LOCAL LUMINOUS INFRARED GALAXIES. II. AGN ACTIVITY FROM SPITZER/IRS SPECTRA
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ABSTRACT

We quantify the active galactic nucleus (AGN) contribution to the mid-infrared (mid-IR) and the total infrared (IR, 8 – 1000 \(\mu\)m) emission in a complete volume-limited sample of 53 local luminous infrared galaxies (LIRGs, \(L_{\text{IR}} = 10^{11} – 10^{12} L_\odot\)). We decompose the Spitzer Infrared Spectrograph (IRS) low-resolution 5 – 38 \(\mu\)m spectra of the LIRGs into AGN and starburst components using clumpy torus models and star-forming galaxy templates, respectively. We find that 50\% (25/50) of local LIRGs have an AGN component detected with this method. There is good agreement between these AGN detections through mid-IR spectral decomposition and other AGN indicators, such as the optical spectral class, mid-IR spectral features and X-ray properties. Taking all the AGN indicators together, the AGN detection rate in the individual nuclei of LIRGs is \(\sim 62\%\). The derived AGN bolometric luminosities are in the range \(L_{\text{bol}}(\text{AGN}) = 0.4 – 50 \times 10^{43} \text{erg s}^{-1}\). The AGN bolometric contribution to the IR luminosities of the galaxies is generally small, with 70\% of LIRGs having \(L_{\text{bol}}(\text{AGN})/L_{\text{IR}} \leq 0.05\). Only \(\approx 8\%\) of local LIRGs have a significant AGN bolometric contribution \(L_{\text{bol}}(\text{AGN})/L_{\text{IR}} > 0.25\). From our results with literature results of ultraluminous infrared galaxies (\(L_{\text{IR}} = 10^{12} – 10^{13} L_\odot\)), we confirm that in the local universe the AGN bolometric contribution to the IR luminosity increases with the IR luminosity of the galaxy/system. If we add up the AGN bolometric luminosities we find that AGNs only account for 5\% – 3\% of the total IR luminosity produced by local LIRGs (with and without AGN detections). This proves that the bulk of the IR luminosity of local LIRGs is due to star formation activity. Taking the newly determined IR luminosity density of LIRGs in the local universe, we then estimate an AGN IR luminosity density of \(\Omega_{\text{AGN}} = 3 \times 10^{-3} L_\odot \text{Mpc}^{-3}\) in LIRGs.

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1. INTRODUCTION

Luminous infrared (IR) galaxies (LIRGs) are defined as having infrared (8 – 1000 \(\mu\)m) luminosities in the range \(L_{\text{IR}} = 10^{11} – 10^{12} L_\odot\). Although an active galactic nucleus (AGN) may contribute, it is believed that the bulk of their IR luminosity is produced by dust heated by intense star-forming activity (Sanders & Mirabel 1996). Using the prescription of Kennicutt (1998) the IR luminosities of LIRGs imply star formation rates in the range 17 – 170 M_\odot\text{yr}^{-1} for a Salpeter IMF. The early studies of the AGN activity in LIRGs made use mostly of the optical spectral range. The classical studies of Veilleux et al. (1995) and Kim et al. (1995) showed that the fraction of sources containing an AGN increases at higher IR luminosities, although the relative contributions of star formation and AGN to the bolometric luminosity of the system were not well determined. Recently Yuan et al. (2010) introduced a new approach for spectral classification of the Veilleux et al. (1995) sample. They found that \(\sim 22\%\) of LIRGs are classified as Seyfert or LINER, \(\sim 37\%\) are AGN/starburst (SB) composites, 24\% are HII-like, and the rest are ambiguous. They also showed that a large fraction of the LIRGs previously classified as LINERs are AGN/SB composites.

Infrared spectroscopy obtained with the Spitzer Infrared Spectrograph (IRS) to estimate the AGN emission at 6 \(\mu\m\text{m}\) of a sample of IR bright galaxies, as an ingredient for their backward evolution model for IR surveys. Locally they found an increasing contribution of the AGN emission at 6 \(\mu\m\text{m}\) with a tendency at higher redshifts, however, when modelling the mid-IR and submillimeter number counts. Petric et al. (2011), as part of the The Great Observatories All-Sky LIRG Survey (GOALS, see Armus et al. 2009), used a number of mid-IR spectral indicators to derive an AGN contribution of 12\% for the GOALS LIRGs. At higher IR luminosities, most ultraluminous IR galaxies (ULIRGs, \(L_{\text{IR}} = 10^{12} – 10^{13} L_\odot\)) are dominated by AGN bolometrically. At higher IR luminosities, this tendency at higher redshifts is relatively well constrained with ultraluminous IR galaxies (ULIRGs, \(L_{\text{IR}} = 10^{12} – 10^{13} L_\odot\)) only being dominated by AGN bolometrically. At higher IR luminosities, this tendency at higher redshifts is relatively well constrained with ultraluminous IR galaxies (ULIRGs, \(L_{\text{IR}} = 10^{12} – 10^{13} L_\odot\)) only being dominated by AGN bolometrically. At higher IR luminosities, this tendency at higher redshifts is relatively well constrained with ultraluminous IR galaxies (ULIRGs, \(L_{\text{IR}} = 10^{12} – 10^{13} L_\odot\)) only being dominated by AGN bolometrically.
We use the volume-limited sample of LIRGs defined by Alonso-Herrero et al. (2006a). This sample was originally drawn from the IRAS Revised Bright Galaxy Sample (RBGS, Sanders et al. 2003), which is a complete flux-limited survey at 60 μm with flux densities greater than 5.24 Jy and Galactic latitude |b| > 5 deg. The distance limit imposed by Alonso-Herrero et al. (2006a) was chosen to allow for Paα observations with the narrow-band F190N filter of HST/NICMOS. The sample here has been completed to include all the IRAS sources in the RBGS with log(LIR/L⊙) ≥ 11.05 and ωhel = 2750 − 5300 km s⁻¹. For the assumed cosmology the distances are in the range 40 − 78 Mpc, with a median value of 65 Mpc.

The sample is presented in Table 1; it contains 45 IRAS systems. Eight IRAS systems in our sample contain...
multiple galaxies, that is, they are interacting galaxies, pairs of galaxies, or galaxies with companions. These can be readily identified in Table 1 as having the same IRAS name. We note, however, that MCG—03-34-063, which is part of IRAS F13197−1627 with MCG—03-34-064 (Surace et al. 2004), is at 6394 km s\(^{-1}\) (from NED) and thus does not meet the distance criterion of our sample. Two galaxies, NGC 5743 and NGC 7769 (see Table 1), have IRS spectroscopy (see Section 2.2), but were not originally included in the IRAS RBGS. However, both galaxies are in interaction with RBGS IRAS sources (see Surace et al. 2004). NGC 5743 is paired with NGC 5734 and shows a diffuse H\(\alpha\) extension toward NGC 5734 (Dopita et al. 2002). NGC 7769 is part of the NGC 7771/NGC 7770 group, and there is evidence that NGC 7769 is undergoing a direct encounter with NGC 7771 (Nordgren et al. 1997). Additionally, these two galaxies not included in the RBGS have IR luminosities similar to the rest of the galaxies (see Table 1) and thus we included them in our sample. The sample contains a total of 53 individual galaxies.

The IR luminosities of the galaxies in the range 8–1000 \(\mu\)m, \(L_\text{IR}\), were calculated as defined by Sanders & Mirabel (1996). The IRAS flux densities were taken from Sanders et al. (2003) and Surace et al. (2004). The latter work used image reconstruction techniques to resolve the IR emission from the individual galaxies of interacting systems detected by IRAS.

For the groups of galaxies and interacting galaxies not resolved by IRAS we assumed that the \(L_\text{IR}\) fraction of each component is proportional to the Spitzer/MIPS 24 \(\mu\)m flux density (see Section 2.3) fraction. In Table 1 we list the IR luminosities for the individual galaxies in our sample, rather than for the systems in the case of pairs of galaxies and galaxies in groups. Note that some of the log \(L_\text{IR}\) values are below the imposed limit either because the galaxy is a member of a pair or because of the revised values of the distances.

