MID-INFRARED IMAGES OF LUMINOUS INFRARED GALAXIES IN A MERGING SEQUENCE

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ABSTRACT

We report mid-infrared observations of several luminous infrared galaxies (LIGs) carried out with the Infrared Space Observatory. Our sample was chosen to represent different phases of a merger sequence of galaxy-galaxy interaction with special emphasis on early/intermediate stages of merging. The mid-infrared emission of these LIGs shows extended structures for the early and intermediate mergers, indicating that most of the mid-infrared luminosities are not from a central active galactic nucleus. Both the infrared hardness (indicated by the IRAS 12, 25, and 60 μm flux density ratios) and the peak-to–total flux density ratios of these LIGs increase as projected separation of these interacting galaxies become smaller, consistent with increasing star formation activities that are concentrated to a smaller area as the merging process advances. These observations provide among the first observational constraint of largely theoretically based scenarios.

Subject headings:
galaxies: individual (Arp 302, NGC 6670, UGC 2369, NGC 7592, NGC 5256, Markarian 848, NGC 6090) — galaxies: interactions — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

Luminous infrared galaxies (LIGs) emit most of their energy in the infrared wavelengths and are the most numerous extragalactic sources with bolometric luminosity larger than 10^{11} L_{⊙} in the local universe (Sanders & Mirabel 1996). The energy source of the infrared emission in these LIGs is a fundamental issue in the studies of this subject. Most LIGs are found to be interacting galaxy systems, suggesting that collisions and mergers are the major mechanisms in triggering the bulk of the luminous infrared emission. Many observations have shown that starbursts, induced by the gravitational interaction of merging galaxies, could account for the infrared emission (see Sanders & Mirabel 1996 for a review). On the other hand, some observations have shown that active galactic nuclei (AGNs) might be the dominant energy source for some of the most powerful LIGs (e.g., Sanders et al. 1988; Genzel et al. 1998).

Numerical simulations of merging gas-rich spiral galaxies have shown how the gas is redistributed during the merging process (e.g., Barnes & Hernquist 1996; Mihos & Hernquist 1996). By assuming that the star formation rate (SFR) was proportional to some power of density (Schmidt law), Mihos & Hernquist (1996) inferred that sharp changes of the SFR of the galaxies occur as merging progresses. This simulated SFR merely reflects the density evolution of the gas. Direct observational evidence is necessary in order to establish how and when starbursts are initiated during the merging process.

We have undertaken a study consisting of millimeter, optical, radio, and mid-infrared observations of an entire merging sequence of LIGs in an attempt to trace the evolution of gas distribution and starbursts. A sample of gas-rich LIGs was chosen to represent different phases of the interacting/merging process, with emphasis on the early and intermediate merging phases so that the physical state of the ISM leading to starbursts can be identified. In this Letter, we present results of mid-infrared images of these LIGs observed with the ISOCAM on the Infrared Space Observatory (ISO). The purpose of the mid-infrared imaging is to locate the source and distribution of star formation with fairly good resolution, which is unavailable at far-infrared.

2. OBSERVATIONS AND DATA REDUCTION

We carried out the mid-infrared observations of a sample of galaxies using the ISOCAM imaging facility (Cesarsky et al. 1996) on board the ISO satellite (Kessler et al. 1996). All of these galaxies have far-infrared luminosities L_{FIR} ≥ 2 × 10^{11} L_{⊙} detected by IRAS and were selected to represent different stages of a merging process. These galaxies were observed with the LW3 (12–18 μm) broadband filter, and when possible some of the galaxies were also observed with the LW2 filter (5–8.5 μm) in order to have a control on the contamination of polycyclic aromatic hydrocarbon (PAH) emission on the continuum flux. Images of these galaxies were obtained in a 2 × 2 raster mode with the 3″ pixel field of view (PFOV) lens and a step size of 48″; the resulting field of view is ∼144″. We conducted 13 exposures of 5.04 s integration per raster position for LW3 and LW2 observations. Ten additional exposures were made before these observations for stabilization.

