MAPPING INFRARED ENHANCEMENTS IN CLOSELY INTERACTING SPIRAL-SPIRAL PAIRS.
I. ISO CAM AND ISO SWS OBSERVATIONS

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ABSTRACT

Mid-infrared (MIR) imaging and spectroscopic observations are presented for a well-defined sample of eight closely interacting (CLO) pairs of spiral galaxies that have overlapping disks and show enhanced far-infrared (FIR) emission. The goal is to study the star formation distribution in CLO pairs, with special emphasis on the role of “overlap starbursts.” Observations were made with the Infrared Space Observatory (ISO) using the CAM and SWS instruments. The ISO CAM maps, tracing the FIR emission of warm dust heated by young massive stars, are compared to new ground-based Hz and R-band images. We identify three possible subgroups in the sample, classified according to the star formation morphology: (1) advanced mergers (Arp 157, Arp 244, and Arp 299), (2) severely disturbed systems (Arp 81 and Arp 278), and (3) less disturbed systems (Arp 276, KPG 347, and KPG 426). Localized starbursts are detected in the overlap regions in all five pairs of subgroups (1) and (2), suggesting that they are a common property in colliding systems. Except for Arp 244, the “overlap starburst” is usually fainter than the major nuclear starburst in CLO pairs. Star formation in “less disturbed systems” is often distributed throughout the disks of both galaxies with no “overlap starburst” detected in any of them. These systems also show less enhanced FIR emission, suggesting that they are in an earlier interaction stage when the direct disk collisions have probably not yet occurred.

Subject headings: galaxies: interactions — galaxies: nuclei — galaxies: starburst — infrared: galaxies — stars: formation

1. INTRODUCTION

It is well established from IRAS studies that many interacting galaxies show enhanced far-infrared (FIR) emission compared to noninteracting galaxies (Lonsdale, Persson, & Mathews 1984; Kennicutt et al. 1987; Telesco, Wolstebroft, & Done 1988). Most of the emission is due to young massive stars formed in recent starbursts, supporting the idea that galaxy-galaxy interactions can stimulate active star formation ( Larson & Tinsley 1978; Rieke et al. 1980; Condon et al. 1982; Balzano 1983; Gehrz, Sramek, & Weeman 1983; Joseph et al. 1984; Cutri & McAlary 1985); albeit, dust-obscured active galactic nuclei (AGNs) might be responsible for the emission in some cases (Sanders et al. 1988b; Surace & Sanders 1999; Genzel et al. 1998; Lutz et al. 1998). The most extreme FIR luminosities (≥10^{12} \, L_\odot; \, H_0 = 75 \, km \, s^{-1} \, Mpc^{-1}) and highest dust temperatures are found in galaxy mergers where the identity of the component galaxies is often indeterminate (Sanders et al. 1988b; Melnick & Mirabel 1990; Mazzarella et al. 1991; Sanders & Mirabel 1996). After these ultraluminous IR galaxies (ULIRGs), violent starbursts are most likely to be found in closely interacting pairs of spiral galaxies with overlapping disks such as Arp 244 (the Antennae). These pairs dominate the FIR luminosity function between 10^{11}–10^{12} \, L_\odot (Xu & Sulentic 1991).

There is clear evidence in the recent deep surveys carried out at (1) optical/UV/NIR wavelengths by HST (Williams et al. 1996; Williams et al. 1998; Thompson et al. 1999), (2) MIR/FIR wavelengths by ISO (Elbaz et al. 1999; Puget et al. 1999), and (3) submillimeter wavelengths by SCUBA (Blain et al. 1999) that much of the evolution in the history of star formation in the universe is related to starbursts in closely interacting/merging systems. Therefore it is of great interest to understand how the enhanced star formation (starburst) is stimulated in these systems. The question of how starbursts are stimulated in interacting galaxies, leads directly to the more fundamental question of how the star formation is modulated in galaxies (Kennicutt 1989, 1998; Hunter, Elmegreen, & Baker 1998; Wyse & Silk 1987; Dopita 1985). Since stars are formed from gas, an obvious necessary condition for a galaxy to be star-formation active is that it should contain significant gas. On the other hand, it appears that interacting galaxies have in general higher star formation rates (SFRs) not because they have more gas than isolated galaxies, but because the star formation rate per unit gas mass (the so-called star formation efficiency) is much higher (Young et al. 1986, 1989; Solomon & Sage 1988; Sanders, Scoville, & Soifer 1991). As pointed out by Kennicutt (1998) in his discussion of the “Schmidt law” (SFR ∝ σ_g^N, \, N \sim 1.4, where σ_g is the gas surface density), the higher efficiency in starbursts in interacting galaxies may simply be a consequence of their much higher gas densities (Scoville et al. 1994; Solomon et al. 1997; Gao & Solomon 1999; Bryant & Scoville 1999). Unusually high gas density, which occurs almost exclusively in the nuclei of interacting galaxies and mergers,
is certainly an interaction-related phenomenon. Interaction-induced gas inflow is predicted by simulations and is due either to the higher gas viscosity (caused by more frequent cloud-cloud collisions in interacting galaxies: Olson & Kwan 1990a; Struck 1997), or to the torque imposed on the gas by an interaction-induced stellar bar (Barnes & Hernquist 1996).

If enhanced star formation in interacting galaxies is due to higher gas density, which has a simple physical interpretation related to the growth rate of gravitational perturbation (Kennicutt 1998), two predictions can be made:

1. Interaction-induced starbursts should concentrate in the nuclear region.
2. Starbursts in interacting systems of later stages (before the majority of the gas is converted to stars) should be stronger than those in early stages, because the later the stage, the more gas will sink into the nuclei.

As far as the ULIRGs are concerned, these two predictions seem to be in good agreement with the observations (see Sanders & Mirabel 1996 for a review). All ULIRGs appear to be in or close to the final stage of the merger process (e.g., Sanders et al. 1991; Murphy et al. 1996; Clements et al. 1996; Clements & Baker 1996; Mihos & Bothun 1998). The starbursts they harbor are primarily in the nuclear regions. Mihos & Bothun (1998) noted a trend between dynamical age and Hz concentration in the ULIRGs they observed that is consistent with the physical scenario behind the two predictions.

Statistical studies of a large pair sample (Xu & Sulentic 1991) demonstrated that a subsample of closely interacting spiral-spiral pairs (hereafter CLO SS) with separations less than a component diameter and showing optical signs of interaction, exhibit higher mean FIR-to-optical luminosity and FIR color ratios. This FIR excess exists not only with respect to isolated galaxies but relative to other pairs as well (see also Telesco et al. 1988; Jones & Stein 1989; Mazzarella et al. 1991). This result is again in line with prediction (2), because the small separations (normalized to the primary component diameter) of CLO SS pairs suggests that they may often be in a more advanced evolutionary state of a merger sequence compared to other SS pairs (Hwang et al. 1999). It should be noted, though, that (1) since final coalescence usually requires several encounters between a pair of galaxies (Barnes & Hernquist 1996, 1998) and (2) since the orbital geometry of interacting systems is complicated, there is no one-to-one mapping between component separation and interaction stage. However, there is a clear tendency for the apoposis of the orbit to decrease rapidly after the first encounter (Barnes & Hernquist 1998). This suggests that the later the stage, the more chance for the two galaxies to remain close together. On the other hand, the lack of one-to-one mapping between component separation and interaction stage for individual galaxy pairs (coupled with the projection effect) may be the reason for the absence of a monotonic dependence between starburst strength and separation, especially for pairs with wider separations (e.g., Figs. 12 and 14 of Xu & Sulentic 1991; see also Keel 1993).