2.2. IRS Spectroscopic Data

All individual galaxies in our sample, except for three, were observed by the Spitzer/IRS (Houck et al. 2004) instrument. We retrieved IRS spectroscopic data for our sample of LIRGs from the Spitzer archive. Fifteen IRAS systems (16 galaxies) in our sample were observed in mapping mode and one in staring mode as part of our own guaranteed time observation (GTO) programs P30577 and P40479 (PI: G. H. Rieke) and were discussed in detail by Alonso-Herrero et al. (2009b) and Pereira-Santaella et al. (2010a). Two more galaxies are from various programs (IC 860 from P1096 and NGC 7469 from P14). The rest of the sample are part of the GOALS legacy program (Armus et al. 2009) and were observed in staring mode. Observations at low-resolution (\(R \sim 60–120\)) with the Short-Low (SL) and Long-Low (LL) modules and at high-resolution with the \((R \sim 600)\) Short-High (SH) and Long-High (LH) modules were available for all the galaxies.

For the staring and mapping data reduction we followed Pereira-Santaella et al. (2010a) and Pereira-Santaella et al. (2010b), respectively. Briefly, we started with the basic calibrated data (BCD). Bad pixels were corrected using the IDL package IRSCLEAN\(^8\). Then we subtracted the sky emission. For the staring data we extracted the spectra using the standard programs included in the Spitzer IRS Custom Extraction (SPICE) package provided by the Spitzer Science Center (SSC) and the point source calibration. For the mapping observations we constructed the data cubes using CUBISM (Smith et al. 2007). The nuclear spectra of the galaxies observed in mapping mode were extracted using a 13.4\(\times\)13.4 aperture. Since the data cubes are calibrated as extended sources we applied a wavelength dependent aperture correction to the mapping data to obtain spectra comparable to those observed in staring mode. To calculate this aperture correction we used the mapping observations of standard stars (HR 7341, HR 6606, HR 6688, and HR 2491).

2.3. IRAC and MIPS Imaging Data

We used Spitzer imaging data obtained with the IRAC (Fazio et al. 2004) and the MIPS (Rieke et al. 2004) instruments, as part of the GOALS legacy program (Armus et al. 2009). We retrieved the BCD from the Spitzer archive. The BCD processing includes corrections for the instrumental response (pixel response linearization, etc.), flagging of cosmic rays and saturated pixels, dark and flat fielding corrections, and flux calibration based on standard stars (see the IRAC and MIPS instrument handbooks for details). We combined the BCD images into mosaics using the MOSaicker and Point source EXtractor (MOPEX) software provided by the SSC using the standard parameters.

We obtained integrated photometry of our LIRGs using an elliptical aperture chosen to encompass the emission of each galaxy. This ellipse was calculated by fitting the emission of the galaxy (3\(\sigma\) over the background) in the IRAC 8 \(\mu\)m band. In this work we only used the IRAC 5.8 \(\mu\)m and MIPS 24 \(\mu\)m images (see Section 4.2). For the IRAC images we applied the extended source aperture correction (up to 25−35\% in the IRAC 5.8 \(\mu\)m band) to the integrated fluxes (see the IRAC Instrument Handbook) to account for the diffuse scattering of the emission across the IRAC focal plane.

3. ANALYSIS

3.1. AGN+SB Spectral Decomposition of IRS Spectra

The main goal of this work is to estimate quantitatively the AGN activity, both in terms of mid-IR detection and bolometric contribution, in a complete sample of local LIRGs. In this section we fit the Spitzer/IRS SL+LL spectra with a combination of SB and AGN templates. Our approach to estimate the AGN contribution is similar to other works in the literature (Nardini et al. 2008, 2010). Basically these methods hinge on the close similarity of the mid-IR spectra of high metallicity starbursts (see Brandl et al. 2006), and the strong differences in the spectral shape of AGN and SB emissions in this spectral range. This makes it possible to use templates to represent the SB and AGN activity (or a power-law continuum for the latter), and thereby make a spectral de-
composition of the observed mid-IR spectra of galaxies into SB and AGN components. The main difference between our method and that of Nardini et al. is that we use the entire spectral range of the SL+LL IRS spectra, ~5 – 38 µm, while they only used the 5 – 8 µm spectral range. In related works both Valiante et al. (2009) and Deo et al. (2009) derived the AGN contribution at different mid-IR wavelengths of samples of local LIRGs and Seyferts, respectively by subtracting a scaled SB template from the observed IRS spectra. We will compare our results with theirs in Section 4.1.

The AGN emission in the mid-IR is emission reprocessed by warm dust in the putative dusty torus that surrounds the AGN (Antonucci 1993). Instead of representing the AGN mid-IR emission as a power law (e.g., as done by Nardini et al. 2010) we used the Nenkova et al. (2008b) clumpy dusty torus models together with the BayesClumpy routine (Asensio Ramos & Ramos Almeida 2009, see the Appendix for more details) to fit the data. These torus models (implemented in the CLUMPY code) are found to reproduce well the nuclear near and mid-IR emission of local Seyfert galaxies and Seyferts, respectively by subtracting a scaled SB template from the observed IRS spectra. We will compare our results with theirs in Section 4.1.

Details of the AGN+SB decomposition method are given in Appendix A2. Figure 1 shows a few examples of the results of the AGN+SB best fits for four different LIRGs with increasing AGN contributions. MCG +02-001 shows no evidence for the presence of an AGN, while the mid-IR continuum emission of IC 4518W is dominated by the AGN component. NGC 5135 and NGC 7469 are intermediate cases. The AGN is clearly detected in NGC 5135, and dominates the ~6 µm emission within the IRS slit, but the SB component accounts for most of the continuum emission at λ > 15 µm. The AGN and SB components of NGC 7469 have similar contributions within the IRS slit up to ~20 µm, but then at >20 µm the SB component clearly takes over. The AGN+SB best fits for the rest of the sample are presented in Figures A1 and A2. For those galaxies requiring an AGN component to fit their IRS spectra, Table 2 gives the AGN contribution within the Spitzer/IRS slit to

The Nenkova et al. (2008b) clumpy torus models are defined by six parameters describing the torus geometry and the properties of the dusty clouds. In Appendix A1 we give a short description of the models. An additional parameter is the normalization needed to match the model to the observed IR data, which scales directly with the AGN bolometric luminosity $L_{bol}(AGN)$. Our use of these models depends on the scaling of the torus model and the AGN bolometric luminosity, rather than on the individual torus parameters. Alonso-Herrero et al. (2011) recently showed that the values of $L_{bol}(AGN)$ derived from the modeling of the nuclear near and mid-IR emission of local Seyfert galaxies with the CLUMPY models were in good agreement with literature estimates.

The AGN fractional contributions within the IRS slit from the AGN+SB decomposition are given in Table 2.

### Table 2

| Galaxy            | $C_{6.6\mu m}^{IRS}$ [AGN] | $C_{20\mu m}^{IRS}$ [AGN] | $C_{24\mu m}^{IRS}$ [AGN] | $C_{30\mu m}^{IRS}$ [AGN] |
|-------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| NGC 23            | 0.16                        | 0.10                        | 0.06                        | 0.02                        |
| NGC 633           | 0.15                        | 0.07                        | 0.03                        | 0.01                        |
| CGCG 468-002-NED01| 0.54                        | 0.83                        | 0.62                        | 0.79                        |
| UGC 3531          | 0.25                        | 0.15                        | 0.11                        | 0.06                        |
| NGC 2369          | 0.26                        | 0.16                        | 0.10                        | 0.04                        |
| NGC 3690          | 0.81                        | 0.70                        | 0.60                        | 0.47                        |
| MCG –02-33-098-W  | 0.09                        | 0.42                        | 0.33                        | 0.23                        |
| MCG –03-34-064    | 0.77                        | 0.93                        | 0.91                        | 0.85                        |
| NGC 5135          | 0.54                        | 0.26                        | 0.16                        | 0.09                        |
| UGC 08739         | 0.33                        | 0.14                        | 0.08                        | 0.03                        |
| NGC 5653          | 0.12                        | 0.10                        | 0.05                        | 0.02                        |
| NGC 5743          | 0.39                        | 0.28                        | 0.18                        | 0.09                        |
| IC 4518W          | 0.53                        | 0.71                        | 0.69                        | 0.60                        |
| NGC 5936          | 0.30                        | 0.13                        | 0.08                        | 0.04                        |
| NGC 5990          | 0.33                        | 0.30                        | 0.21                        | 0.12                        |
| NGC 6156          | 0.49                        | 0.73                        | 0.65                        | 0.57                        |
| IC 4687           | 0.12                        | 0.09                        | 0.05                        | 0.02                        |
| NGC 6701          | 0.25                        | 0.15                        | 0.08                        | 0.04                        |
| MCG +04-48-002    | 0.20                        | 0.40                        | 0.41                        | 0.34                        |
| NGC 7130          | 0.36                        | 0.26                        | 0.18                        | 0.11                        |
| NGC 7469          | 0.49                        | 0.52                        | 0.43                        | 0.34                        |
| NGC 7679          | 0.27                        | 0.33                        | 0.24                        | 0.15                        |
| NGC 7769          | 0.41                        | 0.29                        | 0.19                        | 0.13                        |
| NGC 7770          | 0.58                        | 0.40                        | 0.27                        | 0.15                        |
| NGC 7771          | 0.19                        | 0.09                        | 0.05                        | 0.02                        |
the continuum emission at four different reference wavelengths relatively free of features: 6, 20, 24, and 30 µm.

