N95- 21759





# INTERACTING GALAXIES RESOLVED BY IRAS

J. M. MAZZARELLA AND J. A. SURACE
*Infrared Processing and Analysis Center, MS 100-22*
*California Institute of Technology, Jet Propulsion Laboratory*
*Pasadena, CA 91125*

**ABSTRACT** We discuss procedures, limitations and results of high resolution processing of interacting galaxies observed by the Infrared Astronomical Satellite (IRAS). Among 56 potentially resolvable interacting groups selected from the IRAS Bright Galaxy Sample, 22 systems have been resolved yielding fluxes for a total of 51 galaxies. In about 2/3 of the resolved pairs, both galaxies were detected in the far-infrared. A set of isolated non-interacting galaxies was chosen from the Bright Galaxy Sample for comparison with the interacting galaxies. For the current sample, which naturally excludes close pairs and ultraluminous merging systems, the primary conclusions are: (a) It is not possible to distinguish *individual* interacting galaxies from isolated galaxies of similar luminosity on the basis of infrared properties alone. (b) No direct correlation was found between measures of interaction strength and indicators of enhanced star formation within the resolved systems. (c) Comparison of the interacting and isolated samples indicates ***statistically significant differences between their distributions of far-infrared color ratios, luminosities, and surface brightnesses.*** Even during the early stages of interaction spanned by these systems, in a statistical sense, tidal perturbations substantially boost far-infrared indicators of star formation compared to non-interacting systems. We also briefly discuss future prospects for pushing the IRAS data to its limits for additional interacting systems.

## INTRODUCTION

Results derived from IRAS observations have been largely responsible for the current surge of interest in interacting galaxies (IGs). The empirical and theoretical stage was set in the pre-IRAS era in the seminal studies of Larson & Tinsley (1978), who explained the large dispersion in the UBV colors of IGs compared to non-IGs using global starburst models, and Toomre & Toomre (1972), who used restricted 3-body simulations to demonstrate the gravitational tidal origin of the tails and bridges often observed in peculiar galaxies. Results from studies of IRAS-selected samples showed very early a predominance of IGs; for example, $\approx$ 30% of IRAS MiniSurvey galaxies were noted to be IGs (Lonsdale et al. 1984). As a baseline, it is useful to note that $\approx$ 8% (6440/77838) of field galaxies are *optically* "peculiar" (e.g., Arp & Madore 1987), which usually means gravitationally perturbed. The frequency of IGs in the IRAS Bright Galaxy Sample, a flux-limited sample complete to 5 Jy at 60 $\mu$m (Soifer et al. 1989),

S. Terebey and J. Mazzarella (eds.), *Science with High-Spatial Resolution Far Infrared Data*, 71–79, 1994, Jet Propulsion Laboratory, Pasadena, CA.

increases steadily with infrared luminosity, from $\approx$ 10% at $L_{ir} = 10^{10} - 10^{11} L_{\odot}$, to $\approx$ 40% at $L_{ir} = 10^{11} - 10^{12} L_{\odot}$, and $\approx$ 100% at $L_{ir} > 10^{12} L_{\odot}$(Sanders et al. 1988). Likewise, the warmest global dust temperatures ($f_{60\mu m}/f_{100\mu m} \gtrsim 0.6$) are found primarily in the closest, overlapping IGs and mergers (Telesco et al. 1988; Mazzarella et al. 1991). The most luminous galaxies discovered in the IRAS database have bolometric luminosities comparable to QSOs ($L_{ir} > 10^{12} L_{\odot}$) and emit the bulk of their radiation (> 50%) in the far-infrared part of the spectrum. These "ultraluminous" far-infrared galaxies are the dominant population in the local universe at such high bolometric luminosities, and they have been proposed to be the dusty precursors of classical UV-excess QSOs (Sanders et al. 1988) and some powerful radio galaxies (Mazzarella et al. 1993). Numerical simulations of the dynamics of IGs have shown that dissipative mergers can be very effective in driving material from a gas-rich galaxy disk inward to fuel a nuclear starburst and in some cases an active nucleus (e.g., Barnes & Hernquist 1992).

