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THE MID-INFRARED EMISSION OF LOCAL LUMINOUS INFRARED GALAXIES

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RESUMEN

En este artículo se combinan la sensibilidad de *Spitzer* y la alta resolución espacial de T-ReCS en el Gemini-Sur para estudiar las propiedades en el infrarrojo (IR) medio de galaxias luminosas infrarrojas (LIRGs) locales ($d < 75\,$Mpc). Las imágenes de T-ReCS en $8 - 10\,\mu$m nos han permitido separar la emisión nuclear (formación estelar y/o AGN) de la de las regiones H II en las zonas centrales ($3-7\,$kpc). De la comparación de los cocientes $8\,\mu$m/Paα integrados y de regiones H II resueltas se deduce la existencia de una componente de emisión difusa en $8\,\mu$m. Esta emisión difusa no está directamente relacionada con las poblaciones estelares ionizantes, y puede ser tan luminosa como la que proviene de regiones H II. Por lo tanto, aunque la emisión en el IR medio es un buen indicador de la tasa de formación estelar (SFR) de galaxias con polvo, las calibraciones han de hacerse usando las propiedades integradas de galaxias, y no las de regiones H II únicamente. Se presenta una calibración de la SFR en función de la luminosidad en $24\,\mu$m que es aplicable a galaxias lejanas con polvo.

ABSTRACT

In this paper we use the complementary imaging capabilities of *Spitzer* (sensitivity) and Gemini-South/T-ReCS (spatial resolution) to study the mid-IR properties of local ($d < 75\,$Mpc) LIRGs. The T-ReCS $8 - 10\,\mu$m imaging observations of LIRGs have allowed us to spatially resolve the nuclear emission (star formation and/or AGN) and that of H II regions in the central $3-7\,$kpc regions of LIRGs. From the comparison of the $8\,\mu$m/Paα ratios of the integrated vs. resolved H II regions of LIRGs, we infer the existence of an $8\,\mu$m diffuse component, not directly related to the ionizing stars, that can be as luminous as that from the resolved H II regions. We conclude that although the mid-IR integrated luminosity of galaxies undergoing dusty, intense star formation is a good indicator of the star formation rate (SFR), the empirical calibrations should be based on the integrated emission of nearby galaxies, not that of H II regions alone. To this end we provide a calibration of the SFR in terms of the integrated $24\,\mu$m luminosity that can be used for distant dusty galaxies.

Key Words: **GALAXIES: INFRARED — GALAXIES: SEYFERT — H II REGIONS — STARS: FORMATION**

1. INTRODUCTION

The importance of infrared (IR) bright galaxies has been increasingly appreciated since their discovery more than 30 years ago (Rieke & Low 1972), and the detection of large numbers by *IRAS*. Although the Ultraluminous IR Galaxies (ULIRGs, $L_{\rm IR} > 10^{12}\,{\rm L}_\odot$) get much of the attention because they are so dramatic, Luminous IR Galaxies (LIRGs — $L_{\rm IR} = 10^{11}$ to $10^{12}\,{\rm L}_\odot$) are much more common, accounting for $\sim 5\%$ of the local IR background compared with $< 1\%$ for the ULIRGs (Lagache et al. 2005). LIRGs take part in the controversy over the formation of AGN, and its relation to star formation and high levels of IR emission (see review by Sanders & Mirabel 1996), and should also include former ULIRGs where the SF is dying off. Deep *Spitzer* detections at $24\,\mu$m are dominated by LIRGs (Le Floc'h et al. 2005; Pérez-González et al. 2005), and LIRGs contribute nearly 50% of the cosmic IR background at $z \sim 1$ (Lagache et al. 2005). Interpretation of the *Spitzer* observations at high-z therefore depends on a deep understanding of LIRGs in the local universe.

