Pre-Starbursts in Luminous IR Galaxies

Y. Gao*, R. Gruendl*, K.Y. Lo*, C.Y. Hwang†, & S. Veilleux†

*Lab. for Astronomical Imaging, Dept. of Astronomy, Univ. of Illinois
†IAA, Academia Sinica, Taiwan, ROC
‡Dept. of Astronomy, Univ. of Maryland

Abstract. We present first results of our on-going BIMA Key Project: imaging the CO(1-0) emission from a sample of 10 LIRGs that are at various merging stages, with special emphasis on systems apparently in the early/intermediate stages of merging. We present here CO images with ~ 5″ resolution. An important result is the recognition of a plausible pre-starburst phase in some early LIRG mergers (e.g., Arp 302 and NGC 6670). Our initial analysis suggests that a merger-induced starburst phase may not begin before the nuclear separation between the merging galaxies reaches roughly 10 kpc. The surface gas density seems to increase from a few times 10^2 M_☉ pc^-2 to > 10^3 M_☉ pc^-2 while the prominent CO extent systematically decreases as merging progresses.

INTRODUCTION

Luminous IR galaxies (LIRGs, L_IR > 2 × 10^{11} L_☉, H_0 = 75 km s^-1 Mpc^-1), emit most of their bolometric luminosity in the far-IR (up to > 90% ), and are the dominant class of galaxies in the local universe at these high luminosities [10]. Many LIRGs are interacting/merging galaxies [7,3,6] rich in molecular gas [8,2,11]. It is not well understood whether starbursts produce most of the IR luminosity, how the starbursts are initiated and what role galaxy-galaxy interactions might play in triggering these starbursts.

A study of the molecular gas properties at various phases of the merging process in LIRGs would help identify the key physical processes involved. Previous CO imaging studies have concentrated on relatively advanced merger systems [9] in which the interstellar medium (ISM) has already been highly disrupted by the interaction and starbursts. In order to isolate the conditions in the ISM leading to starbursts, we have started a program to study a sample of LIRGs chosen to represent different phases of the interacting/merging process, using the newly expanded Berkeley-Illinois-Maryland Association (BIMA) millimeter-wave array [12]. The goal is to sample statistically the evolution of physical conditions of the molecular material in LIRGs as compared with the properties of the IR emission along the merger sequence.
TABLE 1. Luminous Infrared Galaxies in a Merger Sequence.

| Source   | cz  | R_{sep}^a | L_{IR} | M(H_2)^b | Beam | CO^c | Σ_{H_2}^d | SFE^e |
|----------|-----|-----------|--------|----------|------|------|----------|-----|
|          | km s^-1 | kpc  | 10^{11} L_⊙ | 10^{10} M_⊙ | "" kpc |      | M⊙ pc^-2 |      |
| ARP302   | 10166 | 25.8 | 4.1 | 8.0 | 6.0 | 3.7 | u+e | 1450 | 5.0 |
|          |       |       |     |     |     |     |      | 60.20 | 6.0 |
| N6670    | 8684  | 14.6 | 3.8 | 5.5 | 4.8 | 2.7 | u+e | 850  | 6.9 |
|          |       |       |     |     |     |     |      | 8.7.6.9 | 8.7 |
| U2369    | 9475  | 13.1 | 3.9 | 3.4 | 6.1 | 3.6 | u+e | 1250 | 11.5 |
|          |       |       |     |     |     |     |      | 15.4  | 15.4|
| ARP55    | 11773 | 10.7 | 4.7 | 5.8 | 4.4 | 3.1 | u+e | 1320 | 8.1 |
|          |       |       |     |     |     |     |      | 15.4  | 15.4|
| I Zw107  | 12043 | 4.8  | 7.2 | 3.4 | 3.9 | 2.9 | u+e | 1000 | 21.2 |
|          |       |       |     |     |     |     |      | 30.   | 30. |
| N5256    | 8239  | 4.7  | 3.1 | 2.7 | 4.6 | 2.3 | u+e | 1260 | 11.5 |
|          |       |       |     |     |     |     |      | 12.5  | 12.5|
| N6090    | 8830  | 3.5  | 3.0 | 2.4 | 5.8 | 3.1 | u   | 930  | 12.5 |
|          |       |       |     |     |     |     |      | 17.2  | 17.2|