Despite the observational and theoretical progress which has been made in studies of IGs (see, for example, recent reviews by Shlosman 1990 and Barnes & Hernquist 1992), numerous outstanding questions remain concerning proposed evolutionary connections between IGs, starbursts, and active galactic nuclei. For example, in a study of optically selected IGs with a median separation of about 20 kpc, Bushouse et al. (1988) found a wide dispersion in far-infrared properties compared to non-IGs, with some IGs in their sample showing no emission-line spectra indicative of currently active star formation. What parameters of the interaction and of the participating galaxies determine the strength of the induced star formation? Since the most excessive far-infrared enhancements are observed only in the most advanced mergers, how does starburst activity evolve during earlier stages of galaxy collisions? Can we track episodic/repetitive starbursts suggested from the simulations of Noguchi (1991)? Answers to these and related questions require far-infrared data for the *individual components* of IGs to match available data at other wavelengths, such as near-infrared and optical array images, spectra, molecular and atomic gas (CO, $H_2$, H I) measurements, and radio continuum synthesis images.

The nominal IRAS resolution is $2' \times 5'$ at 60 $\mu$m; this corresponds to a large galaxy separation of ~85 kpc at a distance of 75 Mpc (cz = 5500 km $s^{-1}$, assuming $H_o$ = 75 km $s^{-1}$ $Mpc^{-1}$), and fails to resolve galaxies at $R \lesssim$ 1-2 diameters, where starburst galaxies begin to "light up" substantially. However, HiRes processing of the IRAS data has the potential to improve resolution by a factor of four or five, to $1'$ at 60 $\mu$m, or ~20 kpc at cz = 5500 km $s^{-1}$. HiRes processing thus presents an opportunity to push the IRAS data to its limits, and begin to investigate questions that will otherwise be untouchable until the next generation of far-infrared satellite observatories become available (ISO and SIRTF). Below we summarize procedures, limitations and results of high resolution processing of some interacting galaxies observed by IRAS.

## GROUPS IN THE IRAS BRIGHT GALAXY SAMPLE

### Sample Selection

The IRAS Bright Galaxy Sample (Soifer et al. 1989, hereafter referred to as the BGS) is a complete flux-limited sample of galaxies with an integrated 60$\mu$m flux density greater than 5.24 Jy. Due to the low resolving power of the IRAS survey at 60 $\mu$m ($\approx 4'$), many of the BGS objects are actually systems of two or more galaxies. In some cases these galaxies are undergoing significant apparent interaction, as indicated by optical tidal features. For purposes of constructing a sample of interacting galaxies which could potentially be resolved by IRAS, an interacting pair was defined as one for which $2S/(D_1 + D_2) < 3$, where $D_1$ and $D_2$ are the major diameters of the two galaxies and S is the separation between their centers. Thus, an interacting galaxy is one for which there is a clearly identifiable companion at a distance which is less than three times their average diameter away (c.f., Byrd et al. 1987; Dahari 1984). Candidates were identified by examining 3× enlarged prints taken from the Palomar Observatory Sky Survey (POSS) plates. Any BGS source that could be identified as consisting of two or more galaxies meeting the above distance–diameter criteria, and which furthermore had a difference in redshift between galactic components of not more than 1000 km $s^{-1}$, was placed in the interacting sample. This selection criterion naturally excludes sources whose extreme distance makes it impossible to distinguish whether they are interacting groups or single galaxies. This also excludes those strongly interacting systems with merging or unrecognizable disks, such as the ultraluminous mergers studied by Sanders et al. (1988). A complete listing of the 56 objects meeting the selection criteria for this interacting sample appears in Surace et al. (1993).