With the advent of a new generation of mid-IR instruments with superior sensitivity and spatial resolution we can now investigate whether the mid-IR emission is a good indicator of the star formation rate (SFR) in dusty galaxies. The mid-IR emission has the advantage of not being affected by the contribution from cold dust heated by old stars that may dominate the far-IR luminosities. *Spitzer* observations of nearby *normal* galaxies show similar $8 - 24\,\mu$m and hydrogen recombination line morphologies (e.g., Helou et al. 2004; Hinz et al. 2004; Calzetti et al. 2005, CAL05 hereafter; Pérez-González et al. 2006, PGPG06 here-

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after; Alonso-Herrero et al. 2006b). At longer wavelengths ($160\,\mu$m) the individual H II regions (current star formation) contribute much less than at 24 and $70\,\mu$m (Hinz et al. 2004). From a quantitative point of view there is a good correlation between the Paα or Hα luminosity (corrected for extinction) and the $24\,\mu$m luminosity of resolved H II regions (CAL05; PGPG06). However there are galaxy-to-galaxy variations in the $24\,\mu$m luminosity to SFR ratios of UV-selected starbursts and ULIRGs (CAL05). CAL05 and PGPG06, on the other hand, questioned the use of the IRAC $8\,\mu$m emission as a SFR tracer, whereas Wu et al. (2005) find a good correlation between the $8\,\mu$m (and $24\,\mu$m) and Hα emission of local star forming galaxies in the *Spitzer* First Look Survey.

We present a detailed study of the mid-IR properties of local LIRGs taking advantage of both the sensitivity of *Spitzer* imaging observations and the high spatial resolution of the Thermal-Region Camera Spectrograph (T-ReCS; Telesco et al. 1998) on the 8.1 m Gemini-South Telescope. In particular we investigate the issue of whether the mid-IR emission is a good tracer of the SFR in dusty galaxies.

2. THE SAMPLE OF LOCAL LIRGS

The sample of 30 LIRGs (34 galaxies) was chosen to be volume-limited to a velocity range of $v = 2750 - 5200\,\mathrm{km\,s^{-1}}$ ($d = 35 - 75\,$Mpc, $H_0 = 75\,$km s^{-1} Mpc^{-1}) so that the Paα emission line ($\lambda_{\rm rest} = 1.876\,\mu$m) could be observed with the *HST*/NICMOS F190N narrow-band filter. We also obtained NICMOS continuum images at 1.1, 1.6, and $1.87\,\mu$m . For the velocity range used here our sample contains $\sim$ 80% of all LIRGs in the *IRAS* Revised Bright Galaxy Sample (Sanders et al. 2003). The missing galaxies are very similar to those observed, and thus this sample is representative of the class of local LIRGs as a whole. The sample covers an IR luminosity range of $\log L_{\rm IR[8-1000\,\mu m]} = 11 - 11.9\,[{\rm L}_\odot]$, and includes a variety of morphologies and environments (isolated systems, galaxies in groups, and interacting galaxies), and nuclear activity (H II, Seyfert, and LINER). Details on the observations and near-IR properties of the sample are given by Alonso-Herrero et al. (2006a, hereafter AAH06).

3. OBSERVATIONS

We obtained T-ReCS imaging observations of all the LIRGs in our sample that can be observed from Gemini-South. We focus here on the first results obtained for four LIRGs (see Alonso-Herrero et al. 2006b). Three LIRGs (NGC 5135, IC 4518W, and NGC 7130) were observed with the N broad-band filter (central wavelength $\lambda_{\rm c} = 10.36\,\mu$m) and NGC 3256 with the Si-2 narrow-band filter ($\lambda_{\rm c} = 8.74\,\mu$m). The T-ReCS observations were effectively diffraction limited (FWHM$\sim 0.30''$) implying spatial resolutions of $\sim 50 - 100\,$pc for our LIRGs.

In addition we have retrieved archival *Spitzer*/IRAC $8\,\mu$m and MIPS $24\,\mu$m images for our sample, with spatial resolutions of $\sim 2''$ and $\sim 5''$, respectively. The *HST*/NICMOS, T-ReCS, and *Spitzer*/IRAC images of three LIRGs are presented in Figure 1.