3.2. Line and Feature Measurements

Most of the galaxies in our sample of LIRGs were part of the compilation of Spitzer/IRS SH and LH fluxes of fine structure lines of [Ne ii] 12.81 µm and [Ne iii] 15.56 µm. For the fainter lines ([O IV] 25.89 µm and [Ne v]) the uncertainties are higher (15 – 30%), except in bright AGN as these lines are intense and the uncertainties are approximately 10%. The [O IV] 25.89 µm line fluxes (or upper limits) are given in Table 3, together with those of the [Ne ii] 12.81 µm and [Ne iii] 15.56 µm emission lines. Additionally we detected the [Ne v] 14.32 µm line in five galaxies in our sample not included in Pereira-Santaella et al. (2010b): CGCG 468-002-NE01, NGC 5990, NGC 6156, MCG +04-48-002, and NGC 7679 (see also Petric et al. 2011). Table 4 lists the [Ne v] 14.32 µm line detections for our complete sample of LIRGs.

To measure the apparent strength of the 9.7 µm silicate feature from the SL spectra we used the definition of Spoon et al. (2007), \( S_{9.7} = \ln(f_{\text{obs}}/f_{\text{cont}}) \) evaluated at 9.7 µm. To estimate the continuum emission we used the same method as Pereira-Santaella et al. (2010a), that is, we fitted a power law between the feature-free continuum pivots at 5.5 µm and 13 µm. We also measured the equivalent width (EW) of the 6.2 µm aromatic feature, also known as polycyclic aromatic feature (PAH). The local continuum was measured using a linear fit between 5.75 µm and 6.7 µm, and the feature was measured between 5.9 and 6.5 µm. Table 4 reports the values of \( S_{9.7} \) and EW(6.2 µm PAH) for our sample of LIRGs. For objects with the silicate feature in emission \( S_{9.7} \) is positive, whereas it is negative for objects with the feature in absorption.

4. RESULTS FROM THE DECOMPOSITION OF THE SPITZER/IRS SPECTRA

4.1. AGN Dust Emission within the Spitzer/IRS Slits

Using the AGN+SB spectral decomposition of the IRS low-resolution data we detected an AGN component in half of the LIRGs in our sample (25/50) with available data. Table 2 gives the AGN fractional contribution within the slit at 6, 20, 24, and 30 µm for each of them. Figure 2 shows the distributions of the AGN fractional...
Also marked are the medians of the AGN fractional contributions within the Spitzer IRS slit at the common continuum wavelengths, while the non-detections are shown as empty histograms. Spitzer detections distributions within the 24 µm (upper panel). The AGN detections are shown as filled histograms, while the non-detections are shown as empty histograms. Also marked are the medians of the AGN fractional contribution (detections) distributions within the Spitzer/IRS slit (see Table 5).

![Graph](image)

**Fig. 2.** Distributions of the AGN fractional contributions within the Spitzer/IRS slit of local LIRGs at 6 µm (lower panel) and 24 µm (upper panel). The AGN detections are shown as filled histograms, while the non-detections are shown as empty histograms. Also marked are the medians of the AGN fractional contribution (detections) distributions within the Spitzer/IRS slit (see Table 5).

Contributions within the IRS slit at two of the reference continuum wavelengths. On average the AGN fractional contribution within the IRS slits is relatively small, as can be seen from Table 2. There are only six galaxies with a dominant AGN contribution within the IRS slit at the four reference continuum wavelengths: CGCG 468-002-NED01, MCG -03-34-064, IC 4518W, NGC 6156, NGC 7469, and NGC 3690.

For the sample of LIRGs the median values of the AGN fractional contributions tend to be similar at 6 and 20 µm for our sample (median $C_{6\mu m}^{\text{AGN}} \approx C_{20\mu m}^{\text{AGN}} = 0.3$, see Table 5), although individual galaxies show larger variations. For the majority of local LIRGs, the AGN fractional contributions decrease significantly at $\lambda > 20 - 30$ µm, as also found in local Seyfert galaxies (Deo et al. 2009) and X-ray selected AGNs (Mullaney et al. 2011).

The median value of the AGN fractional contribution at 24 and 30 µm for the LIRGs with AGN detections are $C_{24\mu m}^{\text{AGN}} = 0.18$ and $C_{30\mu m}^{\text{AGN}} = 0.11$, respectively. For the four Seyfert galaxies in our sample in common with Deo et al. (2009), the AGN fractional contributions within the IRS slit at the common continuum wavelengths are in good agreement.

The fractional AGN contributions listed in Table 2 can also be used to get a rough estimate of the sensitivity of our AGN+SB decomposition method to the presence of a low-luminosity AGN. As discussed in the Appendix, we only considered an AGN detection when its contribution was greater than 5 – 7% at 20 µm. Therefore it appears that our fitting method can only detect an AGN for fractional contributions $C_{20\mu m}^{\text{AGN}} \gtrsim 0.15$, $C_{24\mu m}^{\text{AGN}} \gtrsim 0.05$ and $C_{30\mu m}^{\text{AGN}} \gtrsim 0.02 – 0.04$.

Valiante et al. (2009) estimated the AGN emission at 6 µm of a sample of LIRGs by subtracting a SB template from the observed spectra in a much more limited spectral range, 5.6 – 6.9 µm. They employed the M82 spectrum and the average spectrum of Brandl et al. (2006), the latter to account for the dispersion of properties in star-forming galaxies. Both templates tend to have a lower 6 µm continuum than the LIRG templates of Rieke et al. (2009). A large fraction of the galaxies in our sample were included in their work. For the AGN detections we find a relatively good agreement, within 10 – 50% of each other, for the AGN flux densities at 6 µm. The largest discrepancy is for NGC 5135 for which the Valiante et al. (2009) upper limit is well below our estimate. Apart from our much broader spectral range, the differences may also arise from the different SB templates. We found a similar behavior from our fits. In those cases where we obtained comparable fits with the Brandl et al. (2006) average spectrum and the LIRG 11.50L$_{\odot}$ template, the AGN fractional contribution within the IRS slit at 6 µm using the latter template was lower, almost by a factor of two, than using the former. For those galaxies for which Valiante et al. (2009) did not detect an AGN component, our estimated AGN 6 µm flux densities are compatible with their upper limits.

### Table 3

**New IRS SH+LH Line Fluxes.**

| Galaxy              | [O IV] | [Ne II] | [Ne III] |
|---------------------|-------|--------|---------|
| ESO 297-G012        | 1.09  | 46.68  | 12.38   |
| UGC 02982           | 1.58  | 75.13  | 9.07    |
| CGCG 468-002-NED01  | 8.98  | 0.01   | 7.47    |
| CGCG 468-002-NED02  | < 1.07| 43.32  | 5.91    |
| ESO 264-G057        | 0.91  | 46.67  | 3.52    |
| ESO 173-G015        | < 1.97| 224.85 | 27.34   |
| IC 4280             | < 0.18| 50.76  | 3.76    |
| UGC 08739           | < 0.77| 28.85  | 4.12    |
| ESO 221-IG010       | 2.18  | 86.74  | 11.81   |
| NGC 5990            | 11.77 | 61.92  | 17.86   |
| NGC 6156            | 6.96  | 35.47  | 10.73   |
| IRAS 17578−0400     | < 0.98| 56.29  | 11.46   |
| MCG +04-48-002      | 8.42  | 93.19  | 20.00   |
| NGC 7679            | 34.1  | 77.29  | 30.05   |
| NGC 7770            | < 0.8 | 30.82  | 7.82    |