### IRAS Data Processing and Limitations of HiRes

Due to the highly non-circular nature of the IRAS beam, IRAS observations provide greater resolution of targets aligned in the in-scan direction, as opposed to being aligned normal to the in-scan direction (cross-scan). Therefore, the position angle of the galaxies relative to the IRAS scan tracks was examined to determine if additional processing would likely resolve them. Those which showed a sufficiently favorable alignment and separation were reprocessed with the 2-dimensional spatial deconvolution processing of IRAS data known as HiRes (Aumann et al. 1990). For those interacting systems with very large separations ($S \gtrsim 3'$) and with favorable scan coverage, an attempt was made to resolve the target using the ADDSCAN/SCANPI one-dimensional scan coadder instead of HiRes. Because HiRes processing is highly computer intensive, it was not possible to apply this analysis tool to all the interacting systems chosen from the BGS. To reduce the number of sources where HiRes was applied, the following criteria were applied. First, HiRes is only effective for sources brighter than about 1 Jy. If there is considerable background noise, the local signal-to-noise should be at least 10. All the interacting sources met the brightness criteria at 60 $\mu$m by virtue of being in the BGS. Also, sources must be adequately sampled by the IRAS detectors; they should be covered by at least two survey Hours-Confirmation scans. Again, all the BGS sources met this criteria. Finally, candidate sources must be sufficiently separated; this was determined by examining the galaxy separations on the POSS prints.

For the selected galaxies, all four IRAS bands were processed with twenty iterations of HiRes. The pixel size was set to 15″ with a 1° field centered on the target, and all fields received iterative baseline removal. A source was considered detected if a signal was found within 30″ of the known optical position and had a flux density at least three times that of nearby processing artifacts. If the source was not seen, the flux at its presumed position was measured and reported as a $3\sigma$ upper limit.

Examination of the processed IRAS data was complimented by studies of simulated galaxy pairs which were processed through the same IRAS observation simulator as the real data. Simulations in which the position angle of the vector separating the galaxies was in the cross-scan direction indicated that the resolving power dropped by roughly a factor of three compared to that achieved for galaxies aligned along the in-scan direction. The IRAS detector coverage of the field, both the scan density and the position angles of the scans with respect to the vector separating the galaxies, greatly influences whether or not a source will be resolved by HiRes. The variation of HiRes resolving power with galaxy separation is reported in Table 1.

TABLE 1 HiRes Resolving Power for Galaxy Pairs[a]

| Band ($\mu$m) | Unresolved (arcsec) | | Resolved (arcsec) | | Separated (arcsec) | |
|---|---|---|---|---|---|---|
| 12 | < (33) × | (99) | (33 – 99) × | (45 – 130) | > (99) × | (130) |
| 25 | < (33) × | (99) | (33 – 99) × | (48 – 150) | > (99) × | (150) |
| 60 | < (36) × | (90) | (36 – 108) × | (90 – 280) | > (108) × | (280) |
| 100 | < (72) × | (132) | (72 – 216) × | (132 – 390) | > (216) × | (390) |

[a]Values reported are (in-scan)×(cross-scan) separations in arcseconds.

Several stages of resolution were achieved. In cases where the model sources were completely separated, component fluxes were measured simply using aperture photometry. From the simulations, it was found that HiRes was able to reconstruct the flux ratio between two well separated components with a typical uncertainty of 5–8%. In cases of partial resolution, since the typical HiRes footprint for a single point source has the shape of an elliptical Gaussian, the AIPS routines IMFIT and JMFIT were used to fit 2-d elliptical Gaussian components to the HiRes images. The number of Gaussians fitted was determined by the number of galaxies present. Differences in detector coverage led to appreciable differences in resolution, and the estimated uncertainty was greatly affected by the degree of resolution, particularly in the case where the galaxy separation required Gaussian fitting.

### Results

Figure 1 shows the result of HiRes processing of the IRAS data on the galaxy pair Arp 271. For comparison, contour plots of normal IRAS coadded images and HiRes images are shown overlaid on visible pictures of the galaxies. Although

