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Local luminous infrared galaxies: Spatially resolved mid-infrared observations with *Spitzer*/IRS ☆

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Abstract

Luminous Infrared (IR) Galaxies (LIRGs, $L_{IR} = 10^{11}$–10^{12} $L_{\odot}$) are an important cosmological class of galaxies as they are the main contributors to the co-moving star formation rate density of the universe at $z = 1$. In this paper we present a guaranteed time observation (GTO) *Spitzer* InfraRed Spectrograph (IRS) program aimed to obtain spectral mapping of a sample of 14 local ($d < 76$ Mpc) LIRGs. The data cubes map, at least, the central 20 arcsec × 20 arcsec to 30 arcsec × 30 arcsec regions of the galaxies, and use all four IRS modules covering the full 5–38 μm spectral range. The final goal of this project is to characterize fully the mid-IR properties of local LIRGs as a first step to understanding their more distant counterparts. In this paper we present the first results of this GTO program. The IRS spectral mapping data allow us to build spectral maps of the bright mid-IR emission lines (e.g., [Ne II]12.81 μm, [Ne III]15.56 μm, [S III]18.71 μm,H_2 at 17 μm), continuum, the 6.2 and 11.3 μm polycyclic aromatic hydrocarbon (PAH) features, and the 9.7 μm silicate feature, as well as to extract 1D spectra for regions of interest in each galaxy. The IRS data are used to obtain spatially resolved measurements of the extinction using the 9.7 μm silicate feature, and to trace star forming regions using the neon lines and the PAH features. We also investigate a number of active galactic nuclei (AGN) indicators, including the presence of high excitation emission lines and a strong dust continuum emission at around 6 μm. We finally use the integrated *Spitzer*/IRS spectra as templates of local LIRGs. We discuss several possible uses for these templates, including the calibration of the star formation rate of IR-bright galaxies at high redshift. We also predict the intensities of the brightest mid-IR emission lines for LIRGs as a function of redshift, and compare them with the expected sensitivities of future space IR missions.

Keywords: Galaxies: evolution; Galaxies: nuclei; Galaxies: Seyfert; Galaxies: structure; Infrared: galaxies

1. Introduction

The importance of infrared (IR) bright galaxies has been increasingly appreciated since their discovery more than 30 years ago (Rieke and Low, 1972), and the detection of large numbers by *IRAS* (Soifer et al., 1987). Although the Ultraluminous Infrared Galaxies (ULIRGs, *with IR luminosities* 8–1000 μm,$L_{IR} = 10^{12}$–10^{13} $L_{\odot}$) get much of the attention because they are so dramatic, Luminous Infrared Galaxies (LIRGs, $L_{IR} = 10^{11}$–10^{12} $L_{\odot}$) are much more common,

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accounting for ~ 5% of the local IR background compared with <1% for the ULIRGs (Lagache et al., 2005). They are of intrinsic interest because they provide insight to star formation and nuclear activity under extreme conditions and should also include former ULIRGs where the star formation is dying off (see Murphy et al., 2001). They 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 and Mirabel, 1996).

Local LIRGs may also be prototypes for forming galaxies at high redshift (Lagache et al., 2005). Deep *Spitzer* detections at 24 μm are dominated by LIRGs and ULIRGs. LIRGs are the main contributors to the co-moving star formation rate (SFR) density in the $z \sim 1$–2 range (Elbaz et al., 2002; Le Floc'h et al., 2005; Pérez-González et al., 2005; Caputi et al., 2007), and contribute nearly 50% of the cosmic IR background at $z \sim 1$ (Lagache et al., 2005). Moreover, the mid-IR spectra of high redshift ($z \sim 2$) very luminous IR galaxies ($L_{IR} > 10^{12} L_\odot$) are more similar to those of local starbursts and LIRGs (see e.g., Farrah et al., 2008; Rigby et al., 2008; Alonso-Herrero et al., 2009) than those of local ULIRGs. This may just reflect the fact that at high-z star-formation was taking place over a few kiloparsec scales rather than in very compact (<1 kpc) regions as is the case for local ULIRGs (e.g., Soifer et al., 2000).