The data reductions were performed using the CAM Interactive Analysis and software developed at IPAC. The data were deglitched using the multiresolution median transform filtering model to remove spurious spikes caused by cosmic rays (Siebenmorgen et al. 1996); the data were then checked and deglitched manually as necessary. Detector transients were fitted and removed using the IPAC simplified analytic model. To do dark and flat-field corrections, we used the flat fields estimated from the median of all frames and adopted the dark-current and flat-field corrections. To do dark and flat-field corrections, we used the flat fields estimated from the median of all frames and adopted the dark-current and flat-field corrections. The resulting data were then mosaicked to produce the final sky maps.

3. RESULTS AND DISCUSSION

The ISOCAM LW3 and LW2 images of these LIGs are displayed in Figures 1 and 2. The mid-infrared emission of
These LIGs are extended with respect to the resolution of the beam size even for the most advanced merger, UGC 2369-S (the southern galaxy of UGC 2369). The emission regions extend more than a few kiloparsecs in these merger systems, indicating that the heating sources of the mid-infrared emission also extend over a similar size scale.

The 7 μm emission (Fig. 2) is dominated by PAH emission. For comparison, we summarize the measured LW2 and LW3 fluxes of our observations in Table 1. We note that the flux density ratios $S_{15}/S_7$ are ~2 for the early merger Arp 302 and the northern galaxies of UGC 2369 (UGC 2369-N), while the flux ratios are much higher (~3–5) for the more advanced mergers.

![Fig. 1.—ISOcam LW3 (15 μm, Δλ = 2.75 μm) images of seven LIGs in a merging sequence.](image)

**TABLE 1**

| Source | Separation (kpc) | LW3 Filter (15 μm) | LW2 Filter (7 μm) |
|--------|------------------|--------------------|-------------------|
|        |                  | $S_\lambda^a$ (Jy) | $S_\lambda^a$ (Jy) | $S_\lambda^a$ (Jy) | $S_\lambda^a$ (Jy) |
| Arp 302 | 25.8             | 0.51 ± 0.01        | 0.27 ± 0.01        |
| (VV 340A) | …             | 0.40 ± 0.01        | 0.22 ± 0.01        | 0.01 ± 0.001 |
| (VV 340B) | …              | 0.11 ± 0.01        | 0.0049 ± 0.0007    | 0.053 ± 0.003 | 0.0034 ± 0.0016 |
| NGC 6670 | 14.6             | 0.27 ± 0.01        | …                 | …               |
| (NGC 6670-E) | …         | 0.29 ± 0.01        | 0.023 ± 0.001      | …               |
| (NGC 6670-W) | …      | 0.27 ± 0.01        | 0.018 ± 0.001      | …               |
| UGC 2369 | 2.2              | 0.70 ± 0.01        | 0.21 ± 0.01        |
| (UGC 2369-S) | …        | 0.65 ± 0.01        | 0.11 ± 0.01        | 0.18 ± 0.01 | 0.28 ± 0.001 |
| (UGC 2369-N) | …       | 0.053 ± 0.003      | 0.0023 ± 0.0005    | 0.029 ± 0.002 | 0.0022 ± 0.0006 |
| NGC 7592 | 7.1              | 0.66 ± 0.01        | 0.054 ± 0.001      |
| NGC 5256 | 5.5              | 0.56 ± 0.01        | 0.054 ± 0.002      |
| Mrk 848  | 4.8              | 0.52 ± 0.01        | 0.10 ± 0.01        | 0.014 ± 0.004 |
| NGC 6090 | 3.5              | 0.53 ± 0.01        | 0.15 ± 0.01        | 0.020 ± 0.001 |

Note.—The errors shown in the table are statistical errors; the systematic errors might be larger than 10% (K. Ganga 1998, private communication).

$^a$ $S_{\lambda}$ is total flux density; $S_\lambda$ is peak flux density.

$^b$ NGC 6670-E is the eastern galaxy of NGC 6670; NGC 6670-W is the western galaxy of NGC 6670.

$^c$ The southern galaxy of UGC 2369 shows double nuclei at near-infrared and is assigned as an advanced merger.
advanced mergers. Since the 7 μm wave band is dominated by the PAH features (Acosta-Pulido et al. 1996), our results indicate that the relative strength of the PAH emission might decrease in advanced merging stages.

