Luminous Infrared Galaxies Near and Far: The Promise of *SPICA*

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ABSTRACT

With *ISO*, *Spitzer* and *Herschel*, we have made great strides toward understanding the heating and cooling in Luminous Infrared Galaxies (LIRGs): those sources with $L_{\rm IR} \geq 10^{11}\,{\rm L}_{\odot}$ whose bolometric energy output is dominated by re-radiated infrared emission from dust, which were first discovered with *IRAS*. We have quantified the relative importance of Active Galactic Nuclei (AGN) and starbursts to statistically significant samples of low-z LIRGs, and have used the MIR dust and gas diagnostics to measure the power sources in samples of SMGs and QSOs out to $z \sim 4$ with *Spitzer*/IRS. Recently, we have measured the bright FIR fine-structure cooling lines in large numbers of local LIRGs and starburst galaxies with *Herschel*, establishing key scaling relationships between the central starbursts, AGN, and the FIR emission lines. In addition, fast, massive outflows of cold molecular gas have been detected which provide a direct window on the interaction of the central source and the molecular gas reservoir. *SPICA*, with it's large, cold primary and suite of sensitive instruments promises to once more revolutionize our picture of the infrared Universe, carrying forward the work we have done with *Spitzer* and *Herschel* to fainter and more distant galaxies, building large samples of LIRGs at high-z, and reaching the brightest sources at the earliest epochs.

1. INTRODUCTION

The *Infrared Astronomical Satellite* (*IRAS*) provided the first unbiased survey of the sky at mid and far-infrared wavelengths, giving us a comprehensive census of the infrared emission properties of galaxies in the local Universe. A major result of this survey was the discovery of a large population of luminous infrared galaxies (LIRGs) which emit a significant fraction of their bolometric luminosity in the far-infrared, and have $L_{\rm IR} \geq 10^{11}{\rm L}_{\odot}$. LIRGs are a mixture of single galaxies, disk galaxy pairs, interacting systems and advanced mergers, exhibiting enhanced star formation rates and a higher fraction of Active Galactic Nuclei (AGN) compared to less luminous galaxies. A detailed study of low-redshift LIRGs is critical for our understanding of the cosmic evolution of galaxies and black holes since (1) LIRGs comprise the bulk of the cosmic infrared background and dominate star-formation activity between $0.5 < z < 1$ (Magnelli et al. 2013) and (2) AGN fueling and mass accretion onto a central black hole may preferentially occur during episodes of enhanced nuclear star formation, helping to naturally explain the scaling of black hole and stellar bulge masses seen in the local Universe (e.g., Magorrian et al. 1998).

With the Great Observatories All-sky LIRG Survey — GOALS (Armus et al. 2009), we are measuring the properties of a large, complete sample of low-redshift LIRGs across the electromagnetic spectrum using *Spitzer*, *HST*, *Chandra*, *GALEX*, *Herschel*, and a number of ground-based observatories including Keck, the JVLA, and ALMA. The GOALS targets are drawn from the *IRAS* Revised Bright Galaxy Sample (Sanders et al. 2003), a complete sample of 629 galaxies with *IRAS* $S_{60} > 5.24$ Jy, and Galactic latitudes $b > 5$ deg. There are 202 LIRGs, including 22 ULIRGs (those with $L_{IR} \geq 10^{12}\,{\rm L}_{\odot}$) in the RBGS, and these galaxies define the GOALS sample. At the highest luminosities, LIRGs consist of predominantly interacting systems, covering the entire range of the merger sequence from widely separated pairs to late-stage mergers. They provide an ideal sample for studying interaction-induced star formation and AGN fueling at low-redshift. We have observed the entire GOALS sample with *Spitzer* and *Herschel*, and we summarize some of our key results here, along with the results of others targeting complementary samples of LIRGs and ULIRGs both locally and at high-redshift. These results lay the groundwork for future surveys and detailed studies of individual galaxies with the Space Infrared telescope for Cosmology and Astrophysics, *SPICA*, and we discuss some possible avenues for this research in the following sections.