Notes.— Fluxes are in units of $10^{-17}$ W m$^{-2}$.
The extent of the mid-IR emission of LIRGs shows no clear dependence on the IR luminosity of the system; some galaxies show relatively compact emission (~1 kpc), while others show extended emission over a few kpc (Soifer et al. 2001; Alonso-Herrero et al. 2000b; Diaz-Santos et al. 2008; Pereira-Santaella et al. 2010a). It is only at the high luminosity end of LIRGs (log(L(IR)/L⊙) > 11.80) and in ULIRGs, that the mid-IR emission starts appearing very compact (Soifer et al. 2000; Diaz-Santos et al. 2010). Moreover, the extent of the emission may depend markedly on the wavelength of the emission. For instance, several studies found that in LIRGs and star-forming galaxies the PAH emission tends to be more extended than the mid-IR continuum (see e.g. Helou et al. 2004; Alonso-Herrero et al. 2000b; Pereira-Santaella et al. 2010a). The IRS slits do not generally cover the full extent of the galaxies. For the median distance of our LIRGs the ~ 13′′ slits cover approximately the central 4 kpc. In this section we derive the AGN contribution to the total emission at two continuum wavelengths. To do so, we measured the total galaxy emission in the mid-IR using Spitzer imaging at two wavelengths IRAC 5.8 μm and MIPS 24 μm. The integrated flux densities were then compared with the AGN emission at these wavelengths from the AGN+SB decomposition. Table 4 lists the AGN contribution to the 6 and 24 μm total emission, C_{6/24μm}[AGN] and C_{6/24μm}[AGN] are the AGN fractional contributions to the total 6 and 24 μm emission, respectively. [OIV]/[NeII] is the observed line ratio, with typical uncertainties of 10% for bright AGN, and 15 − 30% for the rest. The EW of the 6.2 μm PAH feature is measured in μm, and the typical uncertainties are 0.05 μm. S_FIR is the apparent strength of the 9.7 μm silicate feature and the typical uncertainties are 0.02. * The integrated flux density is from IRAS 25 μm converted to MIPS 24 μm.

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for those LIRGs dominated by the AGN contribution. It is possible that the IRAC 3.6 μm maps include a significant contribution from the 6.2 μm PAH feature (see Helou et al. 2004, and references therein), as well as some photospheric emission. Additionally, the emission from CLUMPY torus models is expected to be mostly isotropic at 24 μm, whereas that might not be the case at 6 μm for obscured views (i.e., type 2) of the AGN (see e.g., Nenkova et al. 2008b).

In summary, only in 6% (3/50) of local LIRGs is the mid-IR emission dominated by the AGN (C_{24μm}^{AGN} > 0.5). About one-quarter of the sample (12/50) have intermediate AGN contributions (C_{24μm}^{AGN} = 0.1 – 0.5), while the remaining ~ 70% (35/50) have little (C_{24μm}^{AGN} ≃ 0.04 – 0.1) or no AGN contribution in the mid-IR.

5. COMPARISON WITH OTHER AGN DIAGNOSTICS

5.1. Spectroscopic Activity Class

The nuclear activity (AGN versus star formation activity) of local LIRGs has been the subject of numerous studies using optical spectroscopy (see among others, Veilleux et al. 1995, Wu et al. 1998, Kewley et al. 2001; Alonso-Herrero et al. 2009a; Yuan et al. 2010). These works made use of the classical optical spectral diagnostic diagrams (Veilleux & Osterbrock 1987) and/or the more recent classification scheme based on observations of large numbers of galaxies and modeling (Kauffmann et al. 2003; Kewley et al. 2006). Table 1 lists the spectral activity class for the 53 galaxies in our sample and the relevant references. Out of the 42 individual LIRGs with an optical class there are: 17 pure HII-like nuclei, 15 composite (AGN/SB) nuclei, and 10 AGN (Seyfert 1, Seyfert 2, LINER). Two more LIRGs do not have an optical class but have [Ne v] detection and high [O iv]25.89 μm/[Ne ii]12.81 μm ratios (Table 4, and see also Petric et al. 2011), and thus are clearly AGNs. Finally, NGC 5743 and MCG+04-48-002 were optically classified as HII, but both have a [Ne v] detection. Both have also relatively low [O iv]25.89 μm/[Ne ii]12.81 μm ratios, which are typical of star-forming galaxies (see Table 4 and Section 5.4). Therefore, although these two galaxies do contain an AGN, they are likely to be composite in nature. The rest (7 LIRG nuclei) do not have an optical classification. In summary, 23% of our sample are AGNs, 32% are HII-like, 32% are AGN/SB composites, and the remaining 13% do not have a spectral classification.

As can be seen from Table 4, all 13 LIRGs with an optical classification as Seyfert nuclei and/or a [Ne v] detection have an AGN component detected through the AGN+SB decomposition of the IRS spectra. The AGN contributions at 24 μm for these vary from 7% for UGC 3351 to almost 90% for MCG −03-34-064. Among the 14 optically composite nuclei with IRS spectra, 8 have an AGN component detected with AGN contributions at 24 μm in the range 4−28%. Three of the 15 pure HII nuclei have an AGN component, but with a small AGN contribution at 24 μm except for NGC 7770.

TABLE 5

| Quantity          | Mean | Median | 16th – 84th |
|-------------------|------|--------|-------------|
|                   |      |        |             |
| C_{24μm}^{AGN}    | 0.36 | 0.33   | 0.16 – 0.54 |
| C_{24μm}^{SB}     | 0.28 | 0.18   | 0.06 – 0.65 |
| C_{24μm}^{total}  | 0.21 | 0.11   | 0.02 – 0.57 |

Notes.— The columns are the mean, median (50-th percentile), and the 16-th and 84-th percentiles. The numbers in the last column are the 68% confidence interval. This would be equivalent to ±1σ of the distribution around the mean value in a normal distribution.

![Fig. 3. Upper panel. Distribution of the [O iv]25.89 μm emission line luminosities (detections and upper limits) of our sample of local LIRGs. The filled histograms correspond to those LIRGs with an AGN detection using optical and mid-IR methods. The arrows mark the upper limits to the [O iv]25.89 μm luminosity in each bin. Lower panel. Comparison between the observed [O iv]25.89 μm luminosities and the IR luminosities of local LIRGs. The solid line is the relation expected for purely star-forming galaxies derived by Pereira-Santaella et al. (2010a) (see text for details), while the dotted lines are the ±1σ dispersion of the relation. The LIRG observations are color coded according to the AGN contribution to the integrated 24 μm emission: C_{24μm}^{AGN} > 0.5, C_{24μm}^{AGN} = 0.1 – 0.5, and C_{24μm}^{AGN} = 0.04 – 0.1, and the AGN non-detections, for which C_{24μm}^{AGN} ≤ 0.02 – 0.05.](image-url)
5.2. AGN Bolometric Luminosities and Comparison with X-ray Estimates

The AGN bolometric luminosities derived from the torus model fits (Section 3.1) are between 0.4 and 50 \times 10^{43} \text{ erg s}^{-1}, with a median value of \( L_{\text{bol}}[\text{AGN}] = 2 \times 10^{43} \text{ erg s}^{-1} \). Galaxies classified as Seyferts tend to show the highest values of \( L_{\text{bol}}[\text{AGN}] \), whereas the non-Seyferts have a median value of \( L_{\text{bol}}[\text{AGN}] \sim 1 \times 10^{43} \text{ erg s}^{-1} \). The AGN bolometric contribution to the IR luminosity of the individual nuclei range between 1 and 70%, with an average value of \( L_{\text{bol}}[\text{AGN}]/L_{\text{IR}} = 12\% \) (median of 5\%) for those LIRGs with an AGN detection (see Table 5). For the AGN non-detections we estimate that if an AGN is present its bolometric contribution would be \( L_{\text{bol}}[\text{AGN}]/L_{\text{IR}} < 1\% \).

Pereira-Santaella et al. (2011) studied the X-ray emission of a representative, in terms of \( L_{\text{IR}} \) and nuclear activity, sample of local LIRGs drawn from the sample presented in this paper. Table 6 lists the eight Seyfert galaxies with those obtained by Pereira-Santaella et al. (2011) from the hard 2 – 10 keV luminosities, as well as with the values derived from the luminosity of the 6.4 keV FeKα line for the Compton-thick sources. The AGN bolometric luminosities were computed using the bolometric corrections of Marconi et al. (2004). All these values are listed in Table 6. The last column in Table 6 gives the differences of the two estimates (taken in logarithmic units) of the AGN bolometric luminosity, which are on average 0.4 dex. This is similar to the differences in bolometric luminosity estimates found by Alonso-Herrero et al. (2011) for a sample of nearby Seyferts. We excluded NGC 7679 because it appears to be highly variable in X-rays (see the discussions by Della Ceca et al. 2001 and Pereira-Santaella et al. 2011).