4. MID-IR EMISSION ON SCALES OF TENS−HUNDREDS OF PARSECS

4.1. *Morphology*

The morphological resemblance (see Figure 1) between the bright mid-IR regions (traced by T-ReCS) and the H II regions (traced by the NICMOS Paα emission) on scales of tens-hundreds of pc in LIRGs (see also Soifer et al. 2001) is remarkable. The IRAC $8\,\mu$m images, taking into account their limited spatial resolution, are similar to the T-ReCs images, with the advantage that they are more sensitive to the diffuse emission not directly associated with the bright H II regions (see §5 for a detailed discussion). The near-IR continuum emission is more extended than the mid-IR emission, and generally does not resemble the morphology of the ionized gas (see AAH06). As $A_{1.6\,\mu m} \sim 3.3 \times A_N$, the lack of correspondence between the near and mid-IR (and Paα) emitting regions is probably not a differential extinction effect. Rather, this may reflect age differences since the near-IR continuum is produced mostly by stellar populations older than the ionizing stellar populations (see e.g., Alonso-Herrero et al. 2002), even though highly obscured regions tend to be associated with the youngest regions in LIRGs (Soifer et al. 2001).

The nuclei are the brightest mid-IR sources in all the galaxies. The Sy2 nuclei of NGC 5135 and IC 4518W appear unresolved in the T-ReCs images, in agreement with the detection of nuclear point sources in the higher spatial resolution ($\sim 0.15''$) NICMOS images (see AAH06). The nucleus of NGC 7130 (classified as a Sy or LINER) appears marginally resolved in the T-ReCS images, and the NICMOS continuum images reveal the presence of at least three sources of similar flux in the central $\sim 190\,$pc. This suggests that the putative AGN in NGC 7130 does not dominate (see §4.2) the N-band nuclear emission. NGC 3256 is a well-studied merger galaxy, with two bright nuclei, which are also the brightest mid-IR sources in this galaxy. Although it has been argued that this merger may contain obscured AGN, the extended (FWHM $\sim 60\,$pc) nature