Contradicting prediction (1), some famous examples of the CLO SS pairs such as Arp 244 (Hummel & van den Hulst 1986; Vigroux et al. 1996; Mirabel et al. 1998) and Arp 299 (Gerz & Solomon 1992). Indeed, the simulation of Mihos, Bothun, Richstone (1993), which modeled star formation in Arp 244 with a prescription similar to the “Schmidt law,” failed to reproduce the overlap starburst. This motivates the following two questions:

1. Are overlap and other extranuclear starbursts common in CLO SS pairs?
2. If yes, then which starburst mode is the more important in CLO SS pairs, nuclear or overlap starbursts?

One must map the star formation distribution in these systems with spatial resolutions much better than IRAS in order to answer these questions. On the other hand, since dust extinction in interacting galaxies can be very large (Gehrz et al. 1983; Kunze et al. 1996), optical star formation mapping may not provide reliable results. These considerations motivated us to map a sample of CLO SS pairs with overlapping disks using two instruments (ISO CAM and ISO PHOT) on board of the Infrared Space Observatory (Kessler et al. 1996). ISO-SWS spectroscopic observations were also made for some pairs (pointing both to the nuclei and to the overlap regions). The imaging observations provided higher angular resolutions than IRAS and orders of magnitude higher sensitivity than KAO (e.g., Bushouse, Telesco, & Warner 1998). This paper is the first in a series that presents and analyzes the ISO observations. We report the first results of ISO CAM and ISO SWS observations, comparing them with results from new ground based Hz observations. ISO PHOT results and a more quantitative multicolored analysis will be presented in a following paper.

2. OBSERVATIONS

2.1. Sample Selection

The pair sample was selected from two catalogs:

1. Catalogue of Isolated Pairs of Galaxies in the Northern Sky (Decl. > −3°) by Karachentsev (1972), hereafter KPG;
2. Atlas of Peculiar Galaxies (Decl. > −27°) by Arp (1966).

The sample selection criteria were

1. spiral-spiral pairs with overlapping disks
2. pair component redshift difference ∆V < 500 km s⁻¹
3. pairs showing one of the three interaction morphology classes defined in the KPG (LIN = bridges and/or tails, ATM = common halo, or DIS = distortion in one or both components)
4. major axis diameter of the primary component D > 1'
5. a pair luminosity ratio L_{fir}/L_{B} > 1, where L_{fir} is the integrated IRAS FIR (82.5 μm) luminosity (Helou et al. 1988) and L_{B} is the combined monochromatic luminosity (νL_{ν}) at 4400 Å estimated from the photographic magnitudes.

Criterion (1) restricts the sample to galaxy pairs with overlapping disks so that we can assess the role of overlap starbursts. This differs from the criterion used to define CLO SS pairs in Xu & Sulentic (1991), which included systems with projected separations up to one primary component diameter. Criterion (4) restricts the sample to relatively nearby pairs and insuring that the chosen sample could be resolved by ISO PHOT (beamwidth θ ~ 45" at 60
| Name (1) | R.A. (J2000) (2) | Decl. (J2000) (3) | B Magnitude (4) | d [arcminute/(kpc)] (5) | z [km s⁻¹] (7) | SEP [arcminute/(kpc)] (8) | L₆₀/L_B (9) | f₆₀/₁₀₀(μm) (10) | L₁₀⁴₀ (L☉) (11) |
|---------|-----------------|-------------------|----------------|-------------------------|--------------|--------------------------|-------------|-----------------|------------------|
| Arp 157* | 01 24 32.8      | +03 47 56         | 12.59          | 1.66 (14.4)            | Sc           | 2105                     | 0.65 (5.6)  | 4.37            | 0.68             | 4.56             |
| NGC 520a | 01 24 32.8      | +03 47 56         | 12.59          | 1.66 (14.4)            | Sc           | 2105                     | 0.65 (5.6)  | 4.37            | 0.68             | 4.56             |
| NGC 520b | 01 24 32.8      | +03 47 56         | 12.59          | 1.66 (14.4)            | Sc           | 2105                     | 0.65 (5.6)  | 4.37            | 0.68             | 4.56             |
| Arp 276 | 02 28 11.1       | +19 35 58         | 13.74          | 1.76 (27.7)            | Sb           | 4142                     | 1.06 (16.7) | 1.74            | 0.33             | 2.19             |
| NGC 3690 | 11 28 31.0       | +58 33 41         | 12.72          | 1.30 (15.8)            | Sc           | 3132                     | 0.38 (4.6)  | 9.12            | 0.99             | 26.6             |
| IC 694   | 11 28 33.5       | +58 33 47         | 12.49          | 1.47 (17.8)            | Sc           | 3121                     | 0.38 (4.6)  | 9.12            | 0.99             | 26.6             |
| Arp 244 | 12 01 52.8       | −18 51 54         | 10.91          | 5.25 (33.4)            | Sm           | 1642                     | 1.21 (7.7)  | 1.15            | 0.59             | 3.86             |
| NGC 4038 | 12 01 55.2       | −18 53 06         | 11.05          | 3.09 (19.7)            | Sb           | 1641                     | 1.21 (7.7)  | 1.15            | 0.59             | 3.86             |
| KPG 347  | 12 36 32.7       | +11 15 28         | 12.02          | 2.47 (21.7)            | Sb           | 2274                     | 1.30 (11.4) | 1.20            | 0.36             | 3.18             |
| NGC 4567 | 12 36 34.7       | +11 14 15         | 11.99          | 3.50 (30.7)            | Sb           | 2255                     | 1.30 (11.4) | 1.20            | 0.36             | 3.18             |
| KPG 426  | 14 33 46.6       | +40 04 52         | 14.80          | 1.35 (40.3)            | Sb           | 7616                     | 0.88 (26.3) | 1.55            | 0.38             | 4.01             |
| UGC 9376a | 14 33 48.4      | +40 05 39         | 14.56          | 1.52 (45.3)            | Sa           | 7764                     | 0.73 (17.9) | 3.39            | 0.55             | 8.36             |
| Arp 81*  | 18 12 54.7       | +68 21 49         | 14.39          | 0.96 (23.6)            | Sb           | 6210                     | 0.84 (15.0) | 6.61            | 0.46             | 4.57             |
| NGC 6621 | 18 13 00.2       | +68 21 12         | 14.23          | 1.00 (24.6)            | Sa           | 6466                     | 0.84 (15.0) | 6.61            | 0.46             | 4.57             |
| NGC 7253a | 22 19 26.2      | +29 23 55         | 15.03          | 1.46 (26.1)            | Sm           | 4718                     | 0.73 (17.9) | 3.39            | 0.55             | 8.36             |
| NGC 7253b | 22 19 31.3      | +29 23 25         | 14.95          | 1.42 (25.4)            | Sm           | 4493                     | 0.84 (15.0) | 6.61            | 0.46             | 4.57             |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Column (1): Names of galaxy pairs and of pair components. Pairs with ISO SWS observations (see Tables 3 and 4) are marked by an asterisk. Column (2): 2000 epoch right ascension. Column (3): 2000 epoch declination. Column (4): Blue magnitude. Column (5): Major axis. Column (6): Hubble type. Column (7): Redshift. Column (8): Component separation. Column (9): FIR-to-blue luminosity ratio. Column (10): f₆₀/₁₀₀(μm) color ratio. Column (11): Integrated FIR (40–120 μm) luminosity calculated from IRAS 60 μm and 100 μm fluxes (Helou et al. 1988) and the mean redshift of the two components (H₀ = 75 km s⁻¹ Mpc⁻¹).
and 100 μm). The final criterion selects SS pairs with FIR/B greater than 2 times the isolated spiral mean \( <L_{\text{IR}}/L_B> = 0.5\), Xu & Sulentic (1991). This is also at least 2 σ above the mean \( L_{\text{IR}}/L_B\) for normal spiral galaxies studied by Corbelli, Salper, & Dickey (1991). Our sample is biased towards FIR enhanced SS pairs in order to minimize the chance of including false CLO SS pairs (wide pairs or accordant chance alignments). It is worthwhile to mention that although FIR/B is a good measure of starburst strength (Xu & De Zotti 1989), it is affected by several factors relatively unrelated to starburst activity including Band extinction and diffuse FIR cirrus emission. Our original sample contained 10 CLO SS pairs but two (Arp 263 and KPG 536) were dropped because of poor ISO visibility parameters. Basic properties for our sample of eight CLO SS pairs are presented in Table 1.