From the upper limits of the luminosity of the hard X-ray FeKα emission line, Pereira-Santaella et al. (2011) concluded that in the rest of their sample, if there is an AGN the bolometric luminosity should be \( < 10^{43} \text{ erg s}^{-1} \). This is again consistent with the typical AGN bolometric luminosities for the non-Seyfert LIRGs in our sample.

5.3. The \([\text{O} \text{iv}]/25.89 \mu \text{m} \) High Excitation Line

AGNs can be readily identified in the mid-IR via the detection of high-excitation emission lines (see e.g. Genzel et al. 1998; Sturm et al. 2002; Meléndez et al. 2008), especially the \([\text{Ne} \text{v}]/14.32 \mu \text{m} \) and \([\text{Ne} \text{v}]/24.32 \mu \text{m} \) lines. These are unlikely to be produced by star formation, but they are not always detected in relatively bright AGNs (see Weedman et al. 2005; Pereira-Santaella et al. 2010b). The detection rate of the \([\text{Ne} \text{v}]/14.32 \mu \text{m} \) line in our complete sample of local LIRGs is \( \sim 22\% \) (11/50), as can be seen from Table 4.

Because the \([\text{O} \text{iv}]/25.89 \mu \text{m} \) emission line has a lower ionization potential (54.9 eV) than the \([\text{Ne} \text{v}]/24.32 \mu \text{m} \) line (97.1 eV), the mid-IR oxygen line is detected in a larger fraction of known AGNs (Pereira-Santaella et al. 2010b). Moreover, the \([\text{O} \text{iv}]/25.89 \mu \text{m} \) line appears to be a good indicator of the AGN power (Meléndez et al. 2008; Diamond-Stanic et al. 2009; Rigby et al. 2009), although it can also be produced in star-forming galaxies (Lutz et al. 1998; Pereira-Santaella et al. 2010b). The \([\text{O} \text{iv}]/25.89 \mu \text{m} \) line is detected in 70\% of our sample of local LIRGs (35/50 of the individual nuclei with IRS LH spectra available). In this statistic we include NGC 3256 and IC 694 for which the line was detected using IRS staring mode spectra by Bernard-Salas et al. (2009) and Alonso-Herrero et al. (2009b), respectively.
The detection rate in the GOALS\textsuperscript{10} LIRG sample (53%) of their sources, see [Petric et al. 2011] is slightly lower than in our sample. By comparison the [O\textsc{iv}]25.89 \µm line is detected in \(~26\%\) of the ULIRGs studied by Veilleux et al. (2009), but mostly in those galaxies classified as Seyfert and LINER. The detection of this line in the Farrah et al. (2007) ULIRG sample is just under 50%.

In terms of the spectral class the [O\textsc{iv}]25.89 \µm line is detected in all (11) of those galaxies optically classified as AGN, that is, Seyferts and/or [Ne\textsc{v}]14.32 \µm detections. Eleven of the 17 galaxies optically classified as composites also show [O\textsc{iv}]25.89 \µm emission. Interestingly, eight LIRGs optically classified as H II-like galaxies are detected in [O\textsc{iv}]25.89 \µm, but have no evidence of a hot dust component from the IRS AGN+SB decomposition analysis.

Figure 3 (upper panel) shows the distribution of the [O\textsc{iv}]25.89 \µm luminosities of our sample. We also show in this figure as filled histograms those LIRGs with an AGN detection, including Seyferts, composites, [Ne\textsc{v}]14.32 \µm detections and LIRGs with an AGN component from the AGN+SB decomposition. It is clear from this figure that all the LIRGs with \(L_{\text{[OIV]}} \geq 10^7 \text{L}_\odot\) have an AGN detected. For the merger LIRG NGC 3256 we plotted here our upper limit from the IRS spectral mapping data, but the flux measurement of Bernard-Salas et al. (2009) from an IRS staring mode spectrum provides a luminosity of \(L_{\text{[OIV]}} \approx 6 \times 10^6 \text{L}_\odot\). At luminosities \(\sim 10^5 \text{L}_\odot \leq L_{\text{[OIV]}} \leq 10^7 \text{L}_\odot\) approximately 50% of the LIRGs are found to host an AGN.

As mentioned above the [O\textsc{iv}]25.89 \µm line appears to be a good indicator of the AGN power. For those LIRGs with an AGN detection we compare in Figure 4 \(L_{\text{[OIV]}}(\text{AGN})\) from the IRS spectral decomposition and the observed \(L_{\text{[OIV]}}\). The values for LIRGs with AGN detections are between those observed in Seyfert 1 and Seyfert 2 galaxies from the Revised Shapley-Ames (RSA) sample (Rigby et al. 2009), and thus consistent with the [O\textsc{iv}]25.89 \µm emission being produced mostly by the AGN.

The [O\textsc{iv}]25.89 \µm line can also be produced by star formation if the AGN contribution to the total luminosity of the galaxy is below 5% (Pereira-Santaella et al. 2010\textsuperscript{10}). This is indeed the case for non-AGN detections in our sample as we showed in Section 5.2. In Figure 3 (lower panel) we compare the observed [O\textsc{iv}]25.89 \µm luminosities with those expected from pure star-formation activity following Pereira-Santaella et al. (2010). We used the typical [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm line ratios for high metallicity starbursts (Veerm, 2003) and the empirical relation between the [Ne\textsc{ii}]12.81 \µm luminosity and \(L_{\text{IR}}\) (Ho & Keto 2007) to predict the [O\textsc{iv}]25.89 \µm luminosity due to star formation. As can be seen from Figure 3, all the galaxies with no AGN component detected through the AGN+SB decomposition are consistent with pure star formation. On the other hand, all the galaxies but one with \(C_{\text{[24\µm]}}^{\text{tot}}(\text{AGN}) > 0.1\) are more than 1\(\sigma\) above the relation expected for star formation. Moreover, for all galaxies with \(L_{\text{[OIV]}} \geq 10^7 \text{L}_\odot\), this emission line is mostly produced by the AGN, rather than by star formation.

5.4. The \([O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81\) versus EW(6.2 \µm PAH) Diagram

Diagnostic diagrams comparing the [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm line ratio with the EW of one of the mid-IR PAH features are commonly used to assess the AGN contribution to the IR emission of galaxies (see e.g. Genzel et al. 1998, Dale et al. 2000). In particular, this diagram has been used for ULIRGs (Farrah et al. 2007, Armus et al. 2007, Veilleux et al. 2009 and LIRGs (Petric et al. 2011). This is because the [Ne\textsc{ii}]12.81 \µm line is expected to be produced mostly by star formation, while the [O\textsc{iv}]25.89 \µm line tends to be more luminous in AGNs (Pereira-Santaella et al. 2010). In this section we will assess if this diagram and the AGN fraction of the total 24 \µm emission provide consistent results.

Figure 5 presents this diagram for our sample, where the galaxies have been color coded according to the AGN contribution at 24 \µm. We also show in this diagram a mixing curve of pure star formation and pure AGN emission. For the pure AGN emission we used the median [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm line ratio for Seyfert galaxies 2.0 \pm 1.2 (Pereira-Santaella et al. 2010\textsuperscript{10}) and EW(6.2 \µm PAH)= 0.1 \µm. For the pure star formation we used the average value for high-metallicity starbursts without AGN detections observed by IS\textsc{o} in the sample of Verma et al. (2003), [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm=0.011. We also use the median value EW(6.2 \µm PAH)= 0.54 \pm 0.07 \µm (see Table 4) of the HII-like LIRGs with no AGN detection for the pure star formation value.

It is clear from Figure 5 that the AGN fractions derived from this diagram are entirely consistent with the AGN contribution to the total 24 \µm emission. For instance, the three galaxies with \(C_{\text{[24\µm]}}^{\text{tot}}(\text{AGN}) > 0.5\) have [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm > 1 and small values of the EW, which correspond to > 50\% AGN fractions in the simplistic mixing curve plotted in this figure. Most LIRGs with \(C_{\text{[24\µm]}}^{\text{tot}}(\text{AGN}) = 0.1 – 0.5\) have [O\textsc{iv}]25.89 \µm/[Ne\textsc{ii}]12.81 \µm ratios consistent with AGN fractions of 5-50\%. Those LIRGs with small AGN contributions (\(C_{\text{[24\µm]}}^{\text{tot}}(\text{AGN}) < 0.1\)) tend to have values of the line ratio and the EW consistent with those observed in nuclear and extra-nuclear star-forming regions (e.g., Dale et al. 2006). On the other hand, the observed value of EW(6.2 \µm PAH) by itself is only found to be a good indicator of the nuclear activity when the AGN contribution is dominant \(C_{\text{[24\µm]}}^{\text{tot}}(\text{AGN}) > 0.5\). For intermediate AGN contributions there is a range of observed values of the EW of the 6.2 \µm PAH feature, and thus deriving the AGN contribution is not so readily done.