2. PROBING THE HEATING SOURCES WITH *SPITZER*/IRS

There are a number of reasons that mid-infrared spectroscopy is attractive for studying the central power sources and ISM in LIRGs. First, the extinction is low compared to the optical and even the near-infrared, where traditional diagnostic lines are found. Second, lines from highly ionized atomic gas (e.g., Ne^{+4} and O^{+3}) are present, providing effective diagnostics of the radiation field. In addition the pure rotational H_2 lines are direct probes of the warm (100–500 K) molecular gas. This molecular gas can be heated by the central source (young stars and/or an AGN) in addition to large-scale shocks associated with an outflowing wind. The H_2 lines, therefore, are sensitive to the feedback of the energy source responsible for the

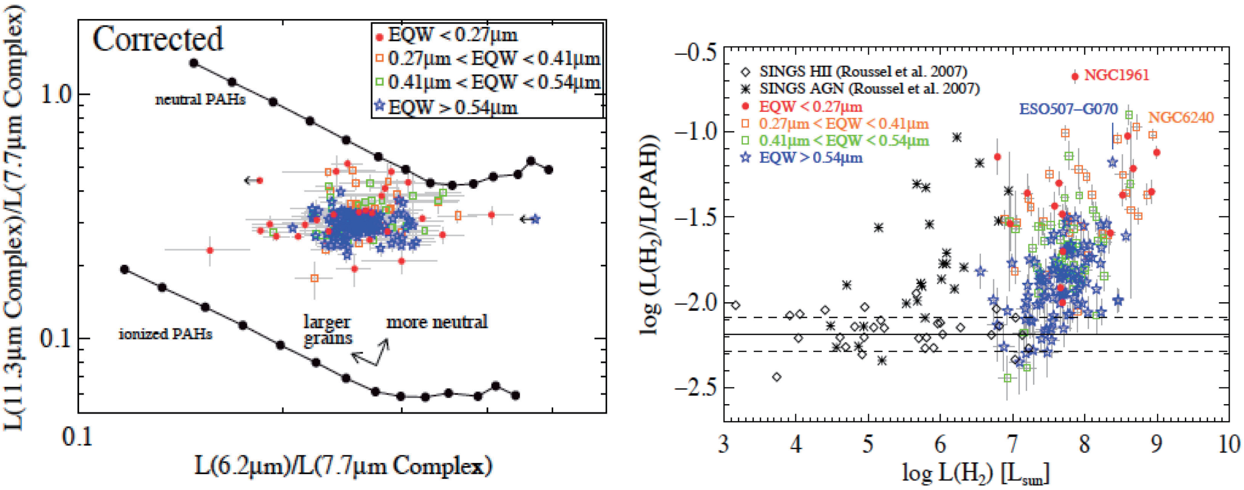

Figure 1. *Left*: Diagnostic PAH feature flux ratio diagram for the GOALS sources color-coded on 6.2μm PAH EQW from Stierwalt et al. (2014). Curves are models for neutral and ionized grains from Draine & Li (2001). The PAH feature ratios have been calculated by multi-component fits to the IRS spectra, including the full PAH feature profiles, and the ratios are corrected for foreground dust extinction. *Right*: H_2/PAH flux ratio as a function of H_2 luminosity. Dashed lines indicate the range of normal star-forming galaxies from Roussel et al. (2007), as shown by the black symbols. Most LIRGs have H_2/PAH ratios that are greater than those found in low-luminosity, star-forming galaxies.

FIR emission, on the reservoir of cold, molecular gas out of which stars form. Finally, aromatic features from Poly-cyclic Aromatic Hydrocarbons (PAHs) are extremely strong, typically dominating the MIR spectrum of a star-forming galaxy. Their relative strength provides information on the average size and ionization state of the transiently heated small grains.

