Studying Merger Processes of GOALS Luminous Infrared Galaxies with *SPICA*

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ABSTRACT

We present the results of an on-going survey of ^{12}CO(J=1-0) with the Nobeyama 45 m telescope of an unbiased sample of 44 Luminous Infrared Galaxies selected from the Great Observatories All-sky LIRG Survey (GOALS). The Nobeyama CO survey is being conducted to investigate molecular gas properties and star-formation efficiencies as a function of merger stage and active galactic nuclei (AGN) fraction in LIRGs. The results show that the $L_{\rm IR}/M_{\rm H_2}$ ratio, which is proportional to the star formation efficiency (SFE), is higher at the last stage of merger than at the early and middle stages. *SPICA* will provide highly spatially resolved mid- / far-IR imaging and spectroscopic data, and will enable us to obtain information on individual star-forming associated with merger for local LIRGs. We will present the importance of the IR continuum and mid/far-IR lines local LIRGs at high spatial resolution to investigate variations of structures and activity of the star-forming regions in the process of merging.

1. INTRODUCTION

LIRGs, which have the infrared luminosity with $L_{\rm IR} > 10^{11}\,{\rm L}_\odot$ (Sanders & Mirabel 1996), are an important class of galaxies for understanding SB and the generation and fueling of AGN. They also dominate the far-IR background for $z > 0.5$. In the local universe LIRGs are in various stages of galaxy-galaxy interaction and have been shown to host powerful SBs and AGN. From detailed studies of the mid-infrared and X-ray spectra of LIRGs (Petric et al. 2011; Díaz-Santos et al. 2010; Iwasawa et al. 2011; Stierwalt et al. 2013) it has been shown that most local LIRGs are SB-dominated. Only about 15–20 % of the energy in LIRGs as a class comes from buried AGN. These diverse environments in which local LIRGs are involved are inferred to affect their star formation activities or their evolutions. In studying the star formation of local LIRGs, molecular gas content is basic information. Moreover the molecular gas mass supplies the star formation efficiency (SFE) together with star formation rate. ^{12}CO (J=1–0) emission line ($\nu_{\rm rest}$ = 115.27 GHz) is a good tracer to estimate molecular gas mass (Solomon et al. 1987). Therefore a large data set of ^{12}CO (J=1–0) of local LIRGs is required to investigate the star formation statistically. However some previous CO surveys for local LIRGs were biased into more luminous LIRGs on infrared and/or CO line (e.g. Gao & Solomon 2004a,b). Therefore we need to obtain a large unbiased data set of CO for local LIRGs. We conducted a CO survey for local LIRGs of the Great Observatories All-sky LIRG Survey (GOALS) sample. GOALS is a comprehensive project investigating a complete sample of local LIRGs utilizing multi-wavelength observational data (Armus et al. 2009).

2. ^{12}CO (J=1–0) SURVEY FOR GOALS LIRGS

We conducted the ^{12}CO (J=1–0) of 74 LIRGs using the 45 m Telescope at the Nobeyama Radio Observatory (NRO) over four observing runs from January 2010 to February 2013. The target sample is uniform and consisting of 67 LIRGs and 7 ULIRGs (z =0.014–0.036) from the GOALS LIRG sample, which includes all LIRGs catalogued in the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003). The target sources include full stages of galactic interaction/merger, has various activities of AGN, and has the IR luminosities of 1.12×10^{11}–$3.72\times10^{12}\,{\rm L}_\odot$, which are calculated from the *IRAS* four bands from 12 μm through to 100 μm using the equation in Sanders & Mirabel (1996).