5.5. The Spoon et al. (2007) Diagram

Spoon et al. (2007) put forward a diagram comparing the EW of the 6.2 \µm PAH feature and the strength of the 9.7 \µm silicate feature to provide a general classification of IR galaxies. This diagram has proven useful to assess the presence of an AGN not only for local galaxies, but also for high-z IR bright galaxies (e.g., Farrah et al. 2007)
Fig. 5.— [O\text{iv}\]25.89 $\mu$m/[Ne\text{ii}\]12.81 $\mu$m line ratio versus EW(6.2 $\mu$m PAH) diagram for our sample of LIRGs, which are color coded according to the AGN contribution to the integrated 24 $\mu$m emission, as in Figure 3. The solid line is a mixing curve between pure star formation and pure AGN emission (see text for details), whereas the dotted lines represent the 1$\sigma$ dispersion in the [O\text{iv}\]25.89 $\mu$m/[Ne\text{ii}\]12.81 $\mu$m line ratio for Seyfert galaxies and EW(6.2 $\mu$m PAH) feature for purely star-forming galaxies. The percentage numbers on the curves indicate the AGN contribution.

Fig. 6.— Apparent strength of the silicate feature $S_{\text{Si}}$ versus EW(6.2 $\mu$m PAH) for our LIRGs color coded as in Figure 3. If $S_{\text{Si}}$ is positive the silicate feature is in emission, and if $S_{\text{Si}}$ is negative the feature is in absorption. The regions shown in the diagram correspond to those defined by Spoon et al. (2007) for their sample of ULIRGs. Class 1A is occupied by unobscured AGNs, class 1C by starburst galaxies (i.e., PAH-dominated galaxies), and class 1B by composite (AGN/SB activity) galaxies. Classes 2A through 2C are moderately obscured galaxies with increasing EW(6.2 $\mu$m PAH). Classes 3A through 3C (not shown here) represent the most deeply embedded objects, although no ULIRGs are found in class 3C.
Figure 7.— Number of AGN detections (shaded histograms) as a function of the IR luminosity of the galaxy for the 53 individual nuclei of our volume-limited sample of local LIRGs (open histograms). The galaxies have been divided into three luminosity bins. The light grey shaded histograms correspond to detections based on the IRS spectral decomposition, while the dark shaded histograms are LIRGs optically classified as AGNs but not detected from the AGN+SB decomposition.

Figure 6 shows the Spoon et al. diagram for our sample of LIRGs, where the galaxies are color-coded according to the AGN contribution at 24 µm. Pereira-Santaella et al. (2010a) presented this diagram for the nuclei, integrated emission, and spatially resolved measurements of those LIRGs in our sample observed in spectral mapping mode.

On the Spoon et al. diagram a large fraction (40%) of the LIRGs appear mostly concentrated in the region occupied by starburst galaxies or class 1C. Approximately 25% are in class 1B, which is where composite (AGN/SB activity) galaxies are located. Only one LIRG is in the region of unobscured AGNs (Seyfert 1s and quasars) or class 1A, which typically tend to show low values of the EW of the PAH features (Roche et al. 1991; Rigopoulou et al. 1999; Buchanan et al. 2006; Tommasin et al. 2008). The rest of the sample, approximately 30%, lie in those regions occupied by moderately obscured nuclei (−2 < SSi < −0.8), classes 2B and 2C. Only one LIRG is in region 2A. There are no deeply embedded (SSi < −2) nuclei among the LIRGs in our sample. On this diagnostic diagram ULIRGs are mostly located along two branches. The first one is a horizontal branch that goes from class 1A to class 1C, and the second is a diagonal going from class 3A, which are deeply obscured nuclei (not shown here), to class 1C (see Spoon et al. 2007, for more details).

The Spoon et al. diagnostic diagram for LIRGs only provides a relatively good separation between AGN-dominated LIRGs, LIRGs with intermediate AGN contributions and LIRGs with very little or no AGN contribution. Only one of the galaxies dominated by the AGN emission (C_{24\mu m}^{\text{AGN}} > 0.5) appears in the 1A class, whereas the other two are in the composite region and in the 2A class. Most of those with intermediate AGN contributions (C_{24\mu m}^{\text{AGN}} = 0.1 - 0.5) are in the composite region, as expected. However, two of them appear in region 1C, which is that occupied by PAH-dominated galaxies. Those with little (C_{24\mu m}^{\text{AGN}} = 0.1 - 0.04) or no AGN contribution are mostly either in the 1C region (starburst region), or near the border between class 2B and class 2C, and therefore are not easily identified as having an AGN from this diagram.

It is interesting to note here that the Nenkova et al. (2008a,b) clumpy torus models never produce a very deep silicate feature (i.e., the models have S_Si ≥ −1). This means that for deeply embedded galaxies the AGN templates used here (see discussion by Levenson et al. 2007) may not be appropriate and an AGN component might be missed. For instance two galaxies with relatively deep silicate features, IC 694 and MCG+02-20-003, are classified as LINER and composite, respectively, but an AGN component has not been detected through our spectral decomposition fit. However, it is important to note here that deeply embedded sources are rare among local LIRGs.

6. DISCUSSION

6.1. AGN Detection Rate in Local LIRGs

In this section we summarize the results of Sections 4 and 5 in terms of the AGN detection rate in our complete volume-limited sample of local LIRGs and investigate any possible dependence with the IR luminosity. We also compare the AGN detection rate in LIRGs with other types of galaxies.

Out of the 50 galaxies with IRS spectroscopy we detected an AGN component in 25 using the AGN+SB spectral decomposition (see Table 2, and Figures 1 and A1). An additional eight galaxies are classified spectroscopically as composite or LINER. Of these, one did not have IRS spectroscopy (the IRS spectrum of NGC 1614 was not well centered) and for the remaining seven the AGN was not detected based on our spectral decomposition (UGC 1845, MCG +02-20-003, IRAS 17138−1017, IC 694, NGC 5734, NGC 7591, Zw049.057). This brings the combined optical+IR AGN detection rate in the individual nuclei of our sample of LIRGs to ~62%. In terms of the 45 IRAS systems, an AGN is found in 32, that is, ~70%. This AGN detection rate is in good agreement with that derived from optical emission lines (Yuan et al. 2010) and X-ray emission (Risaliti et al. 2004; Pereira-Santaella et al. 2011).

Figure 7 shows the number of AGN detections for the individual nuclei of our sample of LIRGs in three IR luminosity bins. As can be seen from this figure, the AGN detection rate stays approximately constant at a ~60−65% rate for the three luminosity bins log(LIR/L_⊙) < 11, log(LIR/L_⊙) = 11−11.3 and log(LIR/L_⊙) = 11.3−11.7. Petric et al. (2011) have conducted a study similar to ours using the GOALS sample of 248 LIRGs. They identified AGN through [Ne v]14.32 µm detections in 18% of their sample, virtually identical to the 22% detection rate for us. They also detected [O iv]25.89 µm in 53% of their galaxies, whereas we detected it in 70% (see Section 5.3). They do not count the [O iv] detections as AGN, whereas we find that many of these galaxies do indeed harbor active nuclei (from the spectral decomposition and/or optical class, see Section 5.3). Petric et al. (2011) also used the EW of the 6.2 µm aromatic feature and the 5 to 15 µm continuum flux ratios as AGN indicators, and concluded
that \( \sim 10\% \) of their sample are dominated by AGN in the mid-IR. We find that \( \sim 6\% \) (Table 4) of our sample have a mid-IR AGN contribution greater than 50% of the total luminosity at 24 \( \mu \)m. The difference may arise from slightly different methodologies, but both studies agree that the AGN plays a substantial role in the mid-IR energetics only in a relatively small minority of these galaxies. However, we also find that 50% of the galaxies in our sample contain AGNs, based on our mid-IR spectral decomposition method, and \( \sim 60\% \) if we combine optical and mid-IR indicators. Our ability to find many more AGNs than Petric et al. (2011) did in the larger but similar sample suggests that our spectral decomposition method is a powerful way to identify subtle AGN features. As a result, we can show that AGNs accompany star formation activity in a large proportion of local LIRGs, although in most cases the AGNs are not energetically important.