While the mid-infrared spectra of local LIRGs and ULIRGs span a large range in shape, caused by variations in the strength of the PAH features, and absorption from dust (silicates) and ices and hydrocarbons (Armus et al. 2004, 2007; Spoon et al. 2007; Farrah et al. 2007; Imanishi et al. 2007; Veilleux et al. 2009), the majority of the LIRGs in the GOALS sample (Stierwalt et al. 2013) have high 6.2 μm PAH equivalent width, ($> 0.4\,\mu$m) and moderate silicate absorption ($s_{9.7} > -1$). The strong PAH emission and (relatively) weak MIR continuum near 5 μm suggest that most LIRGs are starburst dominated. While ~ 20 % show evidence for a buried AGN (Petric et al. 2011), these AGN contribute <10–15 % of the bolometric power across the sample. The scatter in the PAH ratios (6.2/7.7 and 7.7/11) among SB-dominated LIRGs (Figure 1) is consistent with other, low-luminosity starburst galaxies, suggesting no overall change in the ionization state or size of the PAHs in LIRGs compared normal galaxies (Stierwalt et al. 2014). Sources with evidence for an AGN show a much larger scatter in the PAH feature flux ratios, but no obvious trend to have more ionized or larger grains overall (see Figure 1).

There is a general trend among the LIRGs for both silicate depth and mid-infrared (MIR) slope to increase with increasing L_{IR}. Also, LIRGs in the late to final stages of a merger also have, on average, steeper MIR slopes and higher levels of dust obscuration, consistent with dust being funneled towards the nuclei, leading to a compact starburst and high obscuration. As a result, the dust temperature increases leading to a steeper MIR slope. LIRGs with extremely low PAH equivalent widths, which may harbor buried AGN, separate into two distinct spectral types: relatively unobscured sources with a very hot dust component (and thus very shallow MIR slopes) and heavily dust obscured nuclei with a steep temperature gradient.

The most heavily obscured LIRGs are also the most compact in their MIR emission, suggesting that the obscuring (cool) dust is associated with the (outer regions of the) starburst, and not simply a measure of the dust along the line of sight through a large, edge-on, disk. A marked decline is seen for the fraction of high PAH EQW sources as the merger progresses, accompanied by an increase in the fraction of composite sources. Across the merger sequence, the fraction of sources dominated by an AGN remains low.

Most GOALS LIRGs have elevated L_{H2}/L_{PAH} ratios well above those observed for normal star-forming galaxies, and exhibit a trend for increasing L_{H2}/L_{PAH} ratio with increasing L_{H2} (see Figure 1). While LIRGs can exhibit both increased H_2 emission and decreased PAH emission, it is natural to explain the LIRGs with extremely strong H_2 emission as those where the molecular gas has an additional heating component from slow shocks which would not cause enhanced PAH emission — see Stierwalt et al. (2014).

When compared to the MIR spectra of $z \sim 2$ SMGs, LIRGs, and especially ULIRGs, show deeper silicate absorption and stronger PAH emission. However, when the AGN contributions to both the local GOALS LIRGs and the high-z SMGs are removed, the average local SB-dominated LIRG closely resembles the starburst-dominated SMGs (Stierwalt et al. 2013). Local LIRGs have a constant (high) average 6.2 μm PAH EQW over nearly two orders of magnitudes in νL_ν at 24 μm,