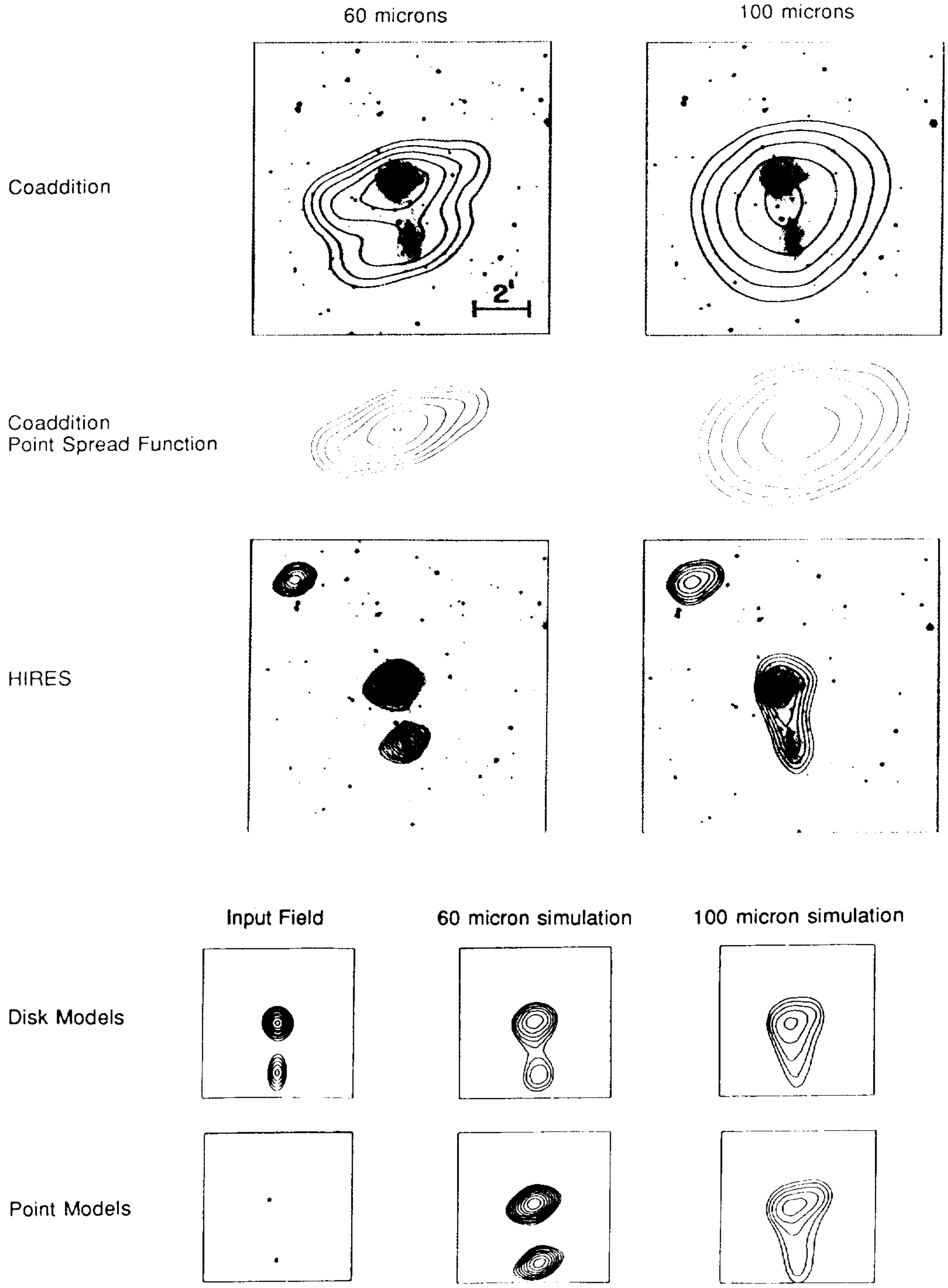


FIGURE 1 HiRes processing of Arp 271. The top two panels show the co-added 60 and 100 $\mu$m IRAS images at the nominal resolution, with contours of the corresponding point-spread functions plotted below each image. The bottom two panels show the result of HiRes processing at 60 and 100 $\mu$m; the HiRes point-spread functions are shown in the upper left corner.

normal coaddition is barely able to resolve the galaxies at 60 $\mu$m, and achieves no resolution at 100 $\mu$m, HiRes is able to resolve two distinct point sources at 60 $\mu$m and is able to significantly resolve the pair at 100 $\mu$m. Of the 56 interacting systems processed with HiRes, 22 were resolved, yielding fluxes for a total of 51 individual galaxies; 24 galaxies have only upper limits for their fluxes at one or more wavelengths. The complete table of data is reported in Surace et al. (1993).

