UNDERSTANDING THE 8 μm VERSUS Paα RELATIONSHIP ON SUBARCSECOND SCALES IN LUMINOUS INFRARED GALAXIES1,2

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ABSTRACT

This work explores in detail the relation between the 8 μm and the Paα emissions for 122 H II regions identified in a sample of 10 low-z LIRGs with nearly constant metallicity [12 + log(O/H) ~ 8.8]. We use Gemini T-ReCS high spatial resolution (≤0.4″~120 pc for the average distance of 60 Mpc of our sample) mid-infrared imaging (at 8.7 or 10.3 μm), together with HST NICMOS continuum and Paα images. The LIRG H II regions extend the L8 μm vs. LPaα relation found for H II knots in the high-metallicity SINGS galaxies by about 2 orders of magnitude to higher luminosities. Since the metallicity of the LIRG sample is nearly constant, we can rule out this effect as a cause for the scatter seen in the relationship. In turn, it is attributed to two effects: age and PAH features. The L8 μm/LPaα ratio, which varies by a factor of 10 for the LIRG H II regions, is reproduced by a model with instantaneous star formation and ages ranging from ~4 to 7.5 Myr. The remaining dispersion around the model predictions for a given age is probably due to differential contributions of the PAH features (the 8.6 μm, in our case) to the 8 μm emission from galaxy to galaxy.

Subject headings: galaxies: nuclei — galaxies: star clusters — galaxies: starburst — infrared: galaxies

Online material: color figures

1. INTRODUCTION

The 8 μm luminosity is potentially one of the most interesting star formation rate (SFR) indicators as it can be used for sources identified in deep infrared (IR) Spitzer MIPS surveys at 24 μm, which at z ~ 2 corresponds to rest-frame 8 μm emission. The MIPS 24 μm (or IRAS 25 μm) luminosities appear to be well correlated with the number of ionizing photons as derived from extinction-corrected Paα and Hα luminosities at least at high metallicities (Wu et al. 2005; Calzetti et al. 2005; Calzetti et al. 2007, hereafter Cal07; Alonso-Herrero et al. 2006b, hereafter AAH06b). The situation for the 8 μm emission is less clear (Cal07; Alonso-Herrero et al. 2006a, hereafter AAH06a). In particular, AAH06a found that the individual H II regions and the integrated emission of luminous infrared galaxies (LIRGs; LIR = 1011—1012 L⊙) show a different behavior in the L8 μm vs. LPaα relation and suggested that only the integrated properties of galaxies should be used when calibrating the SFR in terms of the 8 μm luminosity (see also Wu et al. 2005). Recently, for H II knots identified in the SINGS (Spitzer IR Nearby Galaxies Survey; Kennicutt et al. 2003) galaxies, Cal07 concluded that the larger scatter of the 8 μm vs. Paα relation is due to the combined effects of extinction, metallicity, and the star formation history of the regions.

The emission in the 8 μm spectral region is produced by thermal continuum from hot dust as well as by a polycyclic aromatic hydrocarbon (PAH) feature emission. PAHs are commonly observed in the MIR spectra of local (e.g., Roche et al. 1991; Lutz et al. 1998; Genzel et al. 1998; Brandl et al. 2006; Smith et al. 2007) and high-z star-forming galaxies (Sajina et al. 2007). However, while the dust continuum emission as traced by the MIPS 24 μm emission is found to be more peaked in H II regions, the 8 μm (mostly as Paα) emission arises from photodissociation regions (PDRs; Helou et al. 2004; Bendo et al. 2006; Povich et al. 2007; Lebouteiller et al. 2007). This implies that the PAH carriers can also be excited by the galaxy field radiation (Peeters et al. 2004; Tacconi-Garman et al. 2005) not directly associated with young ionizing stellar populations, explaining why the 8 μm emission appears to be more extended and diffuse than the Hα or Paα emission (Helou et al. 2004; Calzetti et al. 2005; AAH06a; Engelbracht et al. 2006). Consequently, aperture effects may have important implications when measuring the emission from individual star-forming regions.

In this work we further study the 8 μm emission at subarcsecond scales using observations obtained with the Thermal-Region Camera Spectrograph (T-ReCS; Telesco et al. 1998) on Gemini South of a sample of low-z LIRGs (see also AAH06a, AAH06b). In particular, we explore the effects of the age and extinction of the individual star-forming regions on the 8 μm vs. Paα relation and how they may contribute to the observed scatter of the relation. We also compare our results with those of Cal07 for high-metallicity H II knots in star-forming galaxies drawn from the SINGS sample. The paper is organized as follows: In § 2 the sample, observations, and data reduction are presented. Section 3 describes the analysis of the data. The overall morphology of the LIRGs is presented in § 4. Section 5 analyzes the L8 μm/LPaα relationship in detail. The summary of the results is given in § 6. We use H0 = 70 km s⁻¹ Mpc⁻¹, ΩM = 0.27, and ΩΛ = 0.73.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Sample

We have obtained MIR imaging of a total of 10 LIRGs (see Table 1 for details) taken from the complete, volume-limited
sample of local LIRGs defined by AAH06b. The full sample of AAH06b was drawn from the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003) and selected such that the Paα emission line ($\lambda_{\text{rest}} = 1.875$ $\mu$m) could be observed with the NICMOS F190N filter on the Hubble Space Telescope (HST). This restriction means that the full sample is limited to nearby galaxies ($d < 75$ Mpc). The 10 galaxies studied in this paper represent the majority of the LIRGs in the sample that can be observed from the southern hemisphere. Four galaxies were previously studied by AAH06a but are fully reanalyzed and included here for completeness and consistency. The metallicities of the sample, taken from Relaño et al. (2007) and Vacca & Conti (1992), are on average $12 + \log(O/H) = 8.8$ (see Table 1 for individual values).