Our results exclude AGNs and favor a star formation origin for the mid-infrared emission because of their extended emitting sizes. The spatial distribution of infrared emission from these LIGs is different from that of ultraluminous infrared galaxies (ULIGs), which often show point-source emission at mid-infrared wavelengths (e.g., Sanders et al. 1988; Genzel et al. 1998) and are thought to host an AGN as the dominant source for the infrared luminosity. Nonetheless, it cannot be ruled out that an AGN might still contribute to the total luminosity for some of these LIGs. In fact, some LIGs in our sample have been identified as Seyfert 2 galaxies (e.g., NGC 5256 and NGC 7592), and some portion of their infrared luminosity emission might come from a central AGN.

The extension of the 15 μm emission is strongly correlated with the apparent separation between the merging galaxies. To investigate the possible concentration of the mid-infrared emission in the merging process, we use the ratio of the peak to total flux of the 15 μm (LW3) emission as an indicator. In Figure 3a we plot the peak-to-total flux ratio as a function of projected separation between the two nuclei of these interacting galaxies. The peak-to-total flux ratios show a strong anticorrelation with the separation; the linear correlation coefficient is $-0.80$, corresponding to more than 95% significance. For point sources, the ratios only reflect the distribution of the point-spread function of the imaging facility and should be similar for any point source. The theoretical peak to total flux ratio of the point-spread function is about 0.33 with the 3″ PFOV for the LW3 filter; it is obvious that our sample has a more extended distribution than a point source even for the most advanced merger UGC 2369-S. Furthermore, we found that the ratios can be well fitted with a power law:

$$\frac{P}{T} = AD^{-p},$$

where $P/T$ is the peak-to-total flux ratio of these LIGs, $D$ is the separation distance, and $p$ is the power-law index. The best-fit index is found to be $-0.56$. A simple interpretation for the correlation is that the mid-infrared-emitting components (dust and molecular gas) of individual galaxies coalesce together as the merging progresses, and the coalesced gas would have a higher gas density in a smaller volume, which would produce
a higher star formation rate and a higher peak-to-total flux ratio if a Schmidt law is applicable. If the behavior of the infrared emission distribution can be extrapolated to even more advanced mergers, these advanced mergers would have emission with a compact distribution similar to that of ULIGs.

Figures 3b and 3c plot the flux density ratios $S_{\nu}(12 \mu m)/S_{\nu}(25 \mu m)$ and $S_{\nu}(25 \mu m)/S_{\nu}(60 \mu m)$ of IRAS observations as a function of separation distances for these interacting galaxies. The $S_{\nu}(12 \mu m)/S_{\nu}(25 \mu m)$ ratios decrease as the separations become smaller. Since the IRAS 12 $\mu m$ emission is dominated by PAH features, this result indicates that the relative PAH strength decreases as the galactic interaction progresses. This is consistent with our measurements of the ISO CAM 7–15 $\mu m$ flux density ratios. We note that Genzel et al. (1998) have also found a similar trend for the 7.7 $\mu m$ PAH emission among starburst galaxies, ULIGs, and AGNs. On the other hand, the $S_{\nu}(25 \mu m)/S_{\nu}(60 \mu m)$ ratios increase as the separation distances become smaller. These results indicate that the interstellar radiation field that would heat the dust and destroy the PAH molecules in the galaxies becomes stronger as the merging progresses. This is consistent with the star formation rates increasing as the galaxies merge. The representative values of $S_{\nu}(25 \mu m)/S_{\nu}(60 \mu m)$ for a galaxy hosting an AGN is usually greater than 0.18 (Helou 1986); however, the highest $S_{\nu}(25 \mu m)/S_{\nu}(60 \mu m)$ in our sample is only ~0.18, indicating that AGN emission is not important for these LIGs.

The ISO CAM data presented in this Letter was analyzed using CAM Interactive Analysis, a joint development by the ESA Astrophysics Division and the ISO CAM Consortium led by the ISO CAM Principal Investigator, C. Cesarsky, Direction des Sciences de la Matiere, CEA, France. We thank K. Ganga and the ISO staff at IPAC for their help. K. Y. L. and R. A. G. were supported in part by NASA/ISO grant 961504, administered through the Jet Propulsion Laboratory of the California Institute of Technology. C.-Y. H. and K. Y. L. acknowledge support from the Academia Sinica and the National Science Council (grant 88-2112-M-001-020) of the Republic of China in Taiwan. Y. G., R. A. G., and K. Y. L. also acknowledge support from the Laboratory of Astronomical Imaging, which is funded by NSF grant AST 96-13999 and by the University of Illinois.

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