. Small star-forming clusters containing only B- and A-stars (thus, non-ionizing), but not O-stars, could also be partially responsible for the excess 70 μm emission observed in the integrated light of galaxies. However, we expect the IMF to be fully sampled when averaged over whole galaxies, and thus the effect of smaller star-forming regions to be smoothed out.

If we use the SFR calibration of Kennicutt et al. (2009) to derive a reference SFR (Equation (2)), we obtain a calibration coefficient in Equation (3) of 1.285 × 10^{43}, still suggesting that there is ~25% excess 70 μm emission in galaxies. The difference in the fraction also suggests a difference in L(24)/L(70) ratio between the galaxies and HII regions, which is discussed in Section 6.3. As our regions are only slightly larger than the ones used by Calzetti et al. (2007) to establish the reference SFR indicator and also because of the application of local background subtraction, it is reasonable to expect that we should give preference to the calibration of Calzetti et al. (2007) for our reference SFR. In summary, the excess light in galaxies at 70 μm is between 25% and 40% of the total, most likely close to ~40%.
The discrepancy between the calibration for galaxies as a whole and for resolved clusters of H\textsc{ii} regions is real and significant. In Figure 12, we compare the $L(24)/L(70)$ ratio summed up in the selected regions and that in the whole galaxy for each galaxy. Focusing on the AGN-free galaxies (blue squares), the $L(24)/L(70)$ ratio is systematically higher in the line-emitting sub-galactic sources, i.e., the active star-forming regions, than for the integrated light from the whole galaxy, which shows that the dust temperature in star-forming regions is higher than that in the whole galaxy on average. A change in dust temperature for whole galaxies can only be driven by the presence of a stellar population heating the dust to a cooler temperature. We identify this stellar population as “older” and “diffuse”. For the AGN-contaminated galaxies (red circles) located below the one-to-one line in Figure 12, the dust could be heated by the central AGN to a higher temperature and also dominate the total IR luminosity.

From all the analysis above, we conclude that there is at least $\sim 25\%$, or more likely $\sim 40\%$, on average, excess integrated 70 $\mu$m emission from galaxies. This excess comes from dust heated by older and diffuse stellar populations, which we identify as stellar populations not related to current star formation activity.

6.3. Dust Temperature in H\textsc{ii} Regions and Galaxies

From the dust temperature versus SFR comparison (Figure 8), our data follow the models across the full dynamical range, while in Calzetti et al. (2010), a flattening on $L(24)/L(70)$ occurs at the high SFR end. Their high SFR end mostly consists of LIRGs, whose dust distribution becomes optically thick even at IR bands (Rieke et al. 2009) and the observed dust temperature starts to flatten. The difference indicates that the H\textsc{ii} regions in our sample never become optically thick in the IR, even at the highest SFRDs.

6.4. Comparison with SFR(24)

The 70 $\mu$m emission comprises a large portion of the TIR emission both in galaxies and H\textsc{ii} regions/star-forming regions. So, a legitimate question is whether the 70 $\mu$m emission is a better SFR indicator than other wavebands. Lawton et al. (2010) shows that, in the Magellanic Clouds, the 70 $\mu$m emission is better than 8, 24, or 160 $\mu$m as an SFR indicator, based on the dispersion of the data about the mean relations. Furthermore, Calzetti et al. (2007) showed that the relation between the 24 $\mu$m luminosity and SFR is nonlinear for H\textsc{ii} regions/complexes. In the present work, we find that the 70 $\mu$m emission is linearly correlated with the SFR in H\textsc{ii} regions/complexes and shows almost a factor 2 lower dispersion about the mean trend than the 24 $\mu$m emission (0.16 dex versus 0.3 dex for the 24 $\mu$m emission; Calzetti et al. 2007). Our results thus would seem to support Lawton et al.’s (2010) result that the 70 $\mu$m emission is more tightly correlated with the SFR than the 24 $\mu$m emission in H\textsc{ii} regions/complexes. However, we need to caution the reader that the reference SFR used here, a combination of H$\alpha$ and 24 $\mu$m is different from the one used in Calzetti et al. (2007), where the extinction-corrected H$\alpha$ is employed.