### 2.2. MIR Imaging Observations

The MIR observations of the LIRGs were obtained with T-ReCS (Telesco et al. 1998) on the Gemini South telescope during semesters 2005B, 2006A, and 2006B (program IDs GS-2005B-Q-10, GS-2006A-Q-7 and GS-2006B-Q-9, respectively). The data from the first semester were taken with the broadband $N$ filter ($\lambda_c = 10.36$ $\mu$m; $\Delta \lambda = 5.27$ $\mu$m), whereas data obtained in 2006 used the narrowband Si-2 filter ($\lambda_c = 8.74$ $\mu$m; $\Delta \lambda = 0.78$ $\mu$m). Detailed information about the observations is given in Table 2. The $320 \times 240$ pixel detector together with its 0.099$''$ pixel$^{-1}$ plate scale yield a field of view (FOV) of $\sim 28.5 \times 21.5$ arcsec$^2$. At the central wavelengths of the $N$ and Si-2 filter bandpasses, the telescope/instrument system provides resolutions of $\sim 0.32''$ and $0.27''$, respectively. The observing conditions (seeing FWHM of 0.3$''$–0.4$''$; Table 2) indicate that the observations were almost diffraction-limited.

The observations were done in a standard chop-nod mode to remove the time-variable sky background, telescope thermal emission, and the detector noise. The chop throw was 15$''$ and the telescope nodding was performed every 30 s in all cases (see also Packham et al. 2005). The observations were divided in two data sets to avoid observing problems or a sudden change in weather conditions. We observed a Cohen standard star (appropriate for MIR observations; Cohen et al. 1999) for each galaxy to obtain the absolute flux calibration of the images. The standard star observations were always taken with the same instrument configuration and immediately before or after the target to minimize the difference in air mass and hence to reduce photometric uncertainties. The large-scale morphology of some of the targets made it necessary to rotate the detector along the major axis of the galaxy. In those cases the standard stars were observed with the same configuration.

### 2.3. Data Reduction Procedure

The data are stored automatically in “save sets” (indivisible subsets of data) that can be accessed for visual inspection for each chop/nod position. This allows us to discard images affected by any type of instrumental noise pattern (e.g., narrow diagonal stripes of increased signal across the detector or overvariations of the background flux along the array or in between chop sets). There were no bad save sets in our case. Next, the backgrounds were removed and the galaxy images co-added to obtain a single image of the target. This was done for both data sets in which the observation was divided (see above). These and the following procedures were also applied to the standard star.

We applied a flat-field image for each data set that was constructed using the average of all the sky pointings taken at each

### Table 1: The Sample

| Galaxy Name   | $z$ (km s$^{-1}$) | Distance (Mpc) | log $L_{\text{IR}}$ ($L_\odot$) | Type | $12 + \log(O/H)$ |
|---------------|------------------|----------------|-------------------------------|------|-----------------|
| NGC 1614      | 0.01594          | 69.1           | 11.67                         | H ii | 8.6*            |
| NGC 2369      | 0.01081          | 46.7           | 11.14                         | H ii | 8.9             |
| NGC 3256      | 0.00935          | 40.4           | 11.67                         | H ii | 8.8             |
| NGC 5135      | 0.01369          | 59.3           | 11.27                         | Sy2  | 8.7             |
| IC 4518W      | 0.01573          | 68.2           | 11.09                         | Sy2  | 8.6             |
| IRAS 17138–1017 | 0.01734        | 75.3           | 11.39                         | H ii | 8.9             |
| IC 4687       | 0.01735          | 75.3           | 11.55                         | H ii | 8.8             |
| IC 4734       | 0.01561          | 67.7           | 11.28                         | H ii/L| 9.0             |
| NGC 7130      | 0.01615          | 70.1           | 11.39                         | L/Sy | 8.8             |
| IC 5179       | 0.01142          | 49.3           | 11.20                         | H ii | 8.9             |

**Notes:**—Col. (1): Galaxy. Col. (2): Redshift (NED). Col. (3): Distance as obtained with the cosmology: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$. Col. (4): Infrared luminosity as computed from IRAS fluxes (Sanders et al. 2003) and with the prospect given by Sanders & Mirabel (1996, their Table 1). Col. (5): Nuclear activity of the galaxy. Col. (6): Oxygen abundance taken from Relaño et al. (2007).

* Oxygen abundance taken from Vacca & Conti (1992)

### Table 2: Observation Details

| Galaxy Name | Filter | $t_{\text{int}}$ (s) | Date | Seeing (arcsec) |
|-------------|--------|----------------------|------|-----------------|
| NGC 1614    | Si-2   | 1680                 | 09/16–30/2006 | 0.38         |
| NGC 2369    | Si-2   | 840                  | 09/30/2006   | 0.38         |
| NGC 3256    | Si-2   | 300                  | 03/04/2006   | 0.30         |
| NGC 5135    | $N$    | 600                  | 03/04/2006   | 0.31         |
| IC 4518W    | $N$    | 1200                 | 04/10–18/2006| 0.33         |
| IRAS 17138–1017 | Si-2 | 840                  | 09/09/2006   | 0.41         |
| IC 4687     | Si-2   | 840                  | 09/09/2006   | 0.31         |
| IC 4734     | Si-2   | 840                  | 09/09/2006   | 0.31         |
| NGC 7130    | $N$    | 600                  | 09/18/2005   | 0.32         |
| IC 5179     | Si-2   | 840                  | 09/28/2006   | 0.33         |