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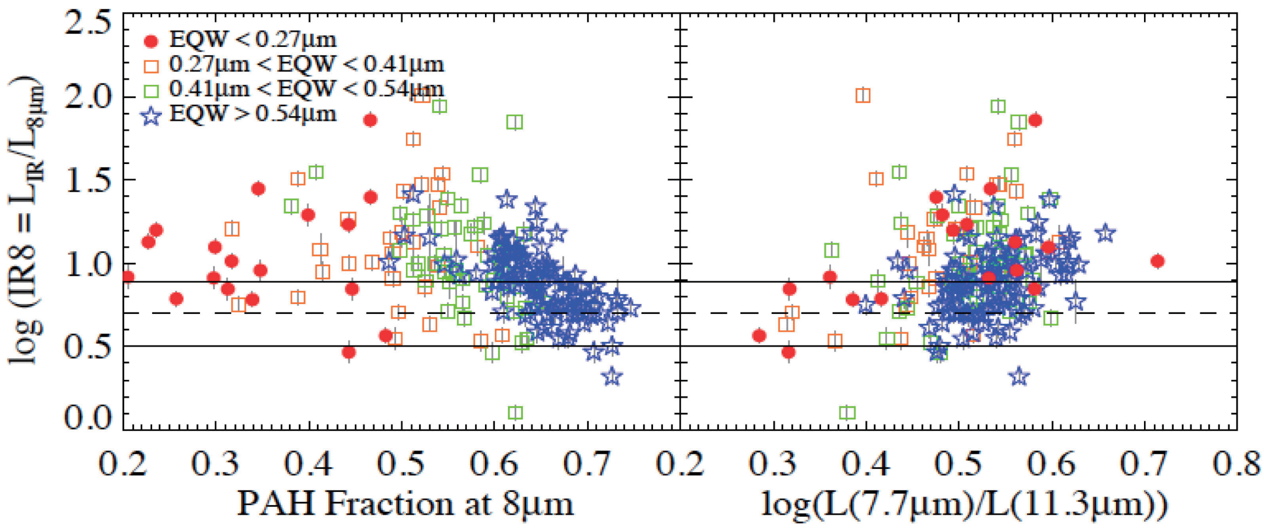

Figure 2. IR8 (LIR/L8) for the GOALS sources as a function of the PAH fraction in the IRAC 8 μm band (*left*), and the 7.7/11.3 PAH flux ratio (*right*). There is a rough correlation of increasing IR8 with decreasing PAH fraction for the SB-dominated LIRGs, although the decrease in the 7.7 + 8.6 μm PAH emission cannot quantitatively account for the majority of the increase in IR8 over the range probed by the GOALS sources. Similarly, the change in IR8 does not seem to be associated with a significant change in the grain properties as traced by the PAH flux ratio.

similar to high redshift SMGs and star forming galaxies at higher νL_ν, but unlike local ULIRGs which show a trend for decreasing EQW with increasing 24 μm luminosity.

For the starburst dominated LIRGs, there is a rough inverse correlation between the ratio of $L_{\rm IR}$ and emission at 8 μm (IR8) — a measure of the distance of a galaxy from the star-forming main sequence (Elbaz et al. 2011), and the MIR PAH fraction. However the fractional drop in PAH emission within the IRAC 8 μm band is much less than the rise in IR8 (see Figure 2). No obvious link is seen between IR8 and the 7.7/11.3 PAH ratio, suggesting that grain processing is not responsible for the lower PAH fraction among sources with high IR8 (Stierwalt et al. 2014). It is more likely a decrease in the PDR emission relative to $L_{\rm IR}$ as the starbursts become more compact, and the warm dust and overall LIR rise (see also Diaz-Santos et al. 2013).

In Inami et al. (2013, and this volume) we compare the IRS high-res spectra to models of starbursts (Levesque et al. 2010) and shocks (Allen et al. 2008), in order to constrain ages, ionization parameters, and metallicities in the (starbursting) LIRG nuclei. Starbursting LIRGs have ages of 1–4.5 Myr, metallicities of 1–2 $Z_\odot$, and ionization parameters of 2–8×10^7 cm s^{-1}. A large number (80) of the GOALS sources have resolved neon emission line profiles (FWHM ≥ 600 km s^{-1}), and a small number (six SB and five AGN) show a clear trend of increasing line width with ionization potential, suggesting a compact energy source and stratified ISM in their nuclei.