### Tables

#### Table 2

ISO CAM Observations of CLO SS Pairs

| Name        | Observation Date | Filter | \( \lambda (\mu m) \) | \( \lambda/\delta \lambda \) | Pixel Size | Sample Step | \( M \times N \) | Map Size          | rms Noise (1 σ) |
|-------------|------------------|--------|-----------------------|-----------------------------|------------|-------------|-----------------|-----------------|-----------------|
| Arp 157...... | 12.29.96         | LW7    | 9.62                  | 4                           | 3° x 3°    | 45° x 45°    | 4 x 4           | 3.8° x 3.8°     | 0.09 mJy pixel^{-1} |
| Arp 267...... | 8.26.96          | LW3    | 15.0                  | 3                           | 3° x 3°    | 45° x 45°    | 4 x 4           | 3.8° x 3.8°     | 0.09 mJy pixel^{-1} |
| Arp 299...... | 8.27.96          | LW7    | 9.62                  | 4                           | 6° x 6°    | 60° x 60°    | 3 x 3           | 5.0° x 5.0°     | 0.11 mJy pixel^{-1} |
| Arp 244...... | 7.16.96          | LW7    | 9.62                  | 4                           | 3° x 3°    | 45° x 45°    | 4 x 4           | 3.8° x 3.8°     | 0.09 mJy pixel^{-1} |
| Arp 244-02... | 7.28.96         | LW3    | 15.0                  | 3                           | 6° x 6°    | 60° x 60°    | 4 x 4           | 6.0° x 6.0°     | 0.17 mJy pixel^{-1} |
| KPG 347...... | 7.4.96           | LW7    | 9.62                  | 4                           | 6° x 6°    | 65° x 65°    | 6 x 6           | 3.5° x 3.5°     | 0.06 mJy pixel^{-1} |
| KPG 426...... | 8.11.96          | LW7    | 9.62                  | 4                           | 6° x 6°    | 60° x 60°    | 3 x 3           | 5.0° x 5.0°     | 0.11 mJy pixel^{-1} |
| Arp 81........ | 8.19.96          | LW7    | 9.62                  | 4                           | 3° x 3°    | 45° x 45°    | 4 x 4           | 3.8° x 3.8°     | 0.10 mJy pixel^{-1} |
| Arp 278...... | 11.16.96         | LW7    | 9.62                  | 4                           | 6° x 6°    | 60° x 60°    | 3 x 3           | 5.0° x 5.0°     | 0.10 mJy pixel^{-1} |
| Arp 278...... | 11.16.96         | LW3    | 15.0                  | 3                           | 6° x 6°    | 60° x 60°    | 3 x 3           | 5.0° x 5.0°     | 0.10 mJy pixel^{-1} |

#### Table 3

ISO SWS Observations of CLO SS Pairs

| Name       | Observation Date | R.A. (2000) | Decl. (2000) | Filter | Aperture (arcsec) | Resolution (\( \lambda/\delta \lambda \)) | Sensitivity (3 σ, Jy) |
|------------|------------------|-------------|--------------|--------|-------------------|------------------------------------------|----------------------|
| Arp 157.... | 1997 Jun 24      | N1 24 34.9  | 3 47 29.8    | LW7    | 14 x 20           | 1470-1750                                | 0.057                |
| Arp 267.... | 1997 Jun 24      | N2 24 32.8  | 3 47 55.9    | LW7    | 14 x 20           | 1540-2130                                | 0.29                 |
| Arp 299.... | 1997 Jun 24      | OV 24 33.9  | 3 47 42.8    | LW7    | 14 x 20           | 1250-1760                                | 0.80                 |
| Arp 81..... | 1997 Jun 24      | N1 12 55.9  | 68 21 50.1   | LW3    | 14 x 20           | 1760-2380                                | 0.69                 |
| Arp 278..... | 1997 May 29     | N1 29 23 52. | 29 23 11.3  | LW3    | 14 x 20           | 1760-2380                                | 0.69                 |

#### Table 4

Parameters of ISO SWS Observations

| Line        | \( \lambda (\mu m) \) | SWS-band | Aperture (arcsec) | Resolution (\( \lambda/\delta \lambda \)) | Sensitivity (3 σ, Jy) |
|-------------|-----------------------|----------|-------------------|------------------------------------------|----------------------|
| Br\(_g\)...... | 2.63                  | SW-1B    | 14 x 20           | 1470-1750                                | 0.057                |
| Br\(_r\)...... | 4.05                  | SW-2A    | 14 x 20           | 1540-2130                                | 0.29                 |
| [Ne II]...... | 12.81                 | LW-3A    | 14 x 27           | 1250-1760                                | 0.80                 |
| H\(_\alpha\)  | 17.03                 | LW-3C    | 14 x 27           | 1760-2380                                | 0.69                 |
A. Coulais, & H. Wozniak (Saclay) and provided to us by M. Sauvage (1999, private communication). This code did a significantly better job than the standard CIA algorithms.

2.3. ISO SWS Observations

We made spectroscopic observations of four emission lines (Brγ: 2.63 μm; Brδ: 4.05 μm; [Ne ii]: 12.81μm, and H2 S(1): 17.03 μm) using ISO SWS in the grating scan mode (AOT SWS02). Observations were obtained for three pairs in our sample (marked by stars in Table 1) with three positions observed (galaxy nuclei plus overlap region) in Arp 81 and 157 and two positions (both nuclei) in Arp 278 (Table 3). Parameters of these observations are given in Table 4. The purpose of these observations was to measure star-formation rates and extinctions in different locations in the pairs. ISO SWS reductions were performed using the SWS Interactive Analysis package (IA3) developed by the international ISO SWS Consortium.

2.4. Hz Observations

Hz and R-band observations were carried out at (1) Palomar in 1996 February using a Tek 1024 × 1024 CCD mounted on the 1.5 m telescope giving a scale of 0′62 pixel−1 and (2) Calar Alto in 1996 May and 1997 August using a 2048 × 2048 CCD on the 2.2 m telescope giving a scale of 0′33 pixel−1 and/or 0′53 pixel−1. Palomar narrow-band filters centered on redshifted Hz (+[N ii] 6548, 6583) with FWHM ~ 100 Å and adjacent continuum broadband filter (R-band) were used. Calar Alto narrowband (FWHM 50–80 Å centered on Hz) and R-band filters were also employed. The standard stars HD 84937, Landolt 104-334 (Palomar), BD +28 4211 and BD +33 2642 Calar Alto were used for photometric calibration. Standard IRAF data reduction procedures were used to reduce this data. Continuum subtracted Hz images were produced by scaling and subtracting the R frames using field stars to match the frames. Subtraction was carried out interactively until stellar residuals were minimized. Matching R-band images were not obtained for all Calar Alto targets. In those cases continuum-free Hz and [N ii] emission-line images were produced by subtracting the off-centered adjacent narrowband image from the one centered on redshifted Hz narrowband maps, using about half dozen stars in the field for normalization. Aperture photometry was done using both elliptical and circular apertures.