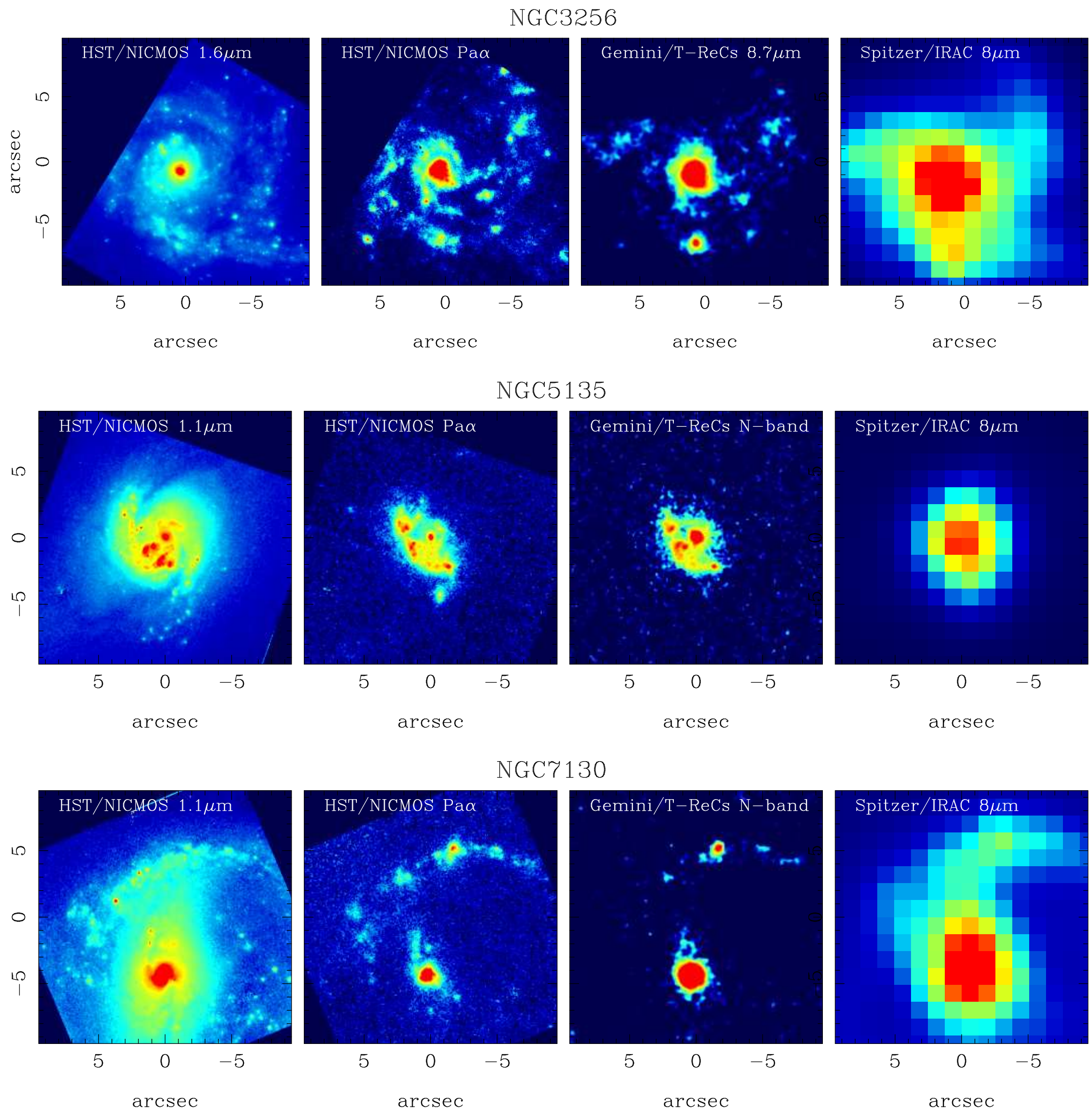

Fig. 1. From left to right: *HST*/NICMOS 1.6 μm or 1.1 μm continuum emission, *HST*/NICMOS Paα emission line, Gemini/T-ReCS 10.4 μm (N-band) or 8.7 μm imaging, and *Spitzer*/IRAC 8 μm imaging of the central regions of three LIRGs in our sample. Orientation is north up, east to the left. The two brightest mid-IR and Paα sources of NGC 3256 are the north and south nuclei of this merger LIRG. For NGC 5135 the bright mid-IR central source is the Seyfert 2 nucleus, whereas the sources located to the east and south of the nucleus are bright H II regions (see §5).

of the near and mid-IR continuum emission of both nuclei suggests that such AGN, if present, are not dominant in the mid-IR.

4.2. *AGN Contribution to the mid-IR emission*

Approximately 25% of local LIRGs, including those in our sample, host spectroscopically confirmed AGN (e.g., Veilleux et al. 1995). The Seyfert nucleus of IC 4518W appears to dominate the mid-IR emission, whereas for NGC 5135 and NGC 7130 the Seyfert nuclei contribute $\sim$ 20 % or less of the N-band emission within the central 10$''$. Three more galaxies in the LIRG sample of AAH06, not observed with T-ReCS, have spectroscopically confirmed Sy nuclei. For two of them, the B1 nucleus of the IC 694/NGC 3690 (Arp 299) system (García-Marín et al. 2006), and NGC 7469, the AGN contribution to the mid-IR emission is $\sim$ 30% (Keto et al. 1997;

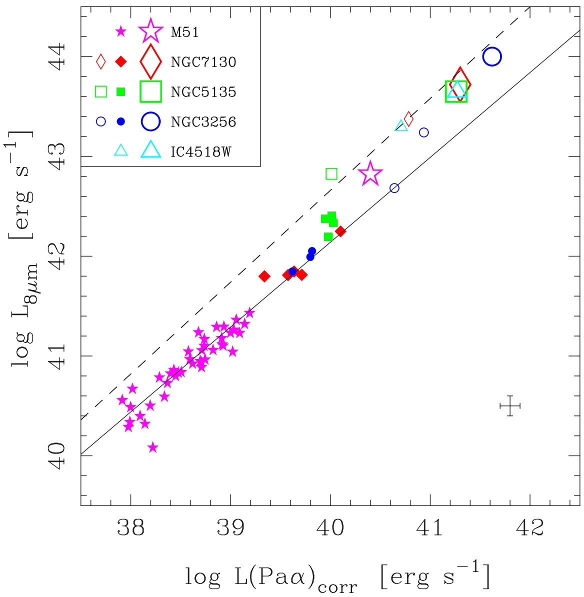

Fig. 2. Monochromatic (ν f_ν) 8 μm vs. extinction-corrected Paα luminosities. The small open and filled symbols are the nuclei and H II regions of LIRGs, respectively. The large open symbols for the LIRGs indicate the integrated properties over the NICMOS FOV ($\sim 19'' \times 19''$, between 3 and 7 kpc for these LIRGs). The central 6 kpc M51 H II regions and integrated emission from CAL05 are shown as star symbols. The solid line is our least-squares fit to the CAL05 M51 H II region data extrapolated to the LIRG luminosities. The dashed line is the Wu et al. (2005) relation for star-forming galaxies.