**Notes:**—Col. (1): Galaxy. Col. (2): Filter with which each galaxy was observed. Col. (3): On-source integration time. Col. (4): Date(s) of the observations. Col. (5): Seeing (FWHM of the reference standard star).
chop integration. The target data sets were then averaged in a single image from which the residual background flux was subtracted. This step requires a special treatment because the final images with long integration times can suffer from a residual noise pattern that introduces low-level flux variations along the short axis of the detector (broad wavelike horizontal stripes). To subtract the residual background, the image was first fitted to a 2D plane with a fitting procedure that iteratively rejects outliers 2.25 σ above/below this plane. At the same time, preselected locations with galaxy emission were masked out. Pixels within these areas with 1.5 σ fluxes above/below the 2D fit were not used in following steps. Next, each row of this 2D-subtracted, masked image was smoothed and fitted to a 1D spline. By combining all these 1D fits, a residual background 2D image was created and subtracted from the object image. All these steps improve the quality of the final images and introduce no more than ~10% uncertainty in the fluxes of the measured regions. The T-ReCS images were rotated to the northeast direction and convolved with a Gaussian kernel of σ ≈ 1 pixel to accurately center the apertures on the faintest H ii regions (see § 3.1).

Figure 1 shows fully reduced MIR images (right) of the sample, together with the HST NICMOS 1.6 μm continuum and Paα images.

2.4. Photometric Calibration

The photometric calibration was obtained with the Cohen standard stars (Cohen et al. 1999). Since the Cohen stars have synthetic flux-calibrated spectra, by convolving the telescope throughput and filter bandpass with the spectra, one can obtain the flux of the standard stars in physical units. In addition, aperture photometry was performed on the standard stars to obtain the count rates, and the flux conversion factor was calculated as the ratio of both quantities. The photometric calibration is accurate to ≤10%–15%.

The need for a color correction for the broad N-filter flux densities was explored. This factor would account for the difference in the spectral slope of the standard stars and those of our galaxies. While the MIR spectrum of a star is similar to that of the Rayleigh-Jeans part of a blackbody, the spectrum of an H ii region or a nucleus may differ significantly. In order to quantify this difference, we used the Spitzer IRS spectra of several LIRGs of the sample classified as H ii–like (NGC 1614, NGC 3256, and IRAS 17138–1017). We normalized their integrated N-band flux densities to those of the T-ReCS reference standard stars observed for flux-calibrating each galaxy. Next, the spectra were convolved with the same T-ReCS configuration used for the observations, and the N-band flux densities of the spectra were calculated. Then they were compared with those of the standards. The differences were within 5%. Given the uncertainties of the method, we decided not to correct the flux density of the H ii regions for this color difference. The same approach was employed for calculating the correction factor of an AGN spectrum. We used a power-law function of $F_{\nu} \propto \nu^{-\alpha}$, with $\alpha \approx 1.75$, to represent its MIR emission (Weedman et al. 2005) and obtained a factor of ~1.15. The MIR flux densities of the two Sy2 (NGC 5135, IC 4518W) and one LINER/Sy (NGC 7130) nuclei in the sample observed with the N-band filter were corrected by this factor. This kind of color correction is not necessary for the Si-2 filter as it is relatively narrow.

Since the galaxies were observed with two different MIR filters, we investigated whether a conversion factor between the N band and the Si-2 filter flux densities was needed. To do so, we used the Spitzer IRS low-resolution spectra of several H ii–classified LIRGs of our sample (NGC 1614, NGC 3256, IRAS 17138–1017, and IC 4734) integrated over their central (10′′ × 3.7′′) regions. We verified that, within a ~10% uncertainty, the 8.7 μm and N-band flux densities were equivalent. The same was assumed for our individual H ii regions. For the Sy nuclei we used a conversion factor $f_{\nu}(8.7 \, \mu m)/f_{\nu}(N\text{-band})$ of 0.56 as done by AAH06a.

2.5. HST NICMOS Images

The sample of LIRG galaxies was observed with the NIC2 camera (pixel size of 0.075″) of NICMOS using two broadband filters (F110W and F160W) and two narrowband filters (F187N and F190N), except for two galaxies (NGC 1614 and NGC 3256) from the NICMOS GTO programs that were observed with the F160W and F222M filters (see Alonso-Herrero et al. 2001, 2002). The full description of the data reduction of the HST NICMOS images can be found in AAH06a. To compare the NICMOS images with the T-ReCS images we performed the following additional steps. The NICMOS images were (1) rotated to the northeast orientation, (2) rescaled to the pixel scale of the T-ReCS detector, (3) shifted to the same position as the MIR images, (4) smoothed with a Gaussian to match the MIR resolution (see Table 2), and (5) background-subtracted. In addition, we constructed $J/H$ (or $H/K$) ratio maps by dividing their F110W and F160W (or F160W and F222M) continuum images, Paα equivalent width (EW) maps by dividing the continuum-subtracted Paα images by their adjacent F187N continuum image, and MIR/Paα ratio maps by dividing the T-ReCS images by the continuum-subtracted Paα images. These maps are presented in Figure 2 for our sample of galaxies.

3. ANALYSIS AND RESULTS

3.1. Selection of the Regions and Aperture Photometry

We identified the nucleus of each galaxy as the source with the highest MIR flux density. Although this is straightforward in most of the galaxies, there are two exceptions, NGC 2369 and IRAS 17138–1017, where the position of the nucleus is not clear from the NIR continuum images. For the selection of the H ii regions, first we visually identified them in the T-ReCS images. A second inspection was done in the Paα images to include sources with high hydrogen recombination line fluxes but low MIR emission. We finally rejected in both sets sources with integrated flux densities (see below) 2 times below the standard deviation of the background (i.e., a 2 σ threshold).