Given the limited resolution of the IRS spectra, it is difficult to measure detailed line profiles or subtle features in the gas dynamics — something that will be much easier with *SPICA* (see below). As expected, there is a strong correlation between the sum of the [Ne II] and [Ne III] emission lines, as well as [S III] line, with infrared luminosity and the L_{24}, consistent with all three lines tracing ongoing star formation. As outlined in Inami et al. (2013) there is no correlation between the hardness of the radiation field or the emission line width and IR8. This may be a function of the fact that the infrared luminosity and the mid-infrared fine-structure lines are sensitive to different timescales over the starburst, or that IR8 is more sensitive to the geometry of the region emitting the warm dust than the radiation field producing the H II region emission.

3. COOLING LINES AND OUTFLOWS WITH *HERSCHEL*

The far-infrared includes several of the most important cooling lines in the neutral and ionized atomic ISM, notably the [C II] 157.7 μm, [O I] 63.2 μm, [O III] 88.4 μm, [N II] 122 μm and [N II] 205 μm far-infrared, fine structure emission lines. The [C II] and [O I] lines dominate the cooling of the warm neutral medium, whereas [O III] and [N II] originate from ionized regions and directly trace young, hot stars. The lines cover an extremely large range in critical density, from ~ 100 cm^{-3} to almost 10^6 cm^{-3}, and the ([O I]+[C II])/LIR ratio provides a measure of the gas heating efficiency.

Observations of the FIR cooling lines in representative samples of local star-forming galaxies and AGN were pioneered with *ISO* (e.g., Malhotra et al. 1997, 2001; Luhman et al. 1997; Helou et al. 2001; Brauher et al. 2008), but the relationships discovered between the FIR cooling lines, $L_{\rm IR}$ and the dust temperature were based on relatively small numbers of bright galaxies (AGN, LIRGs, mergers, etc.) and they showed a great deal of scatter. Recent work with *Herschel*/PACS (Gracia-Carpio et al. 2011) suggests that there may be a bi-modal relationship between the [C II]/FIR ratio and the star formation

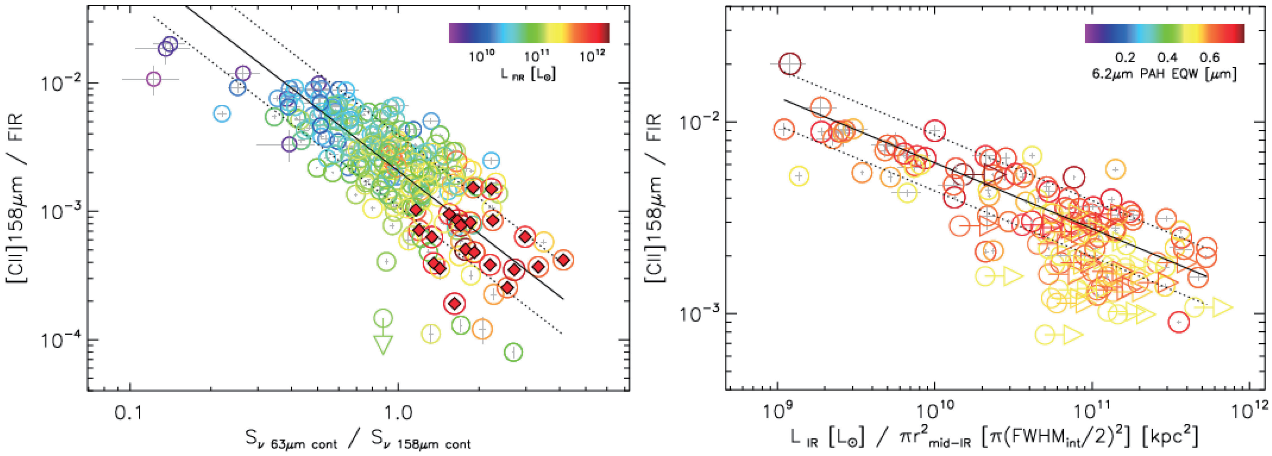

Figure 3. Ratio of [C II] 158 μm to FIR flux as a function of the 63 μm/158 μm flux density ratio (*left*) and luminosity surface density (*right*) for the GOALS sample (Diaz-Santos et al. 2013). The right panel only includes those LIRGs with large PAH EQWs, indicating they their power comes from star formation and not AGN. Galaxies with larger [C II] deficits have warmer FIR colors and more powerful, compact starbursts.