For whole galaxies, Kennicutt et al. (2009) and Rieke et al. (2009) show that the 24 $\mu$m emission has a dispersion of only 0.12–0.16 dex about the mean trend with SFR, while Calzetti et al. (2010) show that the 70 $\mu$m emission has a larger dispersion, by about 25%. Whether this indicates that the 24 $\mu$m emission is a better SFR indicator than the 70 $\mu$m emission for whole galaxies is unclear at this stage. Different calibrations rely on different reference SFR indicators, and there is a risk of circularity in many comparisons, both for whole galaxies and for H\textsc{ii} regions/complexes. A dedicated, independent analysis using a consistent reference SFR indicator should be performed to solve this issue.

7. SUMMARY

A sample of 40 galaxies, with high-quality H$\alpha$ images and Spitzer 24 $\mu$m and 70 $\mu$m images, has been selected from the SINGS legacy survey and 597 sub-galactic regions, in correspondence of peak 70 $\mu$m emission and avoiding AGN contamination, have been identified and measured at H$\alpha$, 24 and 70 $\mu$m. For these sub-galactic line-emitting regions (likely
groups of H\textsc{ii} regions), we have investigated the correlation between 70 \( \mu \)m dust emission and SFR over scales of 0.5–2 kpc to determine whether we could establish an SFR indicator using the monochromatic 70 \( \mu \)m emission. We have also investigated dependences on the metal content of the regions, as determined from nebular line emission, via a model constructed with a simple recipe for the stellar population, dust absorption, and emission. For the reference SFR, we have used the combination of observed 24 \( \mu \)m and the observed H\textalpha flux calibrated in Calzetti et al. (2007) and Kennicutt et al. (2009). We obtain a relatively tight correlation between 70 \( \mu \)m and SFR and we provide both a mean calibration and a metallicity-dependent calibration. The tight correlation between 70 \( \mu \)m and SFR is similar to that found by Lawton et al. (2010) for H\textsc{ii} regions in the Magellanic Clouds, once the difference in physical scale is taken into account. However, our detailed accounting of both the obscured and unobscured SFR in a large variety of galaxies and over a factor \( \sim 10 \) in metallicity enables us to derive a more accurate calibration constant between the 70 \( \mu \)m emission and the total SFR than done in Lawton et al. (2010). As higher resolution infrared imaging will be obtained by the Herschel Space Telescope in the coming years, this correlation will be further tested with higher spatial detail. Comparing with the SFR indicator at 70 \( \mu \)m of Calzetti et al. (2010), which is derived for whole galaxies, we find that there is \( \sim 40\% \) excess 70 \( \mu \)m emission in galaxies, which we attribute to dust heated by non-star-forming stellar populations. Variations in metallicity in the high and intermediate metallicity sample introduce a dispersion about the correlation of \( \sim 0.16 \) dex but does not affect the trend significantly. At the low metallicity end of our sample, the scatter is larger as expected from the lower opacity in the regions. So, for deriving the SFR calibration we exclude low metallicity data points. We obtain a mean calibration constant 1.067 \( \times 10^3 \) with a dispersion around the mean trend of \( \sim 0.16 \) dex.

We avoid the regions possibly hosting or contaminated by AGN, so that the infrared emission in our sample is free from AGN contamination. Thus, our SFR relation will not be applicable to sources dominated by AGNs. Our SFR relation is established under the assumption of a universal stellar IMF. Adopting a different IMF will produce a different (scaled) calibration coefficients in Equations (3) and (4).

This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. This work has been partially supported by the JPL, Caltech, contract number 1316765.

Yiming Li acknowledges fruitful discussions with and helpful suggestions from Mederic Boquien and Guilin Liu. This work has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The authors thank an anonymous referee for valuable comments that have helped improve this paper.