CO emissions from the sources were measured by single-point observations whose coordinates are the brightest points in their 24 μm images of MIPS/*Spitzer*. We applied the mapping observation with half-beam spacing to some extended sources. The main beam size (i.e. the full width to half maximum of the main beam pattern) of the telescope at 115 GHz is 15″, corresponding to ~7.3 kpc at the typical distance of the sample, 100 Mpc. For almost all sources except for those observed in the first run, we utilized a new broad bandwidth spectrometer. This newly introduced spectrometer, SAM45,

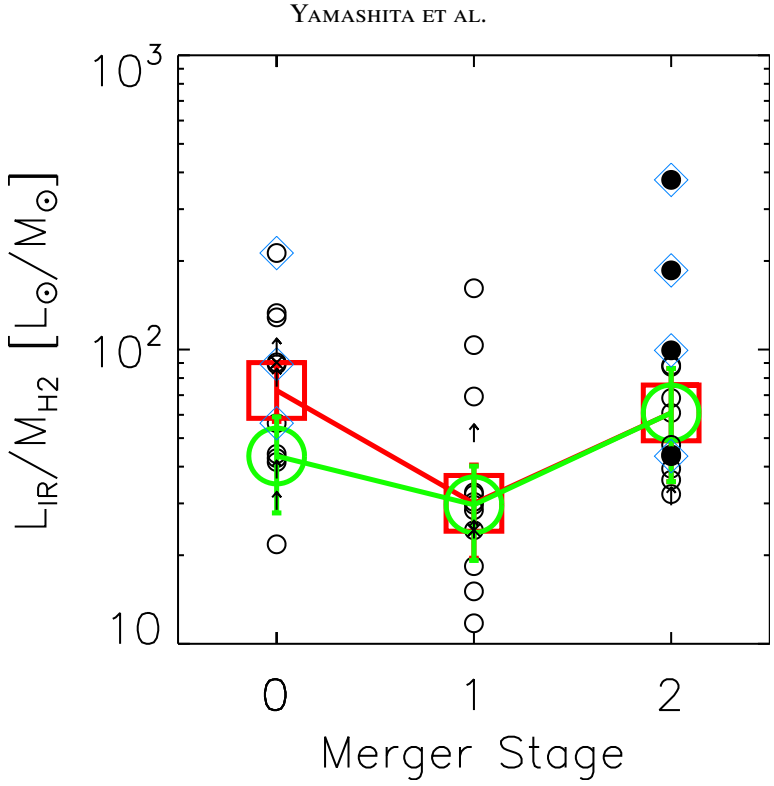

Figure 1. L_{IR}/M_{H_2} ratio with merger stages for 55 galaxies measured by the single point observation in the first three years. The Stage 0 indicates non-interacting galaxies. The Stage 1 represents on-going interacting galaxies (the early and the middle stage), while the Stage 2 has galaxies at the last stage of merger. The open circle represents LIRG, while the filled circle is ULIRG. The blue diamond indicates the AGN-dominated galaxies. The cross indicates the sources extended in far-IR. The arrow represents the limits. The red square and green circle indicate the median and the average of the sources except for ULIRG, the AGN-dominated galaxies and the extended galaxies in far-IR, respectively.

enable us to obtain lines with even much wider velocity-width. SAM45, a FX-type correlator, was employed in the mode of a frequency coverage of 2 GHz (=5217 km/s).

3. RESULT AND DISCUSSION

3.1. Large CO Data of GOALS LIRGs

We present the CO emissions from 44 GOALS LIRGs (55 galaxies) observed with the single-point observations in the first to third run. This provides a large CO data set for local LIRGs without any selection bias. Our observational result shows that M_{H_2} of the sample ranges from $7.4 \times 10^8\,M_\odot$ to $2.6 \times 10^{10}\,M_\odot$ (CO-H_2 conversion factor $\alpha_{CO} = 2.45\,M_\odot\,(K\,km\,s^{-1}\,pc^2)^{-1}$, ref. Bryant & Scoville 1999). Some sources have more than 600 km s^{-1} of the velocity width of the emission line. Some sources have a line with a double-peak.