We attempted to quantify whether the infrared properties of the systems correlate with the degree of interaction. The simplest measure is the projected physical separation. For the resolved systems, the mean projected separation is 34 $\pm$18 kpc, and for the unresolved systems 19$\pm$13 kpc. We also utilized the Q parameter of Dahari (1984), $Q = (D_1D_2)^{3/2}/S^3$, where $D_1$ and $D_2$ are the diameters of the galaxies, and S is the separation between their centers. This quantity is proportional to the degree of tidal perturbation between the galaxies; increasing size (and presumably mass) and decreasing separation increases the parameter, and thus more perturbed galaxies have higher Q parameters. The physical projected separations and Q values were treated as independent variables, and $L_{ir}$, $SB_{fir}$, $f_{60\mu m}/f_{100\mu m}$, and $f_{12\mu m}/f_{25\mu m}$were treated as dependent variables to see if the measures of interaction strength manifested themselves in a significant change in infrared properties of the individual galaxies. No correlations were found. Similarly, the tests were performed by examining the *system* parameters; that is, for each interacting system, the average of the component Q values and FIR measurements was used in the statistical tests. No correlations were found. We might also expect the degree of perturbation to be a function of the relative velocities of the galaxies; small velocities make for longer encounters and hence a greater degree of perturbation. However, again, no correlation was found. These null results indicate that either these simplistic measurements of interaction strength are inadequate, or there are numerous complicating factors which must be considered in order to isolate various sources of scatter which may wash out possible correlations between intrinsic, physical processes which are only weakly sampled by the variables used here.

More encouraging results were obtained in statistical comparisons between the properties of the IGs and non-IGs. To minimize selection biases incurred by using optically-selected galaxies, the non-IGs were chosen from the BGS on the basis of optical morphology. The non-IG set was selected by comparing the distributions of the blue luminosities of the IGs and non-IGs, and then randomly deleting galaxies from the non-IGs until both samples had the same normalized frequency distribution of blue luminosity. Figure 2a shows that the IGs and non-IGs span the same range of far-infrared color ratios, and thus *individual* IGs are not distinguishable from non-IGs in these properties. However, it is clear that over all the IGs are distributed more toward lower values of the $f_{12}/f_{25}$ flux ratio and larger values of the $f_{60}/f_{100}$ flux ratio than the non-IGs. A similar effect was seen by Bushouse et al. (1988) in an optically selected sample. The cumulative distribution functions of these color ratios (Figs. 2b and 2c) indeed show statistically significant differences in the distributions; the two-sample Kolomogorov-Smirnov statistic indicates that the probability that the distributions for the two samples are drawn from the same underlying population is less than 1%. A similar effect is seen in the distributions of the infrared surface brightness, $SB_{fir}$ (which correlates strongly with the color ratios); the infrared surface brightness