APPENDIX A

EMPIRICAL APERTURE CORRECTION

As stated in Section 3.3, we use photometry on unconvolved high-resolution H\textalpha images to establish our empirical mean aperture corrections for the photometry in 16" apertures on the 24 \( \mu \)m and 70 \( \mu \)m images.

Figure 13 shows how the difference between the original unconvolved photometry and convolved photometry is distributed as a function of the original H\textalpha photometry, with local background subtraction. If we had one perfect point source in each of our apertures, the expected correction to the flux would be 0.3 dex (from the MIPS handbook, using background annuli from 18" to 39"). Most of the data distribute a little below the horizontal line of \( \sim 0.3 \) dex; this is expected since a method for local background removal (Section 3.2) makes the aperture correction smaller as it receives a smaller contribution from the PSF wings than the background annuli method used in the MIPS handbook. For decreasing luminosity, we can also see that the difference tends to be smaller or even below 0, which means the convolved photometry is getting larger than the original one. This trend is due to the contamination of neighboring apertures, and the fainter the aperture the higher the contamination. For the extremely faint apertures, the trend flattens, as these regions can only be “identified” in relatively uncrowded regions. Since within a given aperture there is more than one emission peak for most cases, most apertures are not perfectly centered on the emission peak. This will produce a dispersion in the aperture correction due to different distribution of emission peaks within a given aperture. Those few data points indicating aperture corrections greater than a factor \( \sim 2.5 \) (Figure 13) are due to the relatively faint emission within the regions, because either the signal-to-noise ratio is low or the aperture is substantially off-centered to avoid overlapping with adjacent bright sources. This is also reflected in the large error bars in the photometry of these data points. In summary, the trend of Figure 13 indicates that in addition to the overall constant aperture correction due to the PSF wings loss outside our selected apertures (observed in the high-luminosity region of the plot) there is also a surface brightness dependent aperture correction, indicative of the contamination effects of neighboring apertures.
Figure 14 shows the same plot without local background subtraction for either photometric measurement. The significant difference in this figure relative to Figure 13 is the flaring of the data points at the low end of the luminosity distribution, showing a markedly different behavior from the high end. Furthermore, the low-luminosity end is still more than 0.1 dex, on average, below the mean of the high-luminosity end in Figure 14, again showing evidence for contamination from neighboring sources. We interpret the differences and similarities between Figures 13 and 14 as indicating the necessity of subtracting sources. We thus conclude that our original interpretation, within each aperture. A linear fit (dashed line) through the 58 data points at the low end of the luminosity distribution, showing especially for low-luminosity data points. The units are erg s$^{-1}$ kpc$^{-2}$ for LSDs.

A.1. Constant Aperture Correction

Since the most luminous apertures are proportionally less affected by contamination from neighboring apertures, we use the high end of Figure 13 as a gauge to establish the constant aperture correction. From Figure 13, we can see that the 17 high LSD apertures, log$[\Sigma_{\text{org}}(H\alpha)] \gtrsim 40$, more or less lie along one horizontal line with some dispersion. So, we take the low end, 39.971, of these 17 points, ~3% of the total data (blue points in Figure 13), as the cutoff LSD and we take the mean aperture correction of these points and get an aperture correction as 1.788. The choice of LSD cutoff is arbitrary, but it would not change the final correction much as long as it stays in the high-luminosity end.

A.2. Surface Brightness Dependent Aperture Correction

After the constant aperture correction is applied, Figure 16 shows the difference between original and c-corr (constant-corrected, see Appendix A.1) photometry versus c-corr photometry. We change the $x$-axis from original photometry to the c-corr photometry because when we apply the surface brightness dependent aperture correction on the 24 $\mu$m and 70 $\mu$m data, we need to rely on the c-corr photometry as we have no access to the original high-resolution photometry. We fit the data with log$[\Sigma_{\text{org}}(H\alpha)] - 39.971$ with a linear function giving a best fit:

$$\log[\Sigma_{\text{org}}(H\alpha)] - \log[\Sigma_{\text{c-corr}}(H\alpha)] = 0.103[\log[\Sigma_{\text{c-corr}}(H\alpha)] - 39.971]$$

as indicated by the black line in Figure 16. Thus, we have determined the empirical aperture correction for $H\alpha$ as two steps as follows.