3. RESULTS

3.1. MIR Continuum versus Hz Emission

3.1.1. Individual Pair Properties

Figures 1–4 present MIR and Hz images for our sample. Three images are presented for each source. In the top panels ISO CAM 15 μm contours (9.7 μm for KPG 347) are plotted over an optical image from the Digitized Sky Survey. Contour levels are 2n (n = 1, 2, 3, ...) times the rms noise (σ15 μm for KPG 347) as given in Table 2.

The middle panels show a log gray-scale image of the 15 to 9.7 μm MIR color ratio with ISO CAM 15 μm contours superposed (9.7 μm contours for KPG347). Contour levels are 3 + 3n (n = 0, 1, 2, 3, ...) times the rms noise of the corresponding ISO CAM image, with the range of the gray-scale image varied from source to source in order to maximize the dynamic range. In the bottom panels Hz contours are plotted over the R-band image. Contour levels are different for each source because of the different rms noise levels. 15 and 9.7 μm flux densities are given for the sources in Table 5. The f15/μm/9.7μm ratio depends on both small grain emission and silicate absorption in the 9.7 μm band. Detailed modeling of this ratio will be presented in a future paper.

Arp 299 = NGC 3690/IC 6945.—A pair of gas-rich galaxies IC 694 (east) and NGC 3690 (west) regarded as a local example of a merger in progress (Gehrz et al. 1983; Telesco, Decher, & Gatley 1985; Wynn-Williams et al. 1991; Casoli et al. 1999; Hibbard & Yun 1999; Gallais et al. 1999). Arp 299 is the most IR-luminous pair in our sample.

### Table 5

ISO CAM Fluxes of ClOSS Pairs

| Name          | f6.7 μm (mJy) | f15 μm (mJy) |
|---------------|--------------|--------------|
| (1)           | (2)          | (3)          |
| Arp 157       | 358          | 766          |
| NGC 520a      | 32           | 49           |
| NGC 520b      | 327          | 715          |
| Arp 276       | 241          | 300          |
| NGC 935       | 183          | 228          |
| IC 1801       | 63           | 72           |
| Arp 299       | 1699         | 5977         |
| NGC 3690      | 1071         | 3494         |
| IC 694        | 550          | 2158         |
| Arp 244       | 1227         | 2124         |
| NGC 4038      | 489          | 700          |
| NGC 4039      | 738          | 1427         |
| KPG 347a      | 914          | 1269         |
| NGC 4567a     | 124          | 252          |
| NGC 4568a     | 790          | 1017         |
| KPG 426       | 84           | 110          |
| UGC 9376a     | 32           | 41           |
| UGC 9376b     | 52           | 66           |
| Arp 81        | 171          | 270          |
| NGC 6621      | 129          | 216          |
| NGC 6622      | 22           | 15           |
| Arp 278       | 178          | 253          |
| NGC 7253a     | 126          | 200          |
| NGC 7253b     | 44           | 49           |

* The 15 μm data are taken from Bosselli et al. 1998. Column (1): Names of galaxy pairs and of pair components. Column (2): Flux density at 9.7 μm. The uncertainty is ~15%, dominated by the calibration error. Column (3): Flux density at 15 μm. The uncertainty is ~15%, dominated by the calibration error.
Fig. 1.—MIR and Hα emissions of Arp 299 and Arp 244. Arp 299: (a) Contours of 15 μm emission on optical (DSS) image. Contour levels are $2^n (n = 0, 1, 2, 3, \ldots) \times \sigma_{15 \mu m}$ ($\sigma_{15 \mu m} = 4.7$ arcsec$^{-2}$). Scale: 1′ = 12.1 kpc. (b) Gray-scale (logarithmic scale) image of $f_{15 \mu m}/f_{9.7 \mu m}$ ratio, in the range of 1 (dark) and 10 (bright), overlaid with 15 μm contours [levels: $3 + 3^n (n = 0, 1, 2, 3, \ldots) \times \sigma_{15 \mu m}$]. (c) Hα contours [levels: $3 + 3^n (n = 1, 2, 3, \ldots) \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel = 0′′62] on R-band images. Note that the overlap starburst (Source C in Gehrz et al. 1983) is only ~8′′ above the nucleus of NGC 3690 (the western galaxy). Arp 244: (d) Contours of 15 μm emission on optical (DSS) image. Contour levels are $2^n (n = 0, 1, 2, 3, \ldots) \times \sigma_{15 \mu m}$ ($\sigma_{15 \mu m} = 4.7$ μJy arcsec$^{-2}$). Scale: 1′ = 6.4 kpc. (e) Gray-scale (logarithmic scale) image of $f_{15 \mu m}/f_{9.7 \mu m}$ ratio, in the range of 1 (dark) and 10 (bright), overlaid with 15 μm contours [levels: $3 + 3^n (n = 0, 1, 2, 3, \ldots) \times \sigma_{15 \mu m}$]. (f) Hα contours [levels: $2 + 3^n (n = 1, 2, 3, \ldots) \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel = 0′′62] on R-band images. Note that the overlap starburst (Source A in Vigroux et al. 1996) coincides with the southern peak of the 15 μm emission, while the nucleus of NGC 4039 (the southern galaxy) is ~10′′ southwest of the peak.

System in our sample, with $L_{IR} = 2.7 \times 10^{11} L_\odot$. Remarkably, with $f_{60 \mu m} = 108.9$ Jy, it is one of the brightest (60 μm) extragalactic point sources in the IRAS point-source catalog (Soifer et al. 1987). The component disks are in contact suggesting a relatively advanced stage of coalescence, although the nuclei are well separated and are resolved by ISO CAM. The extranuclear starburst (Source C from Gehrz et al. 1983) is about 8′′ north of the NGC 3690 nucleus (Source B in Gehrz et al. 1983, the western galaxy). It is only marginally resolved (seen as a plateau on the contour plot) from the latter by ISO CAM. Gallais et al. (1999) report ISO CAM CVF observations of...
Arp 299 which cover $48'' \times 48''$ with pixel size of $1''.5 \times 1''.5$. This can be compared to our observations (Table 2) which have a $3'8 \times 3'8$ field of view and a $3'' \times 3''$ pixel size. Their LW3 (15 $\mu$m) map clearly resolves the overlap starburst (Source C) from the nucleus of NGC 3690.

The $f_{1.5 \mu m}/f_{9.7 \mu m}$ ratio map is generally smooth with values close to the ratio of the integrated fluxes ($f_{1.5 \mu m}/f_{9.7 \mu m} = 2$; Table 5) across most of the disks. The nucleus of IC 694 (Source A in Gehrz et al. 1983) and a few locations in the outer disk show ratios as high as $f_{1.5 \mu m}/f_{9.7 \mu m} > 10$. While high values for the ratio may have large uncertainty in the outer regions, the high ratio in the IC 694 nucleus implies a high silicate absorption, which may severely depress the 9.7 $\mu$m flux (see also Gehrz et al.)
FIG. 3.—MIR and Hα emissions of Arp 278 and Arp 276. Arp 278: (a) Contours of 15 μm emission on optical (DSS) image. Contour levels are $2 \times 10^{17}$ erg s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel $= 0^\prime.33$. (b) Gray-scale (logarithmic scale) image of $f_{15 \mu m}/f_{9.7 \mu m}$ ratio, in the range of 1 (dark) and 2 (bright), overlaid with 15 μm contours [levels: $3 + 3^n (n = 0, 1, 2, \ldots) \times \sigma_{15 \mu m}$]. (c) Hα contours [levels: $1 + 3^n (n = 1, 2, 3, \ldots) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel $= 0^\prime.33$] on R-band images. Arp 276: (d) Contours of 15 μm emission on optical (DSS) image. Contour levels are $2 \times 10^{17}$ erg s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel $= 0^\prime.53$. (e) Gray-scale (logarithmic scale) image of $f_{15 \mu m}/f_{9.7 \mu m}$ ratio, in the range of 1 (dark) and 2 (bright), overlaid with 15 μm contours [levels: $3 + 3^n (n = 0, 1, 2, \ldots) \times \sigma_{15 \mu m}$]. (f) Hα contours [levels: $1 + 3^n (n = 1, 2, 3, \ldots) \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ pixel$^{-1}$, pixel $= 0^\prime.53$] on R-band images. Note that the Hα observation was nonphotometric, so the calibration is a rough estimate.