The AGN detection rate in local LIRGs is very similar to that of local ULIRGs. The latter is found to be 70% on average using mid-IR diagnostics (Imanishi et al. 2007; Nardini et al. 2010). In lower luminosity galaxies AGNs are detected in much smaller fractions. For instance, in the optically-selected RSA sample Maiolino & Rieke (1995) found a 5 – 16% AGN incidence, based on optical indicators. The AGN fraction in nearby (\( d < 15 \) Mpc) moderately IR luminous galaxies (\( L_{\text{IR}} \geq 10^9 L_\odot \)) is slightly higher, 27%, when including [Ne v]14.32 \( \mu \)m detections, as demonstrated by Goulding & Alexander (2009).

6.2. AGN Bolometric Contribution in Local LIRGs

Although the combined optical+IR AGN detection rate in local LIRGs is relatively high, \( \sim 62\% \), and only slightly less than in local ULIRGs, the important quantity is the AGN bolometric contribution to the IR luminosity of the galaxies. Using the AGN bolometric luminosities derived from the spectral decomposition (Section 5.2), we can derive the AGN bolometric contribution to the total IR luminosity of local LIRGs (both with and without AGN detections). We find that AGNs contribute \( 5^{+8}_{-3}\% \) of the IR luminosity\(^{11}\). The upper and lower limits take into account the uncertainties in the derived AGN bolometric luminosities. For the 9 galaxies with an AGN optical classification but no AGN emission detected from the AGN+SB decomposition, we assumed the typical AGN bolometric luminosity of the composite sources (see Section 5.2). This estimate proves that the bulk of the IR luminosity of local LIRGs is due to star formation activity.

Our estimate of the AGN contribution to the total IR luminosity of LIRGs is in excellent agreement with that estimated from the X-ray properties of the representative sample studied by Pereira-Santaella et al. (2011). Petric et al. (2011) estimated that AGN supply \( \sim 12\% \) of the total energy emitted by the GOALS LIRGs, which is compatible with our upper limit of the AGN contribution.

Taking the newly determined IR luminosity density produced by LIRGs in the local universe of \( \Omega_{\text{IR}} = 6 \times 10^6 L_\odot \) Mpc\(^{-3}\) (Goto et al. 2011), we estimate that the AGN IR luminosity density in the LIRG luminosity range is \( \Omega_{\text{AGN}} = 3^{+5}_{-2} \times 10^6 L_\odot \) Mpc\(^{-3}\). Our estimate of the AGN IR luminosity density is about seven times lower than that of Goto et al. (2011), probably because these authors assumed that in those LIRGs classified as active galaxies and especially those classified as composite the IR luminosity is entirely due to the AGN.

Finally, we can also compare \( C_{6\mu\text{m}}[\text{AGN}] \) and \( C_{24\mu\text{m}}[\text{AGN}] \) with the AGN bolometric contribution to the IR luminosity of the galaxies (Figure 8). The relation between the AGN contribution in the mid-IR and the AGN bolometric contribution is slightly bet-

\(^{11}\) Strictly speaking, this is just an upper limit to the AGN contribution because we are assuming that in LIRGs \( L_{\text{bol}}(\text{AGN}) \sim L_{\text{IR}}(\text{AGN}) \).
ter at 24 μm than at 6 μm. As explained above, the IRAC 5.8 μm images of some LIRGs may include a sizable contribution from the 6.2 μm PAH feature, and/or the 6 μm emission of type 2 AGNs might not be fully isotropic. It can also be seen from Figure 8 that, although \( C_{24 \mu m}^{AGN} \) and \( L_{bol}^{AGN}/L_{IR} \) do not follow a 1:1 relation, the relation is nearly linear. On average \( C_{24 \mu m}^{AGN} = (2.9 \pm 1.6) \times L_{bol}^{AGN}/L_{IR} \). We conclude that estimating the AGN fraction at 24 μm is a good proxy for the bolometric AGN contribution in LIRGs. Moreover, because the fractional AGN contribution is on average higher in the mid-IR than bolometrically, the mid-IR spectral range is very appropriate to study the fractional AGN/SB contribution. Wu et al. (2011) reached a similar conclusion for a sample of IR luminous galaxies at \( z \sim 0.3 \).

6.3. Comparison with Local ULIRGs and high-\( z \) IR bright galaxies

We summarize the AGN bolometric contribution for our sample of local LIRGs (with and without AGN detections) in Figure 9. We also compare in this figure our estimates for local LIRGs with those for local ULIRGs of Nardini et al. (2010). This comparison is meaningful because both our work and that of Nardini et al. quantify the AGN bolometric luminosities. In this figure we separated the AGN bolometric contributions \( L_{bol}^{AGN}/L_{IR} \) in three ranges: < 0.05, 0.05 – 0.25, > 0.25. In approximately one-third of local LIRGs the AGN bolometric contribution is mild, \( L_{bol}^{AGN}/L_{IR} \geq 0.05 \). Only \( \sim 8\% \) of local LIRGs have a significant AGN contribution, \( L_{bol}^{AGN}/L_{IR} > 0.25 \).

It is clear from Figure 9 that the fraction of galaxies with \( L_{bol}^{AGN}/L_{IR} > 0.25 \) increases at higher \( L_{IR} \), going from 30% in local LIRGs to \( \sim 50\% \) to ULIRGs with \( L_{IR} < 3 \times 10^{12} L_{\odot} \). However, it is only at \( L_{IR} > 5 \times 10^{12} L_{\odot} \) that the AGNs start dominating bolometrically the IR luminosity in a large fraction of local ULIRGs; 40% of ULIRGs in the high luminosity bin in Figure 9 have \( L_{bol}^{AGN}/L_{IR} > 0.60 \) (see Figure 9 of Nardini et al. 2010).

In summary, in the local universe there is an increasing bolometric contribution from AGNs at higher IR luminosities, going from 5% in LIRGs to an average of 27% in ULIRGs (Nardini et al. 2010) and 35 – 40% for the 1 Jy ULIRG sample (Veilleux et al. 2009). While the trend for an increased AGN bolometric dominance at high IR luminosities is well established locally, at high-\( z \) it is still a matter of debate. For instance, Valiante et al. (2009) needed to introduce an evolution in the AGN contribution to model the submillimeter to mid-IR number counts and redshift distribution of high-\( z \) IR galaxies. In particular they found that at a given IR luminosity high-\( z \) IR galaxies needed a smaller AGN contribution than locally. This is in line with results of Fadda et al. (2010) using deep mid-IR spectroscopy of \( z \sim 1 \) LIRGs and \( z \sim 2 \) ULIRGs. In both populations the fraction of AGN dominated sources is small, being \( \sim 12\% \) in ULIRGs and \( \sim 5\% \) in LIRGs. Also Wu et al. (2011) found no significant change in the overall star formation contribution to \( L_{IR} \) from LIRGs to ULIRGs at \( z \sim 0.3 \). However, other works found evidence for higher AGN contributions for the most IR luminous galaxies at high-\( z \). Indeed, Menéndez-Delmestre et al. (2009) found that, although submillimeter galaxies are dominated by intense star formation, the average AGN bolometric contribution could be as high 30%. Moreover, Rujopakarn et al. (2011) found a strict upper limit of \( \sim 5 \times 10^{12} – 10^{13} L_{\odot} \) for the IR luminosity to be due to star formation in galaxies at all redshifts. Above that limit, AGN are expected to provide the power.

7. CONCLUSIONS

We have decomposed the Spitzer/IRS \( \sim 5 – 38 \) μm spectra of a complete volume-limited (\( d \sim 40 – 78 \) Mpc) sample of local LIRGs into AGN and SB components. The main goal of this work is to quantify the AGN contribution to the mid-IR and IR emission of these systems. For the SB component we used starburst and
These models are described by six parameters that deal with the torus geometry and cloud properties. These are:

1. Using the AGN+SB spectral decomposition we detected an AGN component in 25 out of the 50 individual LIRG nuclei with IRS spectroscopy. For an additional nine galaxies optically classified as composite (AGN/SB) we did not detect an AGN with our method. The combined optical and mid-IR AGN detection rate is about 62% (33/53) for the individual nuclei of local LIRGs. This is in good agreement with the AGN detection rate obtained from optical spectroscopy, if composite objects do contain an AGN.