Soifer et al. 2003). For the third one, there is no mid-IR information. This is consistent with the majority of AGN in our local LIRGs not dominating the mid-IR emission.

5. NUCLEAR, H II REGION AND INTEGRATED $8-10\,\mu$M EMISSION OF LIRGS

For the nearby galaxy NGC 300 Helou et al. (2004) showed that the 8 μm emission tends to be more extended than the Hα emission and highlights the rims of the H II regions. They concluded that the 8 μm emission is more closely associated with photodissociation regions (PDRs) than with ionized regions. In Figure 2 we compare the Paα and 8 μm emission for resolved H II regions, nuclei, and integrated (central $3-7$ kpc) emission of the four LIRGs observed with T-ReCs. We also show in this figure data for resolved H II knots in M51 from CAL05. The LIRG H II regions, although can be up to 10 times more luminous than those in M51, tend to follow the extrapolation of the CAL05 relation. Conversely, the integrated $\sim 3-7$ kpc emission of LIRGs deviates significantly from the relation found for individual H II regions, but only slightly from the fit of Wu et al. (2005) for star-forming galaxies (Figure 3). This could arise from two causes. First, Wu et al. (2005) may have underestimated the reddening (obtained from the Balmer decrements) in these dusty star-forming galaxies. Second, the 8 μm emission may be dominated by diffuse emission not associated directly with the H II regions (see below).

The LIRG nuclei (except the south nucleus of NGC 3256) show elevated mid-IR/Paα ratios when compared to H II regions. Such spatial differences in the mid-IR emission of nuclear and circumnuclear regions are observed for our LIRGs from high-spatial resolution T-ReCS spectroscopy (see Díaz-Santos et al. 2007). One possibility is that an insufficient extinction correction (as nuclear extinctions in LIRGs tend to be higher than in extranuclear regions) will produce a differential effect, making the nuclei appear more IR-luminous. The AGN present in three of our LIRGs may also play a role, as their continua are produced by dust heated to higher temperatures than H II regions, and do not present the strong PAH emission characteristic of H II+PDRs (e.g., Roche et al. 2006; Díaz-Santos et al. 2007).

Since a variety of H II regions in M51 and LIRGs have a similar 8 μm vs. Paα relation we conclude that their 8 μm emission in the *Spitzer*/IRAC band is well characterized by a thermal continuum plus PAH features with no strong variations over the range of conditions probed here (e.g., metalicity near or over solar, see AAH06 and CAL05).

However, the integrated central $3-7$ kpc 8 μm vs. Paα emission differs significantly in all these environments from the relation found for the individual H II regions. This may be explained by the presence, in addition to the bright and compact H II regions, of a more diffuse and extended 8 μm component (see Figure 1, and Helou et al. 2004; Díaz-Santos et al. 2007). This extra emission at 8 μm would be produced not by local, strong ionizing sources, but by the diffuse radiation field that permeates the ISM. As such, the spectrum in these regions would be characterized by a weak continuum and strong PAH features with a large equivalent width. This has already been confirmed for one of the LIRGs in our sample as discussed in detail by Díaz-Santos et al. (2007). Hence when compared to individual H II regions, an excess of 8 μm/Paα emission can be expected for the integrated properties over a few kpc. This is further supported by the fact that the central $3-7$ kpc emission of LIRGs falls only slightly below the Hα vs. 8 μm relation found for the inte-