Some CO fluxes with NRO 45 m (HPBW=15″) are about 15–70 % lower than those by a previous study with NRAO 12 m (HPBW=55″, Sanders et al. 1991) because of a difference of the beam sizes of the both telescopes. Some galaxies apparently have CO distributions extended over the beam size of NRO 45 m. We therefore flag the extended sources that have a larger spatial profile of the 70 μm image than the NRO 45 m beam. We hereafter discuss the 55 sources measured by the single point observation in the first three years.

3.2. Merger Process in GOALS LIRGs

Galaxy-galaxy interaction can trigger violent star-forming activity and the fueling of central black holes. Since the SFR is not expected to be uniform during the merger process (e.g., Mihos & Hernquist 1996), exploring the ratio of the infrared luminosity and the molecular gas mass can tell us about the star-formation efficiency during the merger. We compare L_{IR}/M_{H_2} ratio, which is proportional to SFE, with the merger stages. The sources are morphologically classified according to the classification in Stierwalt et al. (2013) into three groups. Stage 0 contains the non-interacting galaxies. Stage 1 correspond to the three stages of the *pre-mergers*, the *early-stage mergers* and the *mid-stage mergers* in Stierwalt et al. (2013). The *last-stage mergers* are assigned to Stage 2. Figure 1 shows a significant increase in L_{IR}/M_{H_2} ratio between the Stage 1 and the Stage 2 for a LIRG sample except both AGN-dominated galaxies (Petric et al. 2011; Stierwalt et al. 2013) and the extended galaxies in far-IR. Although this is a preliminary result, it shows higher efficiency of the star formation at the last stage of merger.

4. PLAN FOR *SPICA*

The spatially resolved mid-/far-IR images by *SPICA* enable us to trace the spatial transition of violent star-forming regions at each merger stage. The resolution of MCS/WFC-L (2.″4) compares with giant molecular complexes (a few sub kpc) on local LIRGs. The detailed view on merger processes requires the physical conditions: temperature, density, ionization condition. Fine structure lines observed with SAFARI will provide the physical conditions without effects by heavy dust. While CO(J=1–0) observations trace the cold molecular gas, H_2 pure rotation transitional lines in mid-IR trace the warmer molecular gas, which is associated with PDR, Xray or shock. Therefore H_2 lines observation with *SPICA* provide full amount of molecular gas throughout cold to hot one together with the CO observations. The warm gas fraction at each stage of merger might probe the star-formation in galaxies (Dale et al. 2005). The knowledge of warm molecular gas in local LIRGs can be applied to LIRGs at high redshift. We plan to investigate the evolution of the properties of molecular gas from high redshift to local LIRGs.

5. SUMMARY

We conducted the survey of ^{12}CO(J=1–0) with the Nobeyama 45 m telescope from the unbiased selected 44 GOALS LIRGs. We find that the $L_{\rm IR}/M_{\rm H_2}$ ratio increases between the last stage of merger and at the early/middle stages. The high spatial resolution and the high sensitivity of *SPICA* will enable us to investigate where is the burst induce in local interacting LIRGs and how do the physical conditions or the properties of molecular gas progress as the interacting phase.

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REFERENCES

Armus, L., et al. 2009, PASP, 121, 559
Bryant, P. M., & Scoville, N. Z. 1999, AJ, 117, 2632
Dale, D. A., et al. 2005, AJ, 129, 2197
Díaz-Santos, T., et al. 2010, ApJ, 723, 993
Gao, Y., & Solomon, P. M. 2004a, ApJS, 152, 63
— 2004b, ApJ, 606, 271
Iwasawa, K., et al. 2011, A&A, 529, A106
Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641
Petric, A. O., et al. 2011, ApJ, 730, 28
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, ApJ, 370, 158
Sanders, D. B., et al. 2003, AJ, 126, 1607
Solomon, P. M., et al. 1987, ApJ, 319, 730
Stierwalt, S., et al. 2013, ApJS, 206, 1