Except for some of the most luminous nuclei (NGC 5135, IC 4518W), the majority of the MIR sources appear extended. Therefore, we used circular aperture photometry (instead of point source function fitting) to measure the flux densities of nuclei and star-forming regions of the LIRGs. We note that AAH06b measured the Paα emitting regions with variable apertures depending on the size of the H ii regions instead of with fixed apertures as done in this work. We explored the possibility of a contamination for underlying emission in the MIR images. However, the subtraction of a local background measurement from the flux densities of the H ii and nuclear regions resulted in negligible changes of the results of the paper. Therefore, we decided to work with the values obtained without performing any local background subtraction because it might introduce additional uncertainties.

We chose to use three physical apertures for the photometry with radii of 75, 150, and 300 pc. The 75 pc radius aperture was used to take advantage of the high spatial resolution data and to obtain information about the H ii regions on the smallest scales. At the average distance of our sample (~60 Mpc), the diameter of the smallest aperture corresponds to ~0.52′′ (~5.8 pixels), which is approximately 1.5 times the seeing of our observations.
Fig. 1.—HST NICMOS 1.6 μm continuum (left), and continuum-subtracted Paα line (middle) full spatial resolution images (see also AAH06b), and T-ReCS MIR (8.7 μm or N-band) images (right). All the images are displayed on a logarithmic scale. North is up, and east is to the left. The displayed FOV is optimized to show the extent of the MIR emission. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 1—Continued
(see Table 2). Thus, the centering errors (less than half of a pixel) of the smallest aperture introduce <10% uncertainty in the measured flux densities of the regions (depending on their brightness).

The largest aperture was chosen to compare our results with those of Cal07 for the high-metallicity H II knots of the SINGS galaxies. They used a fixed angular aperture of 13" in diameter. Almost half of the H II knots in the high-metallicity SINGS sample are in galaxies located at distances between 8 and 10.5 Mpc. So using an average (weighed with the number of H II knots) SINGS distance of ~9.2 Mpc, their fixed 13" diameter aperture corresponds to approximately 580 pc. Our 150 pc radius aperture is approximately intermediate between the small and the large apertures. In Figure 3 we show an example of the physical areas covered by the smallest and largest apertures in one LIRG in our sample.

To avoid overlapping among the selected regions when performing aperture photometry, we sorted them in flux density and rejected those regions within 0.75 times the diameter of another selected region(s) with higher flux density. In addition to the 11 (AGN or H II) nuclei (two in NGC 3256), the final number of H II regions selected for photometry were 122, 84, and 41 for the apertures of $r = 75, 150,$ and 300 pc, respectively.

Tables 3 and 4 give a summary of the aperture photometry for the LIRG nuclei, as well as for the H II regions, respectively, for both the smallest and largest apertures. Meaningful comparisons can be made with Spitzer-based works since the conversion factor

![Figure 2](image-url)
between the T-ReCS 8.7 μm and the Spitzer IRAC 8 μm band flux densities is close to unity for these kinds of galaxies (±10%; see Fig. 4 for an example). For this reason from now on we will use the term “8 μm” when referring to both T-ReCS and IRAC 8 μm data. Finally, the 8.7 μm flux densities were converted to monochromatic fluxes. Taking into account all sources of uncertainty (calibration, photometry, filter and color corrections, and background estimation), the MIR photometry of the 3 measurements have an accuracy of ~25% (~0.1 dex) and ~40% (~0.15 dex) for the \( r = 75 \) and \( r = 300 \) pc apertures, respectively.

3.2. Aperture Effects

Since, as discussed in § 1, in nearby galaxies the 8 μm emission appears more extended than the Paα (or Hα) emission, it is important to explore the aperture effects on the measurements. Figure 5 (left) shows the distribution of the observed (not corrected for extinction) \( L_{8.7\mu m}/L_{Pa\alpha} \) ratios for the three physical apertures. Although the peaks of the distributions are similar for all of them, there is a clear tendency for the width of the distributions to become broader for decreasing the aperture size. Moreover, the low end of the \( L_{8.7\mu m}/L_{Pa\alpha} \) distribution for the 75 pc radius aperture disappears for the large aperture distribution.

The behavior of the Paα EWs (Fig. 5, middle) is different, with the peaks of the distributions moving toward smaller EW for increasing physical apertures. This can be readily understood if the larger physical apertures progressively include more continuum emission not associated with the H II regions and/or average together young and old H II regions. This may also indicate that
the typical sizes of the H II regions of LIRGs are smaller than the largest physical aperture used here (see, e.g., Alonso-Herrero et al. 2002 for a detailed discussion).

Finally, the F110W/F160W distributions appear to be similar for the three physical apertures. That is, the selected H II regions in our sample of LIRGs do not appear to have systematically redder NIR colors (that is, they do not appear to be more extincted; see below) than other regions in the central parts of the galaxies.

### 3.3. Comparison with Models

The HST NICMOS imaging data can be compared with evolutionary synthesis models of stellar populations to derive some physical properties of the selected H II regions and nuclei of the galaxies. We ran Starburst99 (SB99, ver. 5.2; Leitherer et al. 1999) for an instantaneous burst of $10^6 M_\odot$, Geneva tracks with high mass-loss rate (see Vázquez & Leitherer 2005), Kroupa initial mass function (exponents of 1.3 and 2.3 for $0.1 M_\odot < M < 0.5 M_\odot$ and $0.5 M_\odot < M < 120 M_\odot$ mass intervals, respectively), and solar metallicity. The model outputs were obtained with a 0.5 Myr step for starburst ages ranging from 0.5 to 10 Myr (other stellar populations are unlikely to be detected in PaO emission; see Alonso-Herrero et al. 2002 for a detailed discussion).

### 3.3.1. Ages

The EW of hydrogen recombination emission lines are a useful age indicator of young stellar populations. We compared the observed PaO EW with the model predictions to estimate the ages of the LIRG H II regions. We note that the derived ages are upper limits to the real ages since the presence of an older underlying stellar population would increase the NIR continuum, thus ageing the region.