^a Projected separation between the two galaxy nuclei.
^b M(H_2)=4.78 L_{CO}, where L_{CO} is the single-dish CO luminosity in K km s^{-1} pc^2.
^c CO morphology, u≡ unresolved peak; e≡ extended structures resolved by the beam.
^d Observed peak surface gas density uncorrected for inclination. Note Arp 302 and NGC 6670 have inclination angles larger than 75°.
^e Given by L_{IR}/M(H_2) [L_⊙/M_⊙]. The far-IR luminosities are estimated by scaling the far-IR emission and extent following that of the radio continuum emission. First number is a global value while the second row shows each peak value.

SAMPLE AND OBSERVATIONS

Our sample emphasizes LIRGs which appear to be in the early and intermediate stages of merging with large nuclear separation (Table 1). These LIRGs are potentially the most molecular gas-rich systems since the CO luminosity is found to increase with increasing separation of the merging nuclei in a sample of \sim 50 LIRG mergers [2].

The BIMA array is ideally suited to study these early/intermediate LIRG mergers given its large primary beam and wide spectral bandwidth. The observations presented here were all made with the 9-element BIMA array in the H/C configurations in 1996.

RESULTS AND DISCUSSIONS

Fig. 1 shows integrated CO intensity (contours) overlayed on broad-band images in 4 LIRGs in an order of decreasing nuclei separation. Although LIRGs in our sample have very small ranges in L_{IR} and L_{CO}, the apparent differences in CO morphology and gas properties are clearly seen along the merger sequence:

- The morphology of the molecular gas in LIRGs changes, along the merger sequence, from the weakly disturbed two separated gas disks, e.g., early or pre-mergers like Arp 302 [4] and NGC 6670 → the disturbed or merged-common-
envelope gas disks (intermediate mergers like Arp 55 and Mrk 848) → a single common gas disk for the double nuclei of the two galaxies (close to the advanced mergers like NGC 6090).

- The total spatial CO extent drops from \( \sim 20 \) kpc for the early mergers to a few kpc for the intermediate and advanced mergers. Very advanced mergers like Arp 220 have typical nuclear CO concentration \( \lesssim 1 \) kpc [9].

**FIGURE 1.** CO contours overlayed on CCD images in four typical LIRGs in order of decreasing nuclear separation. The contours plotted are 2,3,4,6,8,12,16,24,32 \( \sigma \) levels.
• The corrected face-on central gas surface density (lower-limits due to resolution) increases from a few times $10^2 \, M_\odot \, \text{pc}^{-2}$ to $> 10^3 \, M_\odot \, \text{pc}^{-2}$ along the sequence. Whereas advanced mergers such as Arp 220 and Mrk 273 have typical values $> 10^4 \, M_\odot \, \text{pc}^{-2}$.

• The $L_{\text{IR}}/M(\text{H}_2)$ ratio (star formation efficiency, SFE) increases by roughly a factor of two from the early mergers to the intermediate/advanced mergers. When we scale the IR luminosity and extent with those of the radio continuum emission [1] using the well-known correlation between far-IR and radio continuum flux densities [5], we can estimate the central SFE ratio which tends to increase more drastically than the global SFE along the sequence (see Table 1).

• The SFE ratio usually ranges from 20 to 100 $L_\odot/M_\odot$ in LIRGs. However, we found that early mergers like Arp 302 [4] and NGC 6670 appear to have much smaller SFE throughout the entire interacting/merging disks, comparable to that of GMCs in the Milky Way disk. The level of star formation activity in early mergers is therefore remarkably similar to that of GMCs. This strongly suggests that LIRGs in the early stage of merging are in a pre-starburst phase.

• In intermediate stage LIRG mergers the starbursts appear to have “turned-on”, exhibited by higher SFE ratios especially in the nuclei. This may imply that starburst phase does not begin before the separation between the merging galaxies reaches roughly 10 kpc characterizing these intermediate stage LIRG mergers.

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