1. The constant aperture correction

$$\Sigma_{\text{c-corr}}(H\alpha) = 1.788 \times \Sigma_{\text{corr}}(H\alpha)$$

Figure 15. Residual between original and convolved photometry as a function of the FWHM of the point source within the aperture. Filled circles are those with only one bright point source, contributing at least 50% of the flux within the 2FWHM area, and open circles are those with one brighter point source but also a companion weaker point source, where the FWHM of the brighter source is measured. The dashed line is a linear fit to the filled circles. The aperture correction is not correlated with the compactness of the source, represented by the FWHM, within the apertures. The units are arcsecond for FWHM and erg s$^{-1}$ kpc$^{-2}$ for LSDs separately.
otherwise specified. The units are erg s\(^{-1}\) kpc\(^{-2}\) for LSDs.

Figure 17. Corrected photometry as a function of original H\(\alpha\) photometry on the upper panel, and the residual as a function of original H\(\alpha\) photometry on the lower panel, where the 1\(\sigma\) dispersion (68% data envelope, dashed lines) is \(\sim 0.09\) dex. The solid line indicates the one-to-one line. The subscript, l-corr, is used to indicate the surface brightness dependent aperture correction corrected photometry here and in the paper. The units are erg s\(^{-1}\) kpc\(^{-2}\) for LSDs.

Figure 18. l-corr photometry as a function of the original H\(\alpha\) photometry, while the aperture correction used here is established using only the brighter half, in LSD, of the data (circles right of the dashed line). The solid line indicates the one-to-one line and the dashed line separates the brighter half and the dimmer half. The squares show that the aperture correction established with high end half of data applies to the less luminous data as well, which suggests that our aperture corrections are robust. The units are erg s\(^{-1}\) kpc\(^{-2}\) for LSDs.

LSD) and repeating the above analysis. The results are shown in Figure 18, with the brightest half of the sample shown as circles. As can be seen from the figure, the final results do not change whether the entire sample or the brightest half is used to establish the aperture correction.

We then apply these aperture corrections to 70 \(\mu\)m and 24 \(\mu\)m, according to a relation that \(0.031 \times L(24) \sim L(H\alpha)\) and \(0.2 \times L(70) \sim L(24)\) (Calzetti et al. 2007, 2010); an analysis of the distribution of 70 \(\mu\)m and 24 \(\mu\)m versus H\(\alpha\) photometry on our data gives similar factors. The constant aperture correction remains the same for these two IR bands while the second step, Equation (A2), becomes

\[
\Sigma_{\text{c-corr}}(24) = 10^{0.103(\log[0.031\Sigma_{\text{c-corr}}(24)]-39.971)} \times \Sigma_{\text{c-corr}}(24) \quad (A3)
\]

for \(\log[0.031\Sigma_{\text{c-corr}}(24)] < 39.971\), and

\[
\Sigma_{\text{c-corr}}(70) = 10^{0.103(\log[0.2\Sigma_{\text{c-corr}}(70)]-39.971)} \times \Sigma_{\text{c-corr}}(70) \quad (A4)
\]

for \(\log[0.031 \times 0.2\Sigma_{\text{c-corr}}(70)] < 39.971\).

As we have no information about the original photometry of 70 \(\mu\)m and 24 \(\mu\)m, the l-corr photometry will be a proxy to represent the true photometry of these two bands, and for consistency, we will also use the l-corr photometry of H\(\alpha\) in the following analysis. All the luminosity and LSD values hereafter are derived from the l-corr photometry unless otherwise specified.

APPENDIX B

CONSTRUCTION OF THE SIMPLE MODEL

The simple model is constructed based on the model of Calzetti et al. (2007), and it has three basic ingredients: stellar population models (STARBURST99; Leitherer et al. 1999), dust attenuation (Calzetti et al. 2000), and dust emission spectral energy distribution (SED; models from Draine & Li 2007).