Figure 5 (middle) shows the distribution of the inferred ages as a function of the physical aperture. For the smallest aperture ($r = 75$ pc), the majority of the LIRG H II regions have ages ranging from $\sim 5.4$ and 6.8 Myr, but star-forming regions as young as $\sim 4$ Myr can be found. This is in agreement with findings for other LIRGs (Alonso-Herrero et al. 2002; Wilson et al. 2006; Díaz-Santos et al. 2007). When using a larger aperture, the ages inferred for the star-forming regions tend to be higher, and only a few of them appear to be younger than $\sim 5.5$ Myr (see discussion in § 3.2).

### 3.3.2. Extinctions

If the age of the stellar populations is known (see above), one can compare the observed NIR continuum colors with the model predictions to get an estimate of the obscuration to the stars. To do so, the SB99 spectra were convolved (for all the starburst ages) with the corresponding NIR filter band passes and telescope system throughput (F110W, F160W, or F222M, depending on each

### Table 3

**Aperture photometry of the nuclei**

| Galaxy Name (1) | FWHM (arcsec) (2) | MIR (mJy) (3) | PaO (mJy) (4) | MIR (mJy) (5) | PaO (mJy) (6) |
|----------------|------------------|---------------|--------------|---------------|--------------|
| NGC 5135       | 0.36             | 31            | 0.55         | 95            | 3.2          |
| IC 4518W       | 0.39             | 38            | 0.96         | 118           | 3.9          |
| NGC 7130       | 0.45             | 38            | 1.27         | 148           | 5.5          |
| NGC 1614       | 0.63             | 28            | 2.19         | 346           | 34           |
| NGC 2369       | 0.60             | 16            | 0.80         | 95            | 4.1          |
| NGC 3256       | 0.47             | 109           | 6.57         | 427           | 27           |
| IRAS 17138–1017| 0.83             | 6             | 0.20         | 47            | 1.4          |
| IC 4687        | ...              | 4             | 0.09         | 43            | 1.4          |
| IC 4734        | 0.90             | 10            | 0.70         | 80            | 4.7          |
| IC 5179        | 0.87             | 13            | 1.30         | 70            | 4.7          |

**Notes.**—The flux densities presented in this table have not been corrected for extinction and are subject to the uncertainties explained in § 2. MIR and PaO flux densities are shown without the color correction applied (see § 2.4). Col. (1): Galaxy. Col. (2): FWHM of the region selected as the nucleus of the galaxy. Col. (3): Median MIR and PaO flux densities of the nuclei. Col. (4): Median MIR and PaO flux densities of the nuclei. Col. (5) and (6): Median MIR and PaO flux densities of the point sources in the MIR images (cf. Table 2). An aperture correction factor of 2 and 2.5, respectively, should be applied to the values of the smallest aperture if the flux densities of the point sources want to be obtained. Values are given for the smallest ($r = 75$ pc) and largest ($r = 300$ pc) apertures.
galaxy) to obtain the flux densities predicted by the models at those wavelengths. Then the synthetic colors (F110W/F160W or F160W/F222M) were interpolated to the ages of each H\textsc{ii} region (known beforehand) and compared with the observed values. The obscuration was calculated by using the Calzetti et al. (2000) extinction law with a foreground dust screen configuration. The derived extinctions were then used to correct the Pa\textalpha luminosities for obscuration as well as the MIR emission (using the Rieke \\& Lebofsky 1985 extinction law, since the Calzetti et al. law extends only up to the K band). Note that because of the ages obtained from Pa\textalpha EWs are upper limits to the real ages, the extinctions may be lower limits to the real ones.

Regarding the smallest aperture, the majority of the H\textsc{ii} regions show extinctions ranging from \(A_y \approx 4\) to 8 mag (equivalent of Pa\textalpha extinctions of \(A_{1.675\mu m} \approx 0.58\)–1.15 mag; Calzetti et al. 2000), although there are some regions with even higher values. The median value of the extinction for the H\textsc{ii} regions of our sample is \(A_y = 6\) mag. The obscuration to the stars inferred in this work are slightly higher than those estimated by AAH06b, but entirely attributable to the use of different models (AAH06b used the Rieke et al. 1993 models).

The extinction of the LIRG H\textsc{ii} regions are consistent with those derived for other LIRGs (Diaz-Santos et al. 2007; Pollack et al. 2007). The extinctions of the H\textsc{ii} knots of the SINGS galaxies (e.g., Calzetti et al. 2005; Cal07) are in agreement with the lower limit found for our H\textsc{ii} regions (\(A_y \approx 3\)–4 mag), as expected if the obscuration increases with the SFR, i.e., with Pa\textalpha luminosity (Choi et al. 2006 from optical/MIR; Cal07 from NIR data). This is discussed in more detail in § 5.2.3.

The derived extinctions of the nuclei are generally higher than those of the H\textsc{ii} regions in the majority of the LIRGs, except for NGC 1614 (which shows a very “blue” nucleus), IC 4687, IC 4734, and NGC 7130, all classified as H\textsc{ii}–type or LINER. The most extinguished region in our sample is the southern nucleus of NGC 3256 with an estimated extinction of \(A_y \approx 11\) mag, in agreement with findings of other authors (Kotilainen et al. 1996; Lira et al. 2002; AAH06b).

### 4. SUBARCSECOND MORPHOLOGY:

#### OVERALL CHARACTERISTICS

Figure 1 shows that the overall morphologies of the MIR emission and the Pa\textalpha emission line of LIRGs are similar. The MIR and
Paα emissions (which trace the ionizing stellar populations) are rather concentrated in H ii regions and knots with sizes of a few hundred parsecs, with half of the LIRG sample showing Paα only in the central 1–2 kpc, and the other half with Paα emission extending over at least 3–7 kpc (see AAH06b for more details). In contrast, the morphology of the NIR continuum emission (which traces in general more evolved stellar populations; see Alonso-Herrero et al. 2002) differs substantially from that of Paα and the MIR, showing the presence of unresolved star clusters and diffuse emission over the whole NIC2 FOV.