1983). This is consistent with results of CO imaging (Sargent & Scoville 1991; Aalto et al. 1997; Casoli et al. 1999) showing that the nucleus of IC 694 has the highest surface density of molecular gas in the Arp 299 system and comparable to values found in ULIRGs (Downes & Solomon 1998). Allowing for differences in spatial resolution, the inner part of the MIR emission region shows good correspondence with the Hα emission allowing for differences in spatial resolution (Fig. 1c). This indicates that (1) most of the MIR emission is due to dust associated with star formation regions, as suggested by Sauvage et al. (1996) in an ISO CAM study of M51, and (2) the Hα extinction is rather smooth, consistent with the smooth $f_{15 \mu m}/f_{9.7 \mu m}$ ratio image. The outer envelope of the MIR emission is elongated in along P.A. $\sim 45^\circ$ which is also the ISO CAM scan direction. The elongation is contrary to that of the Hα
emission suggesting that the ISO CAM elongation is likely to be an artifact of the transient behavior in the ISO CAM detectors (Cesarsky et al. 1996). Careful transient corrections were included in our reduction of this data, but the very high surface brightness (up to \( \sim 1 \text{ Jy beam}^{-1} \)) in the central region of Arp 299 produce strong effects that are difficult or impossible to remove completely.

Arp 244 = NGC 4038/9 (Figs. 1d–1f).—The “Antennae” are regarded as another local example of a galaxy merger (Rubin et al. 1970; Toomre & Toomre 1972; Schweizer 1978; Hummel & van der Hulst 1986; Vigroux et al. 1996; Mirabel et al. 1998; Evans, Harper, & Helou 1998; Whitemore et al. 1999). ISO CAM images at 6.7 and 15 \( \mu \text{m} \) have been published (Vigroux et al. 1996; Mirabel et al. 1998).
Our 9.7 and 15 μm maps cover a larger area (6′ × 6′). The brightest region in this system at MIR wavelengths involves an extranuclear starburst (Source A) about 15″ northeast of the NGC 4039 nucleus (see Vigroux et al. 1996; Mirabel et al. 1998). There is an Hα peak at Source A, but much fainter than the emission from the NGC 4039 nucleus. Apparently much of the optical emission associated with Source A is extinguished by dust. More intriguingly, the FIR (60, 100, and 160 μm) KAO maps (Evans et al. 1998; Bushouse et al. 1998) show that the FIR peak is displaced north of Source A, at the position of a dark patch in the optical images (e.g., the HST WFC2 images by Whitmore et al. 1999). New SCUBA maps (Haas et al. 2000) at 450 and 850 μm (15″ resolution) reveal large amounts (10^6–7 M☉) of cold dust (<20 K) in the overlap region. There are corresponding radio continuum peaks at both the MIR and FIR peaks (Hummel & van der Hulst 1986). The CO observations (Stanford et al. 1990; Gao et al. 1998; Gruendl et al. 1998) demonstrate that most of the molecular gas in this system is extended throughout the overlap region. The [C II] 158 μm emission also peaks at the dark patch north of Source A (Nikola et al. 1998). All of these observations indicate that, even in MIR, much of the star formation activity in Arp 244 is hidden by dust. Our MIR maps also show some weak emission at the location where the southern tail starts. A similar feature is observed in the radio continuum (Hummel & van der Hulst 1986).

The f_{15 μm}/f_{9.7 μm} ratio map also peaks around Source A with a value of (f_{15 μm}/f_{9.7 μm}) ~ 3. Given that most of the molecular gas is found near this region (Gao et al. 1998), and very strong extinction (~A_v ~ 70) is found from an SWS study of MIR lines in the same region (Kunze et al. 1996), the high (f_{15 μm}/f_{9.7 μm}) level is likely due to significant silicate absorption.

In a separate ISO CAM observation (Arp 244-02, Table 2), we obtained ISO CAM LW3 images further down along the southern tail, including the end of the tail where a dwarf galaxy was found (Schweizer 1978; Mirabel, Dottori, & Lutz 1992). No MIR emission is detected in these tidal features.

Arp 157 = NGC 520a/b (Figs. 2a–2c): This is a very complex system apparently involving two (colliding) disk galaxies, one oriented southeast-northwest (NGC 520a) and another oriented east-west (NGC 520b) (Stanford 1991; Stanford & Balcells 1990, 1991; Bernlöhr 1993a, 1993b). The collision center appears to lie near the nucleus of NGC 520b, where the MIR emission peaks. The CO emission also concentrates at this position (Sanders et al. 1988a). The H I gas shows the kinematic signature of a rotating disk with the same orientation as NGC 520a, while the rotation center is clearly at the nucleus of NGC 520b (Hibbard & van Gorkom 1996). An interesting possibility is that the H I originally belonged to the former but has been captured by the latter (which might have an order of magnitude more mass than the former; Bernlöhr 1993b). Note also that both disks show rotation axes nearly parallel to the axis of the orbital motion (Bernlöhr 1993b), making the hypothesis for migration of the H I gas more reasonable. There is a second, much weaker peak in the MIR emission associated with the nucleus of NGC 520a, where new millimeter synthesis observations failed to detect any CO emission (Hibbard et al. 2000, private communication). The Hα map (see also Hibbard & van Gorkom 1996; and Young, Kleinmann, & Allen 1988) shows very different morphology from the MIR maps which is most likely due to dust extinction of the former. Near the nucleus of NGC 520b, heavy dust lanes are visible in optical images. The (f_{15 μm}/f_{9.7 μm}) ratio, as a rough indicator of silicate absorption, also peaks there. A NIR K-band image of Arp 157 (Bushouse & Werner 1990) shows similar morphology to the MIR images, indicating that the difference between the MIR and optical/Hα morphologies is not due to different angular resolutions. This is consistent with results of Bernlöhr (1993b), whose model predicts that both NGC 520a and NGC 520b have been undergoing starbursts, with the starburst associated with NGC 520a about 2–3 × 10^8 yr older and a factor of ~8 fainter than the starburst associated with NGC 520b.

Arp 81 = NGC 6621/2 (Figs. 2d–2f):—This system was included by Toomre (1978), along with Arp 157 and 244, in a proposed sequence of mergers. A recent HST WFPC B-band image (Keel 1999, private communication) shows that NGC 6622 (the southern galaxy) is likely to be a high-inclination S0 galaxy. Hα and MIR emission from the center of NGC 6622 indicates that some star formation is occurring there but at much lower level than in the nuclear region of NGC6621. The HST image shows a star formation region between the two galaxies along with gas/dust features extend from NGC 6621 and near the center of NGC 6622. There starburst in the overlap region is seen in both Hα and MIR maps. The tidal tail is a marginal (2 ±) detection on ISO CAM images. The nucleus of NGC 6622 and the overlap starburst show rather low f_{15 μm}/f_{9.7 μm} ratios (~1), while the nucleus of NGC 6621 shows a higher level f_{15 μm}/f_{9.7 μm} (~3). A KAO 100 μm observation (Bushouse et al. 1998) detects only the NGC 6621 nucleus. Given the large beam (~50′) it is possible that the overlap starburst may have contributed significantly to the flux. A 1.426 GHz VLA map (Condon et al. 1996) peaks on the NGC 6621 nucleus with an extension that may be due to the overlap starburst or even emission associated with NGC 6622.