Much of our knowledge of the mid-IR spectroscopic properties of local IR-bright galaxies comes from *ISO* (e.g., Genzel et al., 1998; Rigopoulou et al., 1999; Tran et al., 2001) and early results (Armus et al., 2004, 2007) with the InfraRed Spectrograph (IRS, Houck et al., 2004) on *Spitzer*. However, the majority of the *ISO* works focused on samples of local IR-bright galaxies or starburst galaxies, and only include a few luminous LIRGs ($\log L_{IR} \simeq 11.80\ L_\odot$, see e.g., Genzel et al., 1998; Verma et al., 2003). The majority of the recent *Spitzer* results are concentrating on ULIRGs (e.g., Armus et al., 2007; Farrah et al., 2007), starburst galaxies (Brandl et al., 2006), and nearby star-forming galaxies (Dale et al., 2006; Smith et al., 2007a). *Recently,* Armus et al. (2009) *have presented the Great Observatories All-Sky LIRG Survey (GOALS) project which combines multiwavelength data, including Spitzer, of over 200 low-redshift ($z < 0.088$) LIRGs.*

In this paper we summarize the goals and present the first results of a *Spitzer*/IRS program intended to obtain mid-IR (5–38 μm) spectral mapping of a representative sample of fourteen local LIRGs (Table 1) selected from the volume-limited sample of Alonso-Herrero et al. (2006a). It is only by quantifying the integrated spectroscopic properties of a representative sample of local LIRGs that we can interpret measurements at $z \sim 1$, which apply to the integrated galaxy. The final goal of this project is to characterize fully the mid-IR properties of local LIRGs as a first step to understanding their more distant counterparts. The complete results from this LIRG program will be presented in a number of forthcoming papers (Pereira-Santaella et al., 2009a,b in preparation). The paper is organized as follows. Section 2 presents the sample, observations and data reduction. Section 3 characterizes the obscuration of LIRGs and Section 4 discusses

Table 1
The sample of local LIRGs mapped with the IRS.

Galaxy name (1)	IRAS name (2)	v_{hel} (km s^{-1}) (3)	Dist (Mpc) (4)	$\log L_{IR}$ ($L_\odot$) (5)	Spect. class (6)
NGC 2369	IRASF 07160-6215	3237	44.0	11.10	–
NGC 3110	IRASF 10015-0614	5034	73.5	11.31:	H II
NGC 3256*	IRASF 10257-4339	2814	35.4	11.56	H II
Arp 299**	IRASF 11257+5850	3121	47.7	11.88	H II, Sy2
ESO 320-G030	IRASF 11506-3851	3232	37.7	11.10	H II
NGC 5135	IRASF 13229-2934	4112	52.2	11.17	Sy2
Zw 049.057	IRASF 15107+0724	3897	59.1	11.27:	H II
–	IRASF 17138-1017	5197	75.8	11.42	H II
IC 4687/IC 4686***	IRASF 18093-5744	5200/4948	74.1	11.55:	H II (both)
NGC 6701	IRASF 18425+6036	3965	56.6	11.05	Composite
NGC 7130	IRASF 21453-3511	4842	66.0	11.35	Sy/L
IC 5179	IRASF 22132-3705	3422	46.7	11.16	H II
NGC 7591	IRASF 23157+0618	4956	65.5	11.05	Composite
NGC 7771	IRASF 23488+1949	4277	57.1	11.34	H II

Notes. Column (1): galaxy name. **NGC 3256 is a merger system with two nuclei, refered to as north and south.* **Arp 299 is composed of IC 694 (eastern component) and NGC 3690 (western component). ***Only IC 4687 was observed in spectral mapping mode. Column (2): *IRAS* denomination from Sanders et al. (2003). Column (3): heliocentric velocity from NED. Column (4): distance taken from Sanders et al. (2003) assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. Column (5): 8–1000 μm IR luminosity taken from Sanders et al. (2003), where the suffix ":" means large uncertainty (see Sanders et al., 2003 for details). *The IR luminosity is for the system Arp 299 = IC 694 + NGC 3690. Column (6): nuclear activity class from optical spectroscopy. "Sy" = Seyfert, "*Composite*" = *intermediate between LINER and H II (see* Alonso-Herrero et al., 2009b*)*, "H II" = H II region-like, "–" = no classification available. *The classifications for Arp 299 are: nuclear region of IC 694, or source A, is H II-like, and the nuclear region of NGC 3690, or source B1, is a Sy2. The references for the nuclear class are given by Alonso-Herrero et al. (2006a), except for the nuclear region of NGC 3690 which is from García-Marín et al. (2006), and NGC 6701 and NGC 7591, which are reported by Alonso-Herrero et al. (2009b).