A detailed inspection of the MIR and Paα images shows, however, that the spatial coincidence between them is not perfect. There exist examples of this in every galaxy (see Fig. 1, middle and right panels); for example, the northwest part of NGC 2369, the southern nucleus of NGC 3256, an H ii region located to the southeast of the nucleus of NGC 5135, or the nuclear and some outer regions of IC 4687.

Figure 2 already gives some hints about the possible causes giving rise to the observed differences between the MIR and the Paα emission. The distribution of the cold dust, as traced by the F110W/F160W (or F160W/F222M) ratio (Fig. 2, left) does not seem to be correlated with the L_{MIR}/L_{Paα} maps (Fig. 2, right) nor with the MIR emission itself (Fig. 1, right). This would suggest that the dust causing the extinction to the stars might not be related with the dust responsible for the MIR emission. On the contrary, the age, as traced by the Paα EW (Fig. 2, middle), appears to have an important role, with the youngest H ii regions being associated with the lowest 8 μm to Paα ratios. There are many good examples of this as well, like the nuclear regions of NGC 1614 or NGC 3256 where youngest regions are also identified with “holes” in the L_{MIR}/L_{Paα} images. The nuclear region of IC 5179 also shows this behavior. There are some cases where this anticorrelation is not so clear. For example, the central region of IC 4687 is not very old but shows high values of the MIR/Paα ratio, perhaps indicating a larger contribution of the 8.6 μm PAH feature to the 8 μm luminosity than in other galaxies, and/or higher extinction.

5. THE 8 μm VS. Paα RELATIONSHIP

In this section we explore in detail the LIRG 8 μm vs. Paα relation on different spatial scales, compare it with the work of Cal07 for the SINGS H ii knots, and discuss the mechanisms giving rise to the observed scatter.

5.1. The L_{8 μm} vs. L_{Paα} Relation on Different Spatial Scales

Figure 6 shows that there is a good correlation between the 8 μm and Paα emissions for our sample of LIRG H ii regions when measured through the large aperture (r = 300 pc). For an easier comparison with the work of Cal07 this figure is shown in units...
of luminosity surface density (LSD). It is clear from this figure that the LIRG H ii regions [which have $12 + \log (O/H) \approx 8.8$; see Table 1] extend the correlation found by Cal07 for the SINGS high-metallicity [8.5 $\leq 12 + \log (O/H) \leq 8.9$] H ii regions by about 2 orders of magnitude above $S(\text{Pa}_\alpha_{\text{corr}}) = 10^{40.5}$ erg s$^{-1}$ kpc$^{-2}$. A least-squares fit to our data indicates that the $L_{8 \mu m}$ vs. $L_{\text{Pa}_\alpha}$ relationship for the $r = 300$ pc aperture is consistent with a unity slope (1.01 $\pm$ 0.08). The fitted slope is also consistent with that inferred for the SINGS high-metallicity knots (0.94 $\pm$ 0.02; see Cal07) and that for the integrated properties of galaxies (0.92 $\pm$ 0.05; see Wu et al. 2005). The LIRG H ii regions, however, seem to present a lower scatter ($\pm 0.1$ dex) around the fit than the SINGS H ii regions ($\pm 0.3$ dex; Cal07). We attribute the smaller scatter of our relation to the fact that we are using the same physical sizes, whereas the Cal07 aperture photometry is dictated by the angular resolution of their MIPS 24 $\mu m$ images. Their fixed 13$''$ diameter aperture implies physical sizes of between $\sim 220$ pc and 1.3 kpc for their high-metallicity sample, although, as explained in § 3.1, about half of their H ii regions are measured through a $\sim 600$ $\pm$ 100 pc diameter aperture.

The $8 \mu m$ vs. $\text{Pa}_\alpha$ relation holds when using our smallest physical aperture (see Fig. 7, $r = 75$ pc), although with a slightly smaller slope ($0.95 \pm 0.03$) than, but compatible with, that derived for the large aperture. The main difference with the relation for the large aperture is the higher dispersion around the fit ($\pm 0.2$ dex), not surprising since the distribution of the observed MIR to $\text{Pa}_\alpha$ ratios is much broader for the small aperture (Fig. 5, § 3.2). We note that this scatter is real, as the uncertainties associated with the background estimation are smaller for the $r = 75$ pc aperture than for the $r = 300$ pc aperture. The slight trend for the slope of the $L_{8 \mu m}$ vs. $L_{\text{Pa}_\alpha}$ relation to increase with the size of the aperture was already seen by AAH06a when comparing the relation for individual H ii regions and integrated emission.

The nuclei of LIRGs that are classified as containing an AGN (NGC 5135, IC 4518W, NGC 7130) depart from the correlations (see also AAH06a) and are located above the fitted relations. All of them show an excess of MIR emission with respect to their $\text{Pa}_\alpha$ luminosity. This could be attributed to an additional continuum emission due to hot dust heated by the AGN. This component would compensate for the absence of PAH emission, whose carriers are known to be destroyed in the vicinity of a hard radiation field, like that of an AGN (Roche et al. 1991; Voit 1992; Siebenmorgen et al. 2004). Another explanation for this excess could be attributed to the uncertainty of the extinction corrections, as they are based on stellar colors that may not be representative of those of an AGN. The regions identified as the nuclei of IRAS 17138–1017 and IC 4687 (both classified as H ii–type) also deviate from the mean trend. In both cases the most likely explanation is that the extinction has been underestimated.