Arp 278 = NGC 7253a/b (Figs. 3a–3c):—This system looks like a more edge-on version of the famous “Taffy Galaxies” (UGC 12914/5) (Condon et al. 1993; Jarrett et al. 1999). Both galaxies are highly inclined, and much diffuse emission is observed between the two disks (as in case of “Taffy”). Arp 278 shows evidence of starbursts in both galaxies (Bernlöhr 1993a) with a possible time delay of 10–70 Myr between the components (the larger galaxy shows the younger burst). Both galaxies are detected in the radio continuum (Condon et al. 1996). MIR emission from the northwestern galaxy (NGC 7253a, the primary) peaks at the nucleus, while the peak is offset (toward the primary) in the other component. From deep optical image, the two galaxies appear to be in contact near the nucleus of the southeastern galaxy (NGC 7253b), where several Hα knots exist (Fig. 3c). Given the close link between the star formation regions in the two galaxies as shown in the Hα image, at least some of the emission in those Hα knots is likely due to overlap starburst. In connection with the Taffy Galaxy analogy (Condon et al. 1993; Jarrett et al. 1999), the components of Arp 278 may have recently undergone a face-on collision. The plumes (i.e., the diffuse emission between the two disks) may be viewed as debris from that collision. Keel (1993) suggests that NGC 7253a is undergoing a direct (prograde) encounter. Given that NGC 7253a also dominates the MIR emission of the pair (Table 5), it is likely to be...
the more disturbed component that is the source of most of the debris. The $f_{1.25 \mu m}/f_{0.7 \mu m}$ ratio map peaks at the nucleus of NGC 7253a although, in general, that ratio is not high (<2) indicating that the overall dust extinction is less severe than in Arp 244 and 299.

Arp 276 = NGC 935/IC 1801 (Figs. 3d–3f).—Neither galaxy in this pair shows evidence for strong perturbation. Both the MIR and Hz emissions extend over the galaxy disks. Most of the Hz emission in the primary comes from H II regions in the spiral structure while the nucleus shows little or no emission. This Hz “hole” might be due to over-subtraction of the continuum or, alternatively, may indicate a high extinction in the nuclear region where the MIR emission peaks. A foreground star is projected between the two component nuclei (but not on the overlap region) making Hz measures unreliable there. Hz emission from the smaller galaxy appears more concentrated. With the nucleus contributing significantly to the total flux. Two H II regions on either side of the nucleus and perpendicular to the major axis, contribute much of the remaining Hz flux. No localized Hz or MIR feature is detected in the overlap region. Given the differences in angular resolution, the $f_{1.25 \mu m}$ and Hz maps show similar morphology (i.e., the emission in the primary is extended and that in the secondary is more centrally concentrated). The $f_{1.25 \mu m}/f_{0.7 \mu m}$ ratio map is smooth with little dependence on MIR surface brightness. It is unlikely that dust extinction is high in this pair and the temperature of small grains, which are the major contributors to $f_{0.7 \mu m}$ and $f_{1.25 \mu m}$ does not depend sensitively on the radiation intensity (Desert, Boulanger, & Puget 1990).

KPG 347 = NGC 4567/8 (Figs. 4a–4c).—This pair in the Virgo cluster is known as the “Butterfly Galaxies.” The 9.7 $\mu m$ contours are plotted in Fig. 4. The $f_{1.25 \mu m}/f_{0.7 \mu m}$ ratio image used a 15 $\mu m$ map from Boselli et al. (1998). The two galaxies in this system also show little morphological disturbance. A VLA H i map of the system (Cayatte et al. 1994) shows that the H i distribution of the component disks to be reasonably intact. Star formation is widespread in both galaxies, and unlike the CLO SS discussed above, the $f_{1.25 \mu m}/f_{0.7 \mu m}$ ratio shows dips rather than peaks at the positions of the nuclei with high ratio plateaus in the outer disk. The reason for the variations may be different in this pair, related perhaps to heating of small grains that are responsible for MIR continuum emission. In more active pairs (e.g., Arp 299) silicate absorption is the more likely to be the major cause of variations in the flux ratio.

KPG 426 = UGC 9376a/b (Figs. 4d–4f).—Deep optical image show that the component of this pair are embedded in a common envelope. Both the MIR and Hz morphologies look undistorted (symmetric). Most of the star formation in the northern galaxy is concentrated in the nucleus, while that in the southern galaxy shows a nuclear and ring structure. Detailed comparison between the morphology and simulations (Toomre & Toomre 1972) suggest that the northern galaxy has undergone a retrograde encounter, while the southern galaxy a prograde but high inclination (>30°) encounter. Similar to KPG 347, the $f_{1.25 \mu m}/f_{0.7 \mu m}$ ratio shows dips rather than peaks in the nucleus.

3.1.2. Collective Properties

The eight systems studied in this paper provide a small but representative sample of CLO SS pairs with enhanced FIR emission. The MIR and Hz observations provide direct information about the distribution of star formation, which may impose new constraints on models for interaction-induced star bursts. On the other hand, the uncertainties associated with small sample statistics make the following inferences suggestive rather than conclusive.

We divide our sample into three subgroups based upon the star formation morphology:

1. Advanced mergers (Arp 157, 244 and 299): The nuclei in these systems are still well separated (or they would not have been cataloged as pairs by Arp and/or Karachentsev); however, both the stellar and gaseous disks are “entangled” with each other. These pairs have the least separations (<8 kpc) in our sample. They also show line-of-sight velocity differences $\Delta V \leq 60$ km s$^{-1}$, consistent with a significant dissipation of orbital angular momentum. Simulations (e.g., Mihos et al. 1993; Hibbard & Yun 1999) suggest that these pairs will merge in a few times of $10^8$ years.

2. Severely disturbed systems (Arp 81 and 278): The two disks remain separated, but severe tidal distortions are present. Line of sight $\Delta V \sim 200$ km s$^{-1}$ for these pairs.

3. Less disturbed systems (Arp 276, KPG 347 and 426): Galaxies in these pairs show reasonably normal morphologies in both MIR and optical/Hz images. Although all three pairs are classified ATM or DIS by Karachentsev (1972), our R-band images show nearly normal (Arp 276 and KPG 347) or only weakly distorted (KPG 426) morphologies, in contrast to subgroups 1 and 2. $\Delta V$ ranges from 50–150 km s$^{-1}$ for these binary systems.

The following trends can be drawn from our observations:

1. All five CLO pairs (Arp 81, 157, 244, 278 and 299) in the first two subgroups show localized MIR and Hz emission enhancements in the overlap region. Only in Arp 244 is the overlap region starburst more luminous than the nuclei burst while in Arp 81 and 299 the overlap region starbursts are significantly fainter than the most active nucleus in the system (in Arp 157 and 278 the overlap region is close to one of the nuclei). The inference is that star formation induced by the hydrodynamic collisions of gaseous disks is a common phenomenon in closely interacting galaxy pairs. However, it is apparently seldom the dominant source of starburst emission in these systems. The nuclear starburst, driven presumably by a gravitational tidal force that induces infall of large quantities of gas into galaxy nuclei, is perhaps the major mechanism for the enhanced star formation in these galaxy pairs.

2. CLO pairs in the third subgroup show star formation that is more evenly distributed in the component galaxies. This includes both disk and nuclear activity as is observed in isolated samples at a lower average intensity level. Hz emission regions in these components closely follow the spiral arms, similar to the distribution of star formation in M51 (Sauvage et al. 1996). No overlap starbursts are observed in these systems. With a caution about small sample statistics, they also show relatively low FIR/B ratios $\langle L_{100\mu m}/L_B \rangle = 1.30 \pm 0.25$ and cool FIR colors $\langle f_{60\mu m}/f_{100\mu m} \rangle = 0.36 \pm 0.02$ compared to pairs in the first two subgroups, which show $\langle L_{100\mu m}/L_B \rangle = 4.93 \pm 1.37$ and $\langle f_{60\mu m}/f_{100\mu m} \rangle = 0.65 \pm 0.09$.