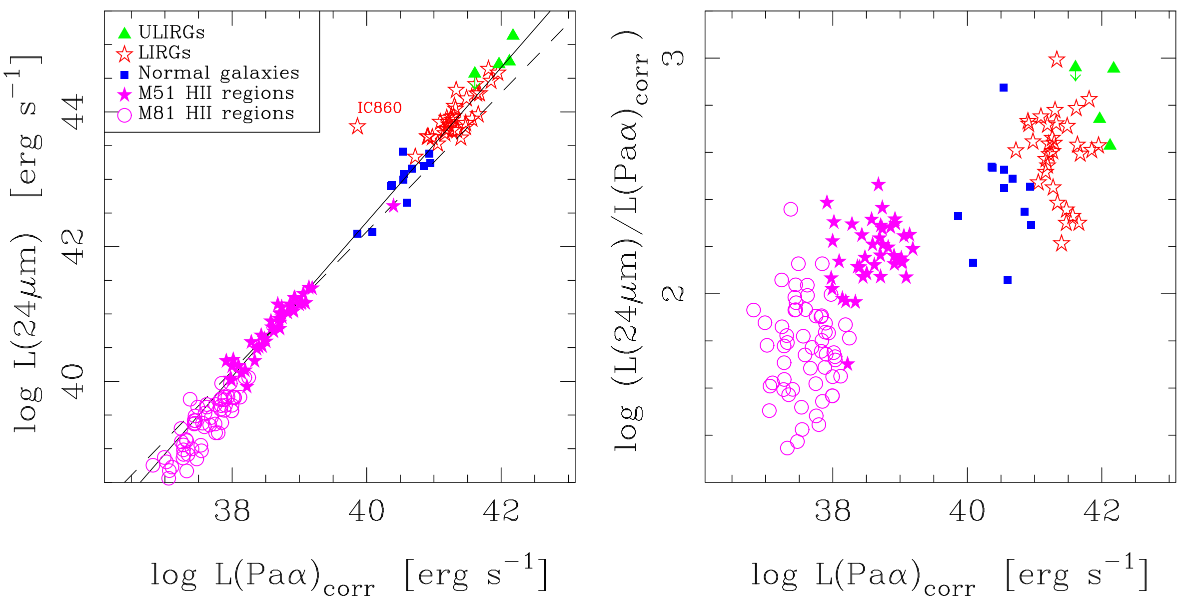

Fig. 3. Monochromatic 24 μm luminosities vs. extinction-corrected Paα luminosities (left) for LIRGs, normal galaxies (Böker et al. 1999), ULIRGs (Murphy et al. 2001), and H II regions in M51 and M81 (see text and AAH06). The solid line is the fit to the M51 H II and the normal galaxies and LIRGs, and dashed line the CAL05 fit to the M51 H II knots. The 24 μm/Paα ratio vs. the extinction-corrected Paα luminosity (right). Symbols are as in left panel.

grated properties of the galaxies studied by Wu et al. (2005), as indicated in Figure 2. We conclude that calibrations of the SFR in terms of the 8 μm emission for distant galaxies should be based on the integrated mid-IR emission of galaxies, not that of the H II regions alone.

6. THE 24 μM EMISSION AS A SFR TRACER FOR DUSTY STAR-FORMING GALAXIES

Helou et al. (2004) showed that in contrast with the 8 μm emission, the 24 μm emission of NGC 300 appears to be more centrally peaked in star-forming regions. In Figure 3 (left) we compare the monochromatic 24 μm luminosities and the extinction-corrected Paα luminosities (see AAH06) for all the LIRGs in our sample. We also include a small comparison sample of normal galaxies and ULIRGs, and data for resolved star-forming regions in M51 from CAL05, and in M81 from PGPG06.

The integrated emission of LIRGs, ULIRGs, and normal galaxies seems to continue the relation between the extinction-corrected Paα luminosity and the 24 μm luminosity observed by CAL05 for the M51 central H II knots, unlike the case of the 8 μm emission. The fit to the LIRGs, ULIRGs, normal galaxies, and M51 H II knots provides a slope of 1.148 ± 0.013 (Figure 3; Wu et al. 2005; AAH06), only slightly larger than the slope of the CAL05 fit to the M51 H II knots. The M81 H II regions, on the other hand, appear to be offset with respect to M51 H II regions, normal galaxies, and LIRGs. This behavior could arise from a lower UV absorption efficiency in the relatively low luminosity and lightly obscured H II regions in M81, as well as to uncertain extinction corrections (see discussion by PGPG06). There are galaxy-to-galaxy variations in the mid-IR to Paα ratios (Figure 3, right), as also noted by CAL05. The variation of the $L(24\,\mu\mathrm{m})/L(\mathrm{Pa}\alpha)_{\mathrm{corr}}$ ratio with the Paα luminosity (i.e., SFR) between the M51 H II knots and our LIRGs and ULIRGs is similar to the $L_{24\,\mu\mathrm{m}}$/SFR ratios found by CAL05. In fact, the gap between the M51 H II knots and the LIRGs/ULIRGs seen in our figure is populated by their UV-selected starbursts.