2. The AGN contribution to the mid-IR continuum emission within the IRS slits is small, and decreases toward longer wavelengths. The median values range from 0.30 to 0.18 and 0.11.

3. We used IRAC 5.8 μm and MIPS 24 μm images to derive the AGN contribution to the total emission at these mid-infrared wavelengths. The median AGN contributions for those LIRGs with an AGN detection are 0.12 and 0.15, with only about 6% (3/50) of local LIRGs having a dominant AGN contribution at 24 μm (C_{24μm}^{AGN} > 0.5).

4. We detected the [O IV]25.89 μm high excitation emission line in 70% (35/50) of the individual LIRG nuclei. All the galaxies in our sample with L_{[O IV]} ≥ 10^7 L⊙ contain an AGN and these luminosities are consistent with those expected from their derived AGN bolometric luminosities. On the other hand, the [O IV]25.89 μm luminosities of those galaxies without an AGN detection can be explained as produced by star formation activity.

5. When compared with other mid-IR spectral AGN diagnostics, we found that our 24 μm AGN fractional components are consistent with those derived from the [O IV]/[Ne II] versus EW(6.2 μm PAH) diagram. Using the Spoon et al. diagram we can identify the presence of an AGN when C_{24μm}^{AGN} ≥ 0.1.

6. From the scaling of the fitted torus models to the AGN component of the IRS spectra we derived AGN bolometric luminosities in the range $L_{bol}(AGN) = 0.4 - 50 \times 10^{43}$ erg s$^{-1}$ with a median value of $L_{bol}(AGN) = 2 \times 10^{43}$ erg s$^{-1}$. These are in a fairly good agreement with those estimated from hard X-ray measurements after applying a bolometric correction.

7. One-third of local LIRGs have $L_{bol}[AGN]/L_{IR} ≥ 0.05$, with only about 8% having a significant AGN contribution $L_{bol}[AGN]/L_{IR} > 0.25$. This is in contrast with the ~ 20% of local ULIRGs with $L_{IR} < 3 \times 10^{12}$ L⊙ and the ~ 60% of ULIRGs with $L_{IR} > 3 \times 10^{12}$ L⊙ having $L_{bol}[AGN]/L_{IR} > 0.25$, respectively.

8. Adding up the AGN bolometric luminosities in our sample we find that AGNs are only responsible for 5% of the total IR luminosity produced by local LIRGs. This translates into an AGN IR luminosity density of $\rho_{IR}^{AGN} = 3^{+5}_{-2} \times 10^5 L_{⊙}$ Mpc$^{-3}$ in local LIRGs. Our results prove that the bulk of the IR luminosity of local LIRGs is due to star formation activity.

In summary, mid-IR spectral decomposition is a powerful tool to estimate the AGN contribution to both the mid-IR emission and the total emission of IR-selected sources. This is because not only are we able to identify all Seyfert-like AGN in local LIRGs but also because this technique is powerful enough to identify subtle AGN features (i.e., low luminosity AGN) that might be missed by other mid-IR methods. As a result, we have shown that AGNs accompany star formation activity in the large majority of local LIRGs, although in most cases the AGNs are not energetically important.

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APPENDIX

A1. THE CLUMPY TORUS MODELS

We used the CLUMPY models (Nenkova et al. 2008a,b) to represent the AGN continuum emission in the mid-IR. These models are described by six parameters that deal with the torus geometry and cloud properties. These are:
the radial thickness of the torus \( Y = R_o/R_d \), where \( R_o \) and \( R_d \) are the outer and inner radii of the torus, respectively. The inner radius of the torus in these models is set by the dust sublimation temperature, which is assumed to be \( T_{\text{sub}} \approx 1500 \) K. (2) The angular distribution of the clouds, which is assumed to have a smooth boundary, is described as a Gaussian with a width parameter \( \sigma_{\text{cloud}} \). (3) The radial distribution of the clouds, which is described as a declining power law with index \( q \) \( \propto r^{-q} \). (4) The mean number of clouds along a radial equatorial ray \( N_0 \). (5) The optical depth of the clouds \( \tau_v \). (6) The viewing angle to the torus, \( i \). In the models the radiative transfer equations are solved for each clump and thus the solutions depend mainly on the location of each clump within the torus, its optical depth, and the chosen dust composition. For the fits done in this work we adopted a dust extinction profile corresponding to a standard cold oxygen-rich ISM dust (Ossenkopf et al. 1992). The total torus emission is calculated by integrating the source function of the total number of clumps convolved with the radiation propagation probability along the torus (Nenkova et al. 2002). For unobscured views of the AGN, it is also possible to include its contribution to the resulting IR emission. The AGN continuum emission in these models is characterized with a piecewise power law distribution (see Nenkova et al. 2008a, for details). In addition to the the six torus model parameters, there is an extra parameter to account for the vertical displacement needed to match the fluxes of a given model to the observations. This vertical shift, which we allow to vary freely, scales with the AGN bolometric luminosity (see Nenkova et al. 2008b).

Given the large number of CLUMPY models (currently more than 10^6) and the inherent degeneracy in the torus model parameters, Asensio Ramos & Ramos Almeida (2009) took a Bayesian approach to fit models to the data and to derive meaningful confidence levels for the fitted parameters. To this end, they developed a tool called BayesClumpy that allows fitting both photometric points and/or mid-IR spectra. For the Bayesian inference of BayesClumpy we used an interpolated version of the CLUMPY dusty torus models. We refer the reader to Asensio Ramos & Ramos Almeida (2009) for details on the interpolation methods and algorithms used by BayesClumpy to perform the torus model fits to the data.

A2. AGN+SB SPECTRAL DECOMPOSITION FITS

We used an iterative method to perform the AGN+SB decomposition. In the first step we started by using only two AGN templates given the large number of CLUMPY torus models and their degeneracy (see Ramos Almeida et al. 2009, 2011, Asensio Ramos & Ramos Almeida 2009, for detailed discussions on this issue). We used the best fit CLUMPY torus model of the average spectral energy distributions of Seyfert 1s and Seyfert 2s inferred by Ramos Almeida et al. (2011). We obtained the best fit to the IRS spectra for each LIRG in our sample with this initial combination of AGN+SB templates. We next subtracted the SB component from the original IRS spectrum to obtain the AGN-only mid-IR spectrum. This AGN-only spectrum was then fitted with the BayesClumpy routine (Asensio Ramos & Ramos Almeida 2009) to infer the best fit torus model and the corresponding scaling for each galaxy. We finally refitted the observed IRS spectrum of the LIRG using its corresponding best-fit torus model, allowing for rescaling, and the appropriate SB template that minimized \( \chi^2 \). The fits were done in the 6–30 \( \mu \)m spectral range to avoid the edges of the spectra and the slightly decreased signal-to-noise ratio of some of the spectra observed in mapping mode at \( \lambda > 30 \) \( \mu \)m. We note, however, that the fits tend to be good also at \( \lambda > 30 \) \( \mu \)m. We considered an AGN detection when its contribution was greater than 5–7% at 20 \( \mu \)m. Below this limit we were not able to fit the AGN-only spectra with BayesClumpy. This is because after subtracting the SB template in these cases a large proportion of the data points were close to zero or even negative. For each fit the formal errors of the AGN fractional contribution within the IRS slit were calculated using the observational errors of the IRS spectra and the covariance matrix. The typical errors of the AGN fractional contribution within the IRS slit at 6 \( \mu \)m are 0.01 – 0.03. If the models fit the data, as is the case for most galaxies, these can be taken as the typical uncertainties of the AGN fractional contributions. This is because the variation of the fitted parameters is compatible with the data observational errors. The uncertainties associated with the use of different SB templates are discussed briefly in Section 4.1.

We present the best AGN+SB fits for all the LIRGs in our sample in Figures 1, A1, and A2. As can be seen from Figure A2 a few LIRGs deemed not to have a mid-IR AGN detection have best fit requiring a small AGN contribution. These are NGC 5734, which is optically classified as composite, and ESO 221–G010 and IC 4734, which are classified as HII (see Table 1). The AGN fraction at 20 \( \mu \)m for all of them was, however, below the imposed limit. In these cases we were not able to fit the AGN-only emission with the torus models, and the AGN template corresponds to the Seyfert 2 template used in the first step of the iteration.

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Figure A1. AGN+SB decomposition fits for those LIRGs with a mid-IR AGN detection. Lines are as in Figure 1.
Figure A1. Continued.

Figure A2. AGN+SB decomposition fits for those LIRGs without a mid-IR AGN detection. Lines are as in Figure 1.
Figure A2. Continued.