efficiency, as defined by the ratio of the FIR emission to the cold molecular gas mass, with the most powerful starbursts having the largest line deficits.

In the first study of the [C II] emission from a large sample of LIRGs with *Herschel*, Diaz-Santos et al. (2013) find a tight inverse correlation of [C II]/FIR with far-infrared color (warmer sources have larger [C II] "deficits"), and between [C II]/FIR and the strength of the 9.7 μm silicate absorption feature (denser, more absorbed starbursts have deeper silicate absorption and large [C II] deficits). A correlation exists as well between the [C II]/FIR ratio and the luminosity surface density of the starburst (see Figure 2). Warmer, more compact starbursts have substantially smaller [C II]/FIR ratios. This is confirmed by the correlation of [C II]/FIR with the normalized specific star-formation rate.

While LIRGs with AGN can have extremely low [C II]/FIR ratios (well below 10^{-3}), the [C II]/FIR ratio among pure SB sources drops by an order of magnitude with FIR flux density ratio, silicate absorption and luminosity surface density, suggesting that the [C II] deficit is a real function of the starburst, and furthermore, that the [C II] luminosity is not a good quantitative indicator of the star-formation rate in powerful starburst galaxies (Figure 3).

Because of the large number of LIRGs in the complete GOALS sample, Diaz-Santos et al. (2013) are also able to estimate the fractional AGN contamination among future [C II]-derived samples, such as those that might be assembled with ALMA or CCAT. As discussed in Diaz-Santos et al. (2013), at least 1/3 of LIRGs with extremely low [C II]/FIR $< 5 \times 10^{-4}$ should be compact SB and not AGN. Furthermore, a measure of the [C II] and FIR emission in high-redshift starbursts should yield a prediction of the size of these starburst (see Stacey et al. 2010), which could be compared directly with measurements of the molecular gas and/or cold dust with ALMA on scales similar to that achieved with PACS on the GOALS sources.

Arguably one of the most spectacular early results from *Herschel* was the discovery of blueshifted absorption in the far-infrared OH lines in Mrk 231 and other nearby ULIRGs (Fischer et al. 2010; Sturm et al. 2011). These features arise from fast ($1000\,\mathrm{km\,s^{-1}}$ or more), massive outflowing winds of molecular gas. Although model dependent, the derived mass outflow rates in these molecular winds can be comparable to the star-formation rates (hundreds of solar masses per year), and therefore a significant factor in the depletion of the molecular ISM. Recently the ubiquity of these winds in ULIRGs has been confirmed (Veilleux et al. 2013; Spoon et al. 2013) along with the correlation of the fastest winds with the presence, and power of a central AGN. Although winds from starburst galaxies and ULIRGs have been known and studied for decades (e.g. Heckman et al. 1990), these blue shifted molecular outflows seen with *Herschel* are a unique way to directly probe the feedback of the central source on the reservoir of cold molecular gas.