5.2. What Causes the Scatter?

Some caveats should be taken into account when interpreting Figures 6 and 7. Assuming that the stellar light component is negligible at $A > 5 \mu m$ (for high-metallicity galaxies, Cal07 found that the stellar contribution to the $8 \mu m$ emission is small), there are two main mechanisms contributing to the $8 \mu m$ emission. First, there is thermal continuum from hot dust heated by young stars (or an AGN). Obviously, hot dust emission heated by an AGN is ruled out in H ii regions and H ii–like nuclei. The second contribution is from PAHs, which could vary from galaxy to galaxy. For instance, Smith et al. (2007) found variations in the contribution of the 8.6 $\mu m$ PAH feature to the total PAH luminosity ($\sim 5\%$–$10\%$) and to the total IR luminosity ($\sim 0.5\%$–$2\%$) among the SINGS star-forming galaxies.

Cal07 modeled the MIR (both 8 and 24 $\mu m$) vs. $\text{Pa}_\alpha$ empirical relations for the SINGS high-metallicity H ii knots with an instantaneous burst of 4 Myr, or equivalently constant star formation of 100 Myr, and an empirical relation between extinction and the $\text{Pa}_\alpha$ LSD. The deviations from the model prediction for the high-metallicity H ii knots are explained in terms of secondary effects such as the age of the stellar population and/or fixed extinction effects. Since the metallicity is almost constant among the LIRGs of the sample, we rule it out as the main cause of the scatter in the $L_{8 \mu m}$ vs. $L_{\text{Pa}_\alpha}$ relation. In the following subsections, we investigate the other effects for our sample of LIRG H ii regions.

5.2.1. The Age

Figure 8 (left) explores the dependence of the $L_{8 \mu m}/L_{\text{Pa}_\alpha}$ ratio (corrected for extinction) on the age of the H ii regions identified in our sample of LIRGs. There is a clear tendency for the youngest H ii regions to be the lowest $8 \mu m/\text{Pa}_\alpha$ ratios. This result is not subject to aperture effects since the same trend is observed if the large aperture is used, although somewhat diluted as the youngest H ii regions are averaged together with older regions and/or continuum regions (see Fig. 5, middle). Another possibility would be that the extinction was systematically underestimated for the most obscured star-forming regions (Rigby & Rieke 2004). This does not seem to be the case, as there is no trend for the regions with high $L_{8 \mu m}/L_{\text{Pa}_\alpha}$ ratios to correspond with H ii regions with the highest extinctions (see Fig. 8, right).

We can use the starburst models described in § 3.3 to try and reproduce the trend seen in Figure 8. Since in star-forming galaxies the MIR monochromatic luminosities are related to their IR luminosities (e.g., Elbaz et al. 2002; Takeuchi et al. 2005; AAH06b), and in LIRGs the IR luminosity accounts for the majority of the bolometric luminosity, we can assume $L_{8 \mu m} \propto L_{IR} \approx L_{\text{bol}}$. The hydrogen recombination line fluxes are, in turn, directly related to the number of ionizing photons provided by SB99 ($L_{\text{Pa}_\alpha} \propto N_{\text{Ly}}$). Taken into account these considerations, the dashed line in Figure 8 represents the evolution of the $L_{\text{bol}}/L_{\text{Pa}_\alpha}$...
evolution of the other galaxies.

Galactic compact H_2 (2004) found that the variation of the 6.2 \mu m luminosity ratio as a function of the age of the starburst as predicted by SB99 is scaled with a factor of 0.026. The scaling factor was calculated by means of a least-squares minimization method. As can be seen from this figure, the general trend is well reproduced by this simple model without any previous assumptions about the mechanisms producing the 8 \mu m emission. In fact, the model accounts for the observed variation (about 1 order of magnitude) of the L_8/\text{L}_{\text{bol}} ratio as the starburst ages from \sim 4 to 7.5 Myr.

5.2.2. PAH Contribution

Although the general tendency seen in Figure 8 is accounted for by the age evolution of the star-forming regions, a significant (vertical) scatter remains (\pm 0.2 dex) around the model predictions for a given age. We propose that this scatter might indeed be caused by the different contribution of the 8.6 \mu m PAH (or PAHs, depending on the filter used) to the integrated IR emission of the galaxies. Figure 8 (left) shows that the H\alpha regions of a given galaxy seem to follow the model prediction with the age, but different galaxies appear to be shifted along the vertical direction (see, e.g., the H\alpha regions of NGC 5135 and those of IC 4687). This would suggest that the overall PAH emission could vary from galaxy to galaxy as a whole (as seen by Smith et al. 2007). There is also the possibility that the PAH spectra vary from H\alpha region to H\alpha region within a galaxy. However, Peeters et al. (2004) found that the variation of the 6.2 \mu m PAH feature of Galactic compact H\alpha regions is smaller than that observed in other galaxies.

As mentioned above, the dashed line in Figure 8 shows the age evolution of the L_{\text{bol}}/\text{L}_{\text{PAH}} ratio predicted by the model, scaled with a factor of \sim 1.59 dex (\sim 0.026). This factor, which comes naturally from the data, can be interpreted as the mean contribution of the 8 \mu m luminosity (dust continuum + 8.6 \mu m PAH) to the L_{\text{bol}} in our LIRGs. For a sample of 59 star-forming galaxies of the SINGS sample, Smith et al. (2007) showed that the contribution of the 8.6 \mu m PAH to the total (integrated) IR luminosity of these galaxies is in the range of \sim 0.5\%–2\%. Since our 8 \mu m luminosities account not only for the 8.6 \mu m PAH but also for the continuum emission, the 2.6\% factor inferred above for our LIRGs is in agreement with their results. Moreover, the dispersion range of the 8.6 \mu m PAH intensity with respect to the L_{\text{IR}} among the SINGS galaxies, \pm 0.3 dex, is also in agreement with the (vertical) scatter seen in our data, suggesting the variation of the overall PAH emission field among the LIRGs as to be the main contributor to this scatter.