3.2. MIR Line Emission

The in-orbit performance of SWS over the observed wavelength regions was much lower than expected at the
time our observations were planned. No Brγ or Brα features were detected while [N II] 12.81 μm and H2 S(1) 17.03 μm were only detected in Arp 157. The ISO SWS results are presented in Table 6. The [N II] 12.81 μm line and H2 S(1) 17.03 μm lines were only detected in the nucleus of NGC 520b (Figs. 5 and 6). A pointing at the overlap region in this pair also detected the [N II] 12.81 μm line (Fig. 7) but this may be contaminated by emission from the NGC 520b nucleus because of the large beam. A Brγ line (EW = 17.0 ± 0.5 Å) was previously reported by Vanzi, Alonso-Herrero, & Rieke (1998).

SWS observations of Arp 244 and 299 exist in the literature. The MIR line ratios, assuming that gas and dust are well mixed, imply rather high dust extinctions: Aν ~ 20 for Arp 299 and Aν ~ 80 for Arp 244 (Kunze et al. 1996; Genzel et al. 1998). It is interesting to compare our new data for Arp 157 with SWS observations of related objects. The [N II] 12.81 μm flux for NGC 520b is comparable to the values detected in the SWS survey of ULIRGs as well as template starburst and AGN sources (Genzel et al. 1998). A more physically meaningful comparison between sources can be made using the ratio of the [N II] 12.81 μm line to total FIR flux estimated from the IRAS observations using $F_{\text{FIR}} = 1.26 \times 10^{-14} (2.58f_{60 \mu m} + f_{100 \mu m})[W m^{-2}]$ (e.g., Sanders & Mirabel 1996). The ratio of $f([N II])/f(\text{FIR}) = 0.001$ for NGC 520b, similar to the values observed in NGC 6240 and Arp 244, and about half the value observed for the nuclei of Arp 299 in the more sensi-

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**Table 6**

| NAME       | POINTING | Brγ (2.63 μm) | Brα (4.05 μm) | [Ne II] (12.81 μm) | H2 S(1) (17.03 μm) |
|------------|----------|---------------|---------------|--------------------|--------------------|
| Arp 157    | N1       | <2.3          | <2.2          | 19.3 (±1.5)        | 2.60 (±0.34)       |
|            | N2       | <0.6          | <2.2          | <1.4               | <1.4               |
|            | OV       | <0.6          | <2.2          | 4.88 (±0.96)       | <1.4               |
| Arp 81     | N1       | <0.6          | <3.0          | <1.4               | <1.4               |
|            | N2       | <2.3          | <2.2          | <0.7               | <0.5               |
|            | OV       | <0.6          | <3.0          | <1.9               | <1.2               |
| Arp 278    | N1       | <0.4          | <3.0          | <1.2               | <0.9               |
|            | N2       | <0.5          | <2.2          | <2.3               | <1.2               |
tive observations reported by Genzel et al. (1998). This is another direct indication that the physical conditions of active star formation in NGC 520b are similar to those observed in Arp 244 and 299, the other two sources in our first subgroup.

4. DISCUSSION

4.1. Overlap Starbursts

What is special about the overlap region? It is the actual interface region of a disk-disk collision. An overlap starburst could then be triggered by direct collisions between giant molecular clouds (GMCs) (Noguchi 1991). At the same time this mechanism may not be very efficient because the galactic disk filling factor of GMCs is very low (<0.01). Jog & Solomon (1992) proposed a more efficient model in which collisions between HI clouds lead to the formation of a hot ionized, high-pressure remnant gas. The overpressure due to this hot gas causes a radiative shock compression of the outer layers of existing GMCs in the overlap region. These layers become gravitationally unstable and trigger a burst of massive star formation in the initially barely stable GMCs. This model can be tested with X-ray observations of the hot remnant gas. High-resolution ROSAT observations of Arp 244 (Fabbiano, Schweizer, & Mackie 1997) revealed X-ray emission in the overlap region. However, given the morphology of the X-ray emission (localized, point-source-like), it is more likely due to supernova remnants associated with the ongoing starburst rather than a hot remnant gas which would be more diffuse. The X-ray emission and star formation associated with the ongoing collision in Stephan’s Quintet (Pietsch et al. 1997; Xu, Sulentic, & Tufts 1999; Sulentic et al. 2000) may be closer to this situation. Future higher resolution AXAF observations could provide more definite results.

If cloud-cloud collisions can indeed trigger star formation (Scoville et al. 1986; Olson & Kwan 1990a, 1991b) then this may be a mechanism (in addition to the gas-density dependence of star formation rate) for interaction-induced star formation enhancements in general. Simulations (Olson & Kwan 1990a, 1991b; Noguchi & Ishibashi 1986; Noguchi 1988, 1991) have shown that cloud-cloud collisions are significantly enhanced throughout the disk owing to the orbit-crossing of gas clouds triggered by gravitational perturbations. This may provide an interpretation for more widely distributed star formation, that shows more moderate enhancement, in “less disturbed” CLO pairs.

It is interesting to compare the overlap starbursts in Arp 299 (Source C-C’ in Gehrz et al. 1983) and Arp 244 (Source A in Vigroux et al. 1996). Table 7 gives the MIR fluxes of overlap starbursts and galactic nuclei for these two systems. The overlap starburst in Arp 244 is significantly brighter than both nuclei combined! On the other hand, the overlap starburst in Arp 299 is much fainter than either of the component nuclei. One possible reason for this difference is that the two pairs are in different stages of the merging process. Arp 299 may be in a later merging stage where more gas has fallen into the galactic nuclei powering intensive starbursts (especially in IC 694; Casoli et al. 1999). Interaction kinematics may also play a role in Arp 299, where IC 694 is undergoing a retrograde encounter (Augarde & Lequeux 1985; Hibbard & Yun 1999). This apparently allows it to retain most of its gas which is then available to the nucleus as fuel for the violent starburst. On the other hand, both disks in Arp 244 are undergoing prograde encounters (Toomre & Toomre 1972; Mihos et al. 1993), and the gas disks have suffered severe disruption (Barnes & Hernquist 1996, 1998) with much of the gas moved away from the central regions (van der Hulst 1979; Gao et al. 1998; Grundl et al. 1998). The highest gas concentration is, in fact, found in the overlap region (Stanford et al. 1990; Gao et al. 1998; Grundl et al. 1998). It is possible that such a gas distribution is unstable and transient (retardation of infall), which might be the reason why such bright overlap starbursts are rare.

4.2. Less Disturbed Systems

Our third CLO SS subgroup shows a modest FIR enhancement but less structural distortion and more extended star formation. These properties are consistent with the hypothesis that they are in an earlier interaction stage than the first two subgroups. The absence of overlap starbursts in these may indicate that a disk-disk collision has not yet occurred. Although no firm conclusion can be reached about their physical separation, the calculation of Xu & Sulentic (1991, Appendix A) shows that components in most close pairs are physically proximate (physical separation ≤ diameter of the primary). Examination of component morphologies in KPG 426, the pair with components most clearly separated in our sample, and consider-

| Name          | R.A. (J2000) | Decl. (J2000) | $f_{6.7 \mu m}$ (mJy) | $f_{15 \mu m}$ (mJy) |
|---------------|-------------|--------------|----------------------|----------------------|
| Arp 299       |             |              |                      |                      |
| NGC 3690a     | 12 28 31.0  | +58 33 41s   | 613 (±65)            | 1410 (±150)          |
| IC 694a       | 12 28 33.5  | +58 33 49s   | 221 (±25)            | 1044 (±110)          |
| Overlap starburstb | 12 28 31.0 | +58 33 49   | 123 (±25)            | 471 (±70)            |
| Arp 244       |             |              |                      |                      |
| NGC 4038a     | 12 01 52.8  | -18 51 54    | 74 (±10)             | 135 (±20)            |
| NNGC 4038b    | 12 01 55.2  | -18 53 06    | 39 (±10)             | 76 (±20)             |
| Overlap starburst4 | 12 01 54.8 | -18 53 03  | 142 (±18)            | 359 (±50)            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Fluxes estimated from point-source extractions.
b Fluxes estimated by summing up the counts in a region of size ~ 15′ after the source associated to the nucleus of NGC 3690 is extracted.
4.3. Variations in the Strength of Star Formation Activity

We suggest that the following sequence of sources of increasing star formation efficiency—isolated galaxies, wide pairs, closely interacting pairs, ULIRGs—may be viewed as an evolutionary sequence for mergers. Results in this paper show further that, within the population of closely interacting pairs (CLO SS), the less disturbed systems may be in earlier stages of interaction and have less enhanced star formation activity compared to severely disturbed systems and advanced mergers.