4. THE PROMISE OF *SPICA*

The high spatial resolution, spectral resolution, and sensitivity of *SPICA* will allow us to study local LIRGs and ULIRGs in much greater details than has been possible with *Spitzer*/IRS, and build up large samples of LIRGs at high-redshift with high SNR MIR spectra for the first time. In particular, the high-spectral resolution of the MCS/MRS instrument ($\sim 100\,\mathrm{km\,s^{-1}}$ — about a factor of five higher than the IRS), will allow us to explore outflows and large-scale gas motions via the MIR fine-structure lines in the most dusty galaxies, even when extremely high-velocity, AGN-driven motions are not present. Even in the GOALS sample, obtaining high SNR, high-res spectra for the more distant sources was difficult, and only the most powerful galaxies at $z > 0.1$–0.2 were within reach of the SH and LH modules of the IRS. Since the fine-structure lines are often narrow, the increased spectral resolution or MCS/MRS facilitates greater sensitivity (a gain of nearly an order of magnitude over the IRS), allowing us to measure the flux and line profiles of the key diagnostic emission lines in LIRGs and ULIRGs out to $z = 1$–2 in an hour of integration (see Inami et al. in this volume). In the local Universe, the 3–4× higher spatial resolution of *SPICA* compared to *Spitzer* will also enable sub-kpc studies of the gas in and around galaxy nuclei, further enhancing our ability to look for direct connections between ongoing starbursts and AGN in even the most obscured sources.

By targeting the FIR molecular lines, such as OH with *SPICA*, we will not only be able to build a complete census of molecular driven outflows in ULIRGs out to $z \sim 1$, we will be able to carefully disentangle the multiple velocity components in the multi-phase outflows and link these to the physical conditions in the gas and the central source by directly comparing the FIR absorption features to the MIR emission lines.

While the [C II] line itself will not be visible in high-z galaxies with *SPICA*, other fine structure cooling lines (e.g., [O I], and [O III]) will be readily detected. These could be effective probes of the sizes and physical properties of the starbursts, even in unresolved, distant galaxies. High-redshift, high-luminosity galaxies with strong [O I] emission, compared to FIR, should have cool dust temperatures, and extended star formation. Sources with weak [O I] emission, and warm dust temperatures, should be extremely compact, and/or have a buried AGN (if the deficit is extremely large).

SPICA/SAFARI will deliver unbiased surveys of ULIRGs out to $z \sim 4$ and beyond, with large samples of LIRGs to $z \sim 1$–2. With more than an order of magnitude leap in sensitivity compared to *Herschel*, *SAFARI* will reach FIR line flux levels of 10^{-19} W m^{-2} in about an hour of integration, and be able to measure the key cooling lines in hundreds of starburst galaxies and AGN out to the peak in the star formation rate density at $z \sim 2$–3 (Spinoglio et al. 2012). Of course, the real diagnostic power of *SPICA* will be in it's broad wavelength coverage and far-infrared sensitivity, enabling a direct comparison of the heating and cooling of the atomic and molecular ISM in actively star-forming galaxies over a huge range of cosmic time. The synergy of *SPICA* and *JWST* to image and study the physical conditions in dusty starbursts and AGN across the complete infrared spectrum will be truly astounding.

From *IRAS* to *ISO*, *Spitzer* and *Herschel*, and with ongoing ground-based studies with CARMA, CSO, PdBI, the JVLA and most recently, ALMA, we have unmasked the power sources and probed the physical conditions in the most heavily obscured, and powerful galaxies in the local Universe, reaching out to $z \sim 6$ (Pope et al. 2008; Rigby et al. 2008; Menendez-Delmestre et al. 2009; Farrah et al. 2008; Maiolino et al. 2009; Walter et al. 2009; Stacey et al. 2010; Sturm et al. 2010; Diaz-Santos et al. 2013; Carilli et al. 2013; Wagg et al. 2014; Vieira et al. 2013; Wang et al. 2013; Riechers et al. 2013). However, our knowledge of the general properties of high-redshift IR luminous galaxies is still quite limited, due to small sample sizes and/or natural selection biases. We are now ready to take the next big step in our understanding of the far-infrared Universe of star formation and black hole growth with *SPICA*.

I would like to personally thank the organizers for an exciting and productive conference, and for the opportunity to once more visit the University of Tokyo, to see the spectacular Hotaru at the Hotel Chinzanso and, most importantly, to participate in the discussions about, and planning for, *SPICA*.

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