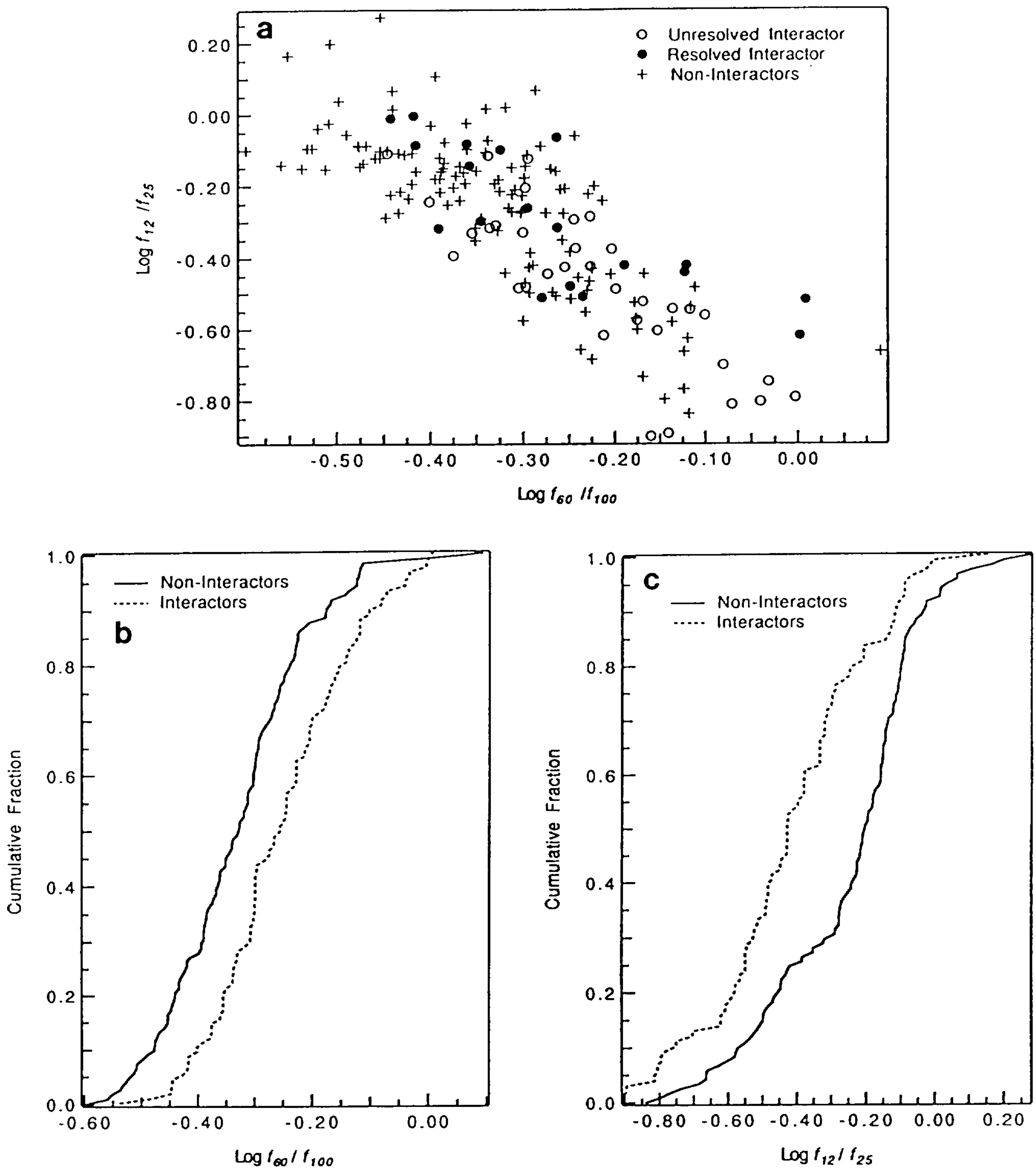


FIGURE 2 (a) Far-infrared color-color diagram for interacting and non-interacting galaxies in the IRAS Bright Galaxy Sample, and cumulative frequency distributions for (b) $f_{60\mu m}/f_{100\mu m}$ and (c) $f_{12\mu m}/f_{25\mu m}$.

distribution of the interacting systems rapidly reaches higher values than those of the non-interactors. The IGs have a median $SB_{fir}$ which is a factor of $\approx 10$ greater than the median $SB_{fir}$ for the non-IGs; likewise, the median $L_{fir}$ is a factor of $\approx 2.5$ higher than the median $L_{fir}$ for the non-IGs. The probability of the samples being drawn from the same underlying population is less than 1%. Additional details of the HiRes processing, simulations and results are presented by Surace et al. (1993).

## FUTURE PROSPECTS

There is, of course, a limit to how far the IRAS data can be pushed for studies of IGs: for example, ultraluminous far-infrared galaxies are much too close together to resolve with IRAS, and it is not possible to separate nuclear and disk components or to study the detailed spatial distribution of the far-infrared emission in even the closest IGs. The high resolution and sensitivity provided by future far-infrared satellites (ISO & SIRTF) will allow us to track the full range of galaxy interaction stages, push to higher redshifts and $L_{ir}$, produce far-infrared color maps to study dust temperature distributions, and investigate nuclear versus disk far-infrared emission components. In the mean time, what can HiRes processing of IRAS data for additional IGs do for us? Studies of far-infrared selected IGs such as those in the Extended IRAS Bright Galaxy Sample (Sanders et al. 1994, in preparation), as well as optically selected binary galaxies, can improve upon the current low-number statistics and selection biases. The IRAS data for additional IGs could also be combined with existing observations at other wavelengths to begin disentangling the numerous factors that are likely responsible for the large scatter in the far-infrared properties of IGs, such as their molecular and atomic gas properties, Hubble types, and interaction dynamics (prograde versus retrograde encounters, etc.).