5.2.3. Extinction vs. Ionizing Flux

Although we find that the scatter of the L_8/\text{L}_{\text{PAH}} ratio is not related with a residual extinction effect (Fig. 8, right), Cal07 found that SINGS H\alpha knots with increasing Pa\alpha luminosities tend to show higher extinctions. Figure 9, plotted in LSD units so that it can be directly compared with Figure 12 of Cal07, shows that such a tendency is present in our sample. We find, however, that the LIRG H\alpha regions do not follow the extrapolation of the best fit of Cal07, which lies well above \sim 1 dex in E(\pmb{B-V}) the location of our star-forming regions. We note that the tendency seen for the LIRG H\alpha regions appears to be consistent with an apparent flattening of the relation for the few data points of Cal07 with log S(Pa\alpha) \sim 10^{40} erg s^{-1} kpc^{-1}.

One possibility is that we are underestimating the extinctions, as they are derived from NIR colors. However, even if we assumed that A_v(stars) \sim 0.44A_v(gas) (Calzetti et al. 2000), this would imply a correction of only \sim 0.3 dex, which still would not put the LIRG H\alpha regions on the extrapolation of the Cal07 fit. In
fact, the extrapolation of the Cal07 fit to our Paα LSD regime (≥10^{40.5} erg s^{-1} kpc^{-2}) would imply color excesses \( E(B-V) > 10 \), i.e., visual extinctions \( A_V > 40 \) mag (for a foreground dust configuration). In contrast, we have obtained relatively modest attenuations for our H II regions in the range of ~4-8 mag. AAH06a also used \( \text{He}\alpha/\text{Pa}\alpha \) and \( \text{Pa}\alpha/\text{Br}\gamma \) line ratios to calculate the extinction to the gas and found integrated \( (\approx 2\times10^7) \) values for the sample of LIRGs of \( A_V \approx 2-14 \) mag, still well below the values we would obtain from the extrapolation of the Cal07 fit.

6. SUMMARY

In this paper we presented T-ReCS subarcsecond (FWHM ~ 0.4 arcsec) MIR (8.6 or 10.3 \( \mu \)m) imaging observations of a sample of 10 low-z \( (d < 76 \text{ Mpc}) \) nearly solar metallicity [12 + log (O/H) ~ 8.8] LIRGs, as well as \( HST \) NICMOS continuum and Pa\( \alpha \) images. The main goal was to study in detail the \( L_{8\mu m} \) vs. \( L_{\text{Pa}\alpha} \) relationship for H II regions in LIRGs on scales of a few hundred parsecs (FWHM~120 pc for the average distance \( d = 60 \text{ Mpc} \)). We performed photometry of H II regions through apertures with radii of \( r = 75 \) pc (122 H II regions), \( r = 150 \) pc (84 H II regions), and \( r = 300 \) pc (41 H II regions). The first aperture was chosen to take advantage of the high angular resolution afforded by T-ReCS and NICMOS. The large aperture is useful to compare our results with those of Cal07 for H II regions in the high-metallicity SINGS galaxies observed with \textit{Spitzer} IRAC at 8 \( \mu \)m.

We find that although the overall Pa\( \alpha \) (tracing the youngest ionizing stellar populations) morphologies of LIRGs are similar to those in the MIR, there are some differences on the ~100 pc scales. The morphological differences appear to be related to the age of the young stellar populations, with regions of low \( L_{8\mu m}/L_{\text{Pa}\alpha} \) ratios showing large Pa\( \alpha \) EW. In general, we do not find a relation between red NIR colors, which would indicate high extinction to the stars, and regions of high or low \( L_{8\mu m}/L_{\text{Pa}\alpha} \) ratios.

On scales of \( r = 300 \) pc the LIRG H II regions extend the SINGS \( L_{8\mu m} \) vs. \( L_{\text{Pa}\alpha} \) relation by about 2 orders of magnitude (as already found by AAH06a) for Pa\( \alpha \) LSD above 10^{40.5} erg s^{-1} kpc^{-2}. When studied on small scales \( (r = 75 \text{ pc}) \), the relation holds, although with a slightly shallower slope and a greater (real) scatter around the fit \( (\pm 0.2 \text{ dex}) \). Taking into account that our sample has a nearly constant metallicity, the scatter of this relation is explained in terms of the ages of the ionizing population and different PAH contributions. There is a tendency for the youngest H II regions in our sample to show low \( L_{8\mu m}/L_{\text{Pa}\alpha} \) ratios. Considering instantaneous star formation and assuming that \( L_{8\mu m} \propto L_{\text{IR}} \approx L_{\text{bol}} \), we naturally reproduce the observed \( L_{8\mu m}/L_{\text{Pa}\alpha} \) ratios, which vary by a factor of 10, with ages ranging from ~4 to 7.5 Myr. The residual dispersion around the model prediction is likely to be caused by the different contribution from galaxy to galaxy of the 8.6 \( \mu \)m PAH feature (in our case) to the 8 \( \mu \)m emission (and in general, to the IR luminosity), as observationally found by Smith et al. (2007) for the SINGS galaxies.

Although we see a trend for the LIRG H II regions with the largest Pa\( \alpha \) LSD to show the highest extinctions to the stars, they do not follow the extrapolation of the relation between the \( E(B-V) \) color excess and the Pa\( \alpha \) LSD found by Cal07, which would imply extinctions in excess of \( A_V = 40 \) mag. In contrast, they show relatively modest attenuations.

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