For the stellar population models, we adopt a continuous star formation history based on the analysis of typical crossing timescale for our regions, calculated by using the sound speed and the aperture size, which is \(\sim 100\) Myr. We take this timescale to correct the convolved photometry to the c-corr photometry and

2. The surface brightness dependent aperture correction

\[
\Sigma_{\text{c-corr}}(H\alpha) = 10^{0.103(\log[\Sigma_{\text{c-corr}}(H\alpha)]-39.971)} \times \Sigma_{\text{c-corr}}(H\alpha) \quad (A2)
\]

for \(\log[\Sigma_{\text{c-corr}}(H\alpha)] < 39.971\) to correct the c-corr photometry to l-corr (luminosity-corrected) photometry.

Figure 17 shows the corrected (l-corr) photometry and the difference between the corrected (l-corr) and original photometry versus the original photometry. We estimate the 1\(\sigma\) aperture correction uncertainty to be \(\sim 22.3\)% by calculating the rms of the deviation from the unity slope line (lower panel in Figure 17).

We further test the robustness of an aperture correction by considering only the brightest half of our sample (in terms of
as representative of our stellar population, but, for completeness, we generate constant star formation models between 2 Myr and 10 Gyr. For the stellar atmosphere metallicity provided by the STARBURST99 code, we choose \( Z = 0.004, 0.02, \) and 0.05, which is roughly 0.3 \( Z_\odot \), 1.4 \( Z_\odot \), and 3.7 \( Z_\odot \), where \( Z_\odot \) is equivalent to \( 12 + \log(O/H) = 8.69 \) (Asplund et al. 2009). We derive H\( \alpha \) luminosities as a function of the spectrum, and assuming case B recombination. After this step, we have a stellar population SED and the intrinsic H\( \alpha \) luminosity.

Then, we take the population SED and apply the attenuation curve by Calzetti et al. (2000) to get the TIR emission, assuming that all the absorbed UV-optical light has been reradiated in the IR. The \( E(B-V) \) value needed for the attenuation curve is calculated from the ionizing photon number using an empirical relation in Calzetti et al. (2007). The scaling of \( E(B-V) \) with metallicity is also taken into account (Calzetti et al. 2007). For the nebular line attenuations, we adopt differential extinction coefficients by Calzetti et al. (2000) plus the Milky Way extinction curve. With the observed H\( \alpha \) luminosity and 70\( \mu \)m luminosity, we have the TIR emission, assuming case B recombination. After this step, we have a stellar population SED and the intrinsic H\( \alpha \) luminosity.

We finally use the dust model from Draine & Li (2007) to determine the 24\( \mu \)m/TIR and 70\( \mu \)m/TIR fractions and to further get 24\( \mu \)m luminosity and 70\( \mu \)m luminosity. The dust emission models are parameterized as a function of \( q_{PAH} \), the fraction of polycyclic aromatic hydrocarbon (PAH) molecules, and \( U \), the average stellar radiation field strength. \( q_{PAH} \) has only a modest impact on our output, and we adopt two values: \( q_{PAH} = 4.6\% \) for solar and super-solar metallicity models and \( q_{PAH} = 0.47\% \) for the sub-solar metallicity model. We obtain estimates of \( U \) by integrating the stellar population SED using an approach similar to that presented in Calzetti et al. (2000) plus the Milky Way extinction curve. With the attenuation curve applied, we have the TIR luminosity and the observed H\( \alpha \) luminosity.

Finally, we assume each model is observed within an unresolved 700 pc aperture, which is the median physical size of all the apertures, and get the LSD values for H\( \alpha \), 24\( \mu \)m and 70\( \mu \)m of the model, to compare with the data. The change in the LSD values for deriving model LSDs only causes a small shift (smaller than the dispersion of data) of the model lines. Also, a test on the data of two fixed physical sizes (\(~250\) pc and \(~650\) pc with \(~100\) apertures each) reveals that the correlations for data of difference physical sizes are consistent with each other.

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