## SUMMARY

We have reviewed procedures, limitations and results of high resolution processing of interacting galaxies potentially resolvable by IRAS. Simulations and processing of real sources show that the IRAS detector coverage, both the scan density and the position angles of the IRAS scans with respect to the vector separating the galaxies, greatly influences whether or not any particular galaxy pair will be resolved by HiRes. Among 56 groups chosen from the IRAS Bright Galaxy Sample for HiRes processing, 22 systems have been resolved yielding fluxes for a total of 51 galaxies. In about 2/3 of the resolved pairs, both galaxies were detected in the far-infrared. A set of isolated non-interacting galaxies was chosen from the Bright Galaxy Sample for comparison with the interacting galaxies. For the current sample of interacting systems resolved by IRAS, which naturally excludes close pairs and ultraluminous merging systems, the primary conclusions are: (a) It is not possible to distinguish individual interacting galaxies from isolated galaxies of similar luminosity on the basis of infrared properties alone. (b) No direct correlation was found between measures of interaction strength and indicators of enhanced star formation within the resolved systems. (c) Comparison of the interacting and isolated samples indicates statistically sig-

nificant differences between their distributions of far-infrared color ratios, luminosities, and surface brightnesses. These differences can be attributed to heating of the dusty, gas-rich interstellar medium due to the triggering of starbursts in the interacting galaxies. Even during the early stages of interaction spanned by these systems, in a statistical sense, tidal perturbations substantially boost far-infrared indicators of star formation compared to non-interacting systems. HiRes processing of additional interacting galaxies observed by IRAS can provide us with a head start in identifying the best candidates for more sensitive, high-resolution studies with ISO and SIRTF.

## ACKNOWLEDGMENTS

This work was supported by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). This research was done in collaboration with B. T. Soifer and A. E. Wehrle. We thank J. Fowler for useful discussions concerning HiRes processing.

## REFERENCES

Arp, H. C., & Madore, B. F. 1987, *A Catalogue of Southern Peculiar Galaxies and Associations* (Cambridge: Cambridge University Press)

Aumann, H. H., Fowler, J. W., & Melnyk, M. 1990, AJ, 99, 1674

Barnes, J. E., & Hernquist, L. 1992, ARA&A, 30, 705

Byrd, G. G., Sundelius, B., & Valtonen, M. 1987, A&A, 171, 16

Bushouse, H. A., Lamb, S. A., & Werner, M. W. 1988, ApJ, 335, 74

Dahari, O. 1984, AJ, 89, 966

Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46

Lonsdale, C. J., Persson, S. E., & Matthews, K. 1984, ApJ, 287, 95

Mazzarella, J. M., Bothun, G. D., & Boroson, T. A. 1991, AJ, 101, 2034

Mazzarella, J. M., Graham, J. R., Sanders, D. B., & Djorgovski, S. 1993, ApJ, 409, 170

Noguchi, M. 1991, MNRAS, 251, 360

Sanders, D. B, Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K. Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74

Shlosman, I. 1990, in Paired and Interacting Galaxies, I.A.U. Colloquium No. 124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA CP-3098), p. 689

Soifer, B. T., Boehmer, G., Neugebauer, G., & Sanders, D. B. 1989, AJ, 98, 766

Surace, J. A., Mazzarella, J. M., Soifer, B. T., & Wehrle, A. E. 1993, AJ, 105, 864

Telesco, C.M., Wolstencroft, R.D., & Done, C. 1988, ApJ, 329, 174

Toomre, A., & Toomre, J. 1972, ApJ, 178, 623