At the same time, CLO SS pairs show a large scatter in star formation indicators such as $L_{\text{fir}}/L_B$ and $f_{60\,\mu m}/f_{100\,\mu m}$ ratios (Xu & Sulentic 1991). Even among sources from the same subgroups in this study there is a wide range in star formation activity indicators (such as FIR/B). Arp 244, one of the advanced mergers, shows FIR/B lower than the less disturbed systems and one of the lowest $L_{\text{fir}}/M_{\text{gas}}$ ratios in interacting systems (Gao et al. 1998). One explanation for the large scatter in star formation indicators involves variations in galaxy gas content. Galaxies with less gas have less fuel for starbursts, consistent with previous results (Sulentic 1989; Xu & Sulentic 1991). These authors found that SS pairs show higher FIR emission than normal galaxies but little FIR emission from pairs of early-type galaxies (E/S0), which are gas poor. Differences in gas content between CLO SS pairs with strong and weak star formation enhancement will be an interesting area of study for future H I and CO surveys of galaxy pairs. A surprising lack of H I gas depletion was found in a statistical study of an FIR enhanced sample of E+S pairs (Zasov & Sulentic 1994).

Even within a sample of gas rich pairs significant differences in their star formation rates are found. This is true even for galaxies with the same gas surface density where the "star formation efficiency" can differ by as much as an order of magnitude (see, e.g., Fig. 2 of Solomon & Sage 1988). Much of this scatter may reflect the episodic nature of starbursts. Several physical mechanisms may contribute to this episodic behavior. Feedback from massive star formation (such as supernovae explosions and stellar winds) may quench a burst after a few $10^7$ yr (Krugel & Tutukov 1993). This effectively breaks the interaction-induced star formation into pulses, which is confirmed by observations: All starburst durations derived from observation (Rieke et al. 1980; Gehrz et al. 1983; Bernl"ohr 1993a) are on the order of a few times $10^7$ yr even though interactions typically last for several $10^8$ yr (e.g., Hibbard & Yun 1999). When an interacting galaxy is observed in the "off" stage, only a "poststarburst" is seen (examples can be found in Bernl"ohr 1993a). A poststarburst, with most of the OB stars already gone, will have a much reduced effect on star formation indicators (e.g., FIR and Hα emissions).

As demonstrated by the simulations of Noguchi (1991), the periodic orbital motion, which swings the two galaxies back and forth relative to each other several times before they eventually merge, will induce sharp peaks (corresponding to the passages of periapses) in the cloud collision rate, which in turn may also cause pulsational star formation (see also Olson & Kwan 1990a, 1990b).

The episodic nature of starbursts could be a key to understanding why only a single component in many pairs shows enhanced star formation (Joseph et al. 1984). Since the star formation in the members of a pair may well be unsynchronized (Bernl"ohr 1993a), there is a good chance for one of them to be in the "on" phase while the other is "off." At the same time there is a significant probability that both components will be "on" (Lutz 1992; Surace et al. 1993). This suggests that the duration of the "on" and "off" phases must be comparable (a few $10^7$ yr).

Another reason for the scatter in star formation activity could be the interaction geometry. As shown in the pioneering work of Toomre & Toomre (1972), retrograde and high inclination encounters cause much less distortion than direct (prograde) and low inclination encounters. If, as suggested, the less disturbed systems have unfavorable interaction geometries, then the lower star formation activity might result from this rather than from an earlier merger evolutionary stage. However the evidence that the galaxies in Arp 244 (lowest FIR/B in our sample) show prograde rotation (van der Hulst 1979), while IC 694 in Arp 299 (highest FIR/B in our sample) shows retrograde rotation (Hibbard & Yun 1999), argues against this possibility (see also Keel 1993; Lutz 1992). This is not meant to imply that orbital geometry plays no role in the star formation enhancement process. It suggests only that this role is likely to be complex. For example an unfavorable orbital geometry may preserve most of the original gas in a galaxy until a very late stage in the merger process, similar to the role played by a massive bulge in the simulation of Miyoshi & Hernquist (1996; see also Evans, Surace, & Mazzarrella 2000), making a ULIRG-like starburst more possible (see, e.g., the simulations of Noguchi 1991).

4.4. Galaxy Pairs and Mergers

Throughout this discussion we have adopted a scenario where galaxy pairs merge after a few close encounters, as implied by models (e.g., Barnes & Hernquist 1996, 1998). Recent studies on the cosmic evolution of merger rate using HST data (Wu & Keel 1998; Le Fèvre et al. 2000) also hint that the timescale of mergers is much shorter than the Hubble time. However, pair merger timescales as short as $\sim 1$ Gyr require an explanation for the large number of isolated binary galaxies ($\sim 10\%$ of all galaxies; Xu & Sulentic 1991), the majority of which must have been gravitationally bound systems for $\sim 10$ Gyr (Chaterjee 1987). They must also account for the rarity of candidate (early-type) merger postcursor found in the the same environments as these large pair (and compact group) populations (Sulentic & Rabaca 1994).

A possible solution for this dilemma is that today's galaxy pairs are evolved from galaxy groups. Through coalescence, within the context of hierarchical galaxy formation (White 1997), two giant galaxies observed now may be products of a long history of mergers/accretions of smaller galaxies which were formed as a bound system. One possibility is that some mixed pairs (E+S) represent the last stages in the coalescence of a compact group (Rampazzo & Sulentic 1992). Such a picture may apply to the two giant galaxies in the Local Group (Milky Way and M31), which may represent the early stages in the formation of a CLO SS
5. CONCLUSION

We present MIR imaging and spectroscopic observations for a well-defined sample of eight closely interacting pairs of spiral galaxies with overlapping disks and enhanced FIR emission. Our goal was to study the star formation distribution in these pairs with special emphasis on the importance of overlap starbursts. We identified three possible subgroups in our sample according to star formation morphology:

1. advanced mergers
2. severely disturbed systems
3. less disturbed systems.

Overlap region starbursts are detected in all of the five pairs of subgroups (1) and (2), suggesting that they are a common property of colliding systems. On the other hand, except for Arp 244, the "overlap starburst" is less intense than the nuclear starbursts in such pairs. Star formation pairs of subgroup (3) is often more widely distributed in the disks of both components with no evidence for overlap starbursts. These systems also show a smaller FIR enhancement, implying weaker star formation and suggesting that they may be in earlier interaction stages in which direct disk-disk collisions have not yet occurred. Only one pair (Arp 157) is detected in our ISO SWS observations. The $F([Ne \, II 12.81 \mu m]/F(11.25 \mu m))$ ratio in the NGC 520b component of Arp 157 is 0.1, comparable to values for other luminous infrared galaxies.

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