There are two possibilities which might explain the deviation from strict proportionally of the 24 μm vs. Paα relation. First the nuclear extinctions of LIRGs may be underestimated (the values averaged over the Paα emitting regions are $A_V \sim 2-6$ mag, see AAH06), whereas some LIRGs and ULIRGs are known to contain highly obscured regions, usually associated with the nuclei of the galaxies (e.g., Genzel et 1998; Alonso-Herrero et al. 2000). From the observed ratios of mid-IR emission lines of star-forming galaxies there is evidence that some of the youngest stars in LIRGs may still embedded in high density ultracompact H II regions and hidden from us by large amounts of extinction (Rigby & Rieke 2004). In such regions the dust competes increasingly effectively for ionizing photons and UV continuum photons, so that an increasing fraction of the luminosity is expected to emerge in the IR. The second possibility would be if the LIRG emission is dominated by AGN, but as discussed in §4.2 AGN do not appear to dominate the mid-IR emission in our sample of LIRGs.

6.1. *The empirical calibration of SFR vs.* $24\,\mu m$

In deriving his relationship between the SFR and the IR luminosity Kennicutt (1998) assumed that the great majority of the luminosity from young stars would be absorbed by dust and reradiated in the far-IR. Although this assumption is likely to be correct, observationally there may be other contributions to the total IR luminosity from older populations of stars or other luminosity sources. Therefore, a true total IR luminosity measurement may overestimate the recent star formation in a galaxy, although estimates based on *IRAS* measurements alone are less subject to these issues because they only poorly sample the output of the cold dust (because the longest band is at 100μm). Second, Kennicutt assumed a direct proportionality between the Hα luminosity and the total IR. We find empirically that the increasing absorption efficiency in more luminous and obscured galaxies leads to a deviation from strict proportionality, causing the IR output to rise with increasing star-forming luminosity.

Assuming Case B recombination, and using the relation between SFR and Hα quoted by Kennicutt (1998) and the fit between the $24\,\mu$m and Paα luminosities (AAH06) we derive the following relation between the SFR rate and the $24\,\mu$m luminosity for luminous, dusty galaxies:

$$\mathrm{SFR} = 8.45 \times 10^{-38}\,(L(24\,\mu\mathrm{m}))^{0.871} \qquad (1)$$

where the SFR is in $\mathrm{M_\odot\,yr^{-1}}$ and the $24\,\mu$m luminosity is in $\mathrm{erg\,s^{-1}}$. This relation is analogous to the widely used relation between SFR and IR luminosity (Kennicutt 1998) but it is not affected by the uncertain contribution to the total IR luminosity of a galaxy of dust heating from old stars.

Summarizing, we have used the sensitivity of *Spitzer* and the high spatial resolution of T-ReCS on the Gemini-South telescope to study the mid-IR properties of LIRGs. The T-ReCS $8-10\,\mu$m imaging observations of LIRGs have allowed us to resolve the nuclear emission (star formation and/or AGN) from that of circumnuclear H II regions. The comparison of the $8\,\mu$m/Paα ratios of the integrated and resolved H II regions of LIRGs reveals an $8\,\mu$m diffuse component, not directly related to the ionizing stars, that can be as luminous as that from the resolved H II regions. Therefore the calibration of the SFR for distant galaxies should be based on the integrated mid-IR emission of nearby galaxies, not that of H II regions alone. We provide a calibration of the SFR in terms of the integrated $24\,\mu$m luminosity. Similar mid-IR studies with the GTC/CanariCam system will be possible in the near future.

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