*RevMexAA (Serie de Conferencias)*, 6, 42–47 (1997)

# LUMINOUS INFRARED GALAXIES

D. B. Sanders[1]


## RESUMEN

Los brotes estelares más intensos en el Universo se encuentran en las galaxias infrarrojas luminosas. El fenómeno que produce estos sistemas parece ser la fusión de galaxias espirales, ricas en gas molecular. Estos objetos podrían representar una etapa inicial en la formación de cúmulos globulares y núcleos de galaxias elípticas, y los sistemas más luminosos podrían representar la etapa inicial en la formación de cuasares.

## ABSTRACT

At luminosities above $10^{11}L_\odot$, infrared galaxies become the dominant population of extragalactic objects in the local Universe (z <0.5), being more numerous than optically selected starburst and Seyfert galaxies, and QSOs at comparable bolometric luminosity. Multiwavelength observations clearly show that the trigger for the intense IR emission is the strong interaction/merger of molecular gas-rich spirals, and that the bulk of the IR luminosity for all but the most luminous objects is due to dust heating from an intense starburst within giant molecular clouds (GMCs). At the highest luminosities ($L_{ir} > 10^{12}L_\odot$), nearly all IR selected objects appear to be advanced mergers that are powered by both a circumnuclear starburst and AGN, both of which are fueled by an enormous concentration of molecular gas ($\sim 10^{10}$ $M_\odot$) that has been funneled into the merger nucleus. The intense circumnuclear starburst that accompanies the luminous IR phase may represent a primary stage in the formation of elliptical galaxy cores, the formation of globular clusters, and the metal enrichment of the intergalactic medium by gas and dust expelled from the nucleus due to the combined forces of supernova explosions and powerful stellar winds.


*Key words:* **GALAXIES: STARBURST — INFRARED: GALAXIES**

## 1. INTRODUCTION

One of the major results of the Infrared Astronomical Satellite (*IRAS*) all-sky survey was the identification of a class of luminous IR galaxies (LIGs: $L_{ir} > 10^{11}$ $L_\odot$)[2], objects that emit more energy in the far-IR/submillimeter than at all other wavelengths combined. Redshift surveys of complete samples of *IRAS* galaxies now agree that IR selected galaxies become the dominant population of extragalactic objects at bolometric luminosities above $\sim 4L^*$ (i.e., $L_{\rm bol} > 10^{11}$ $L_\odot$). Reasonable assumptions about the lifetime of the IR phase suggest that a substantial fraction of all galaxies with $L_{\rm B} > 10^{10}$ $L_\odot$ may pass through such a stage of intense IR emission (Soifer et al 1987). Extensive ground-based observations of complete samples of the nearest IR galaxies have provided substantial information on the origin and evolution of LIGs (see review by Sanders & Mirabel 1996). Of particular relevance to this conference is the fact that all LIGs appear to pass through an intense starburst phase that can be at least an order of magnitude more powerful than the more familiar nearby starbursts in M82 or NGC 253. It is now also clear that LIGs may hold the key to understanding a major stage in the transformation of galaxies including the formation of elliptical galaxies, and may provide evidence for linking powerful nuclear starbursts with the fueling of active galactic nuclei (AGN).

## 2. ORIGIN AND EVOLUTION OF LIGS

Substantial multiwavelength observations now exist for large samples of IR galaxies. There is general agreement that strongly interacting/merger systems are responsible for the majority of LIGs. The fraction of observed mergers clearly increases with increasing IR luminosity, from ~10% at $L_{ir} < 10^{11}$ $L_\odot$ to near 100% for the ultraluminous IR galaxies (ULIGs) at $L_{ir} > 10^{12}$ $L_\odot$ (Sanders et al 1988a; Melnick & Mirabel 1990; Kim 1995; Murphy et al. 1996; Clements et al. 1996). Figure 1 illustrates the range of morphology observed among a

[1]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA.

[2]$L_{ir} \equiv L(8 - 1000\mu m)$; $H_o = 75$ km s$^{-1}$Mpc$^{-1}$, $q_o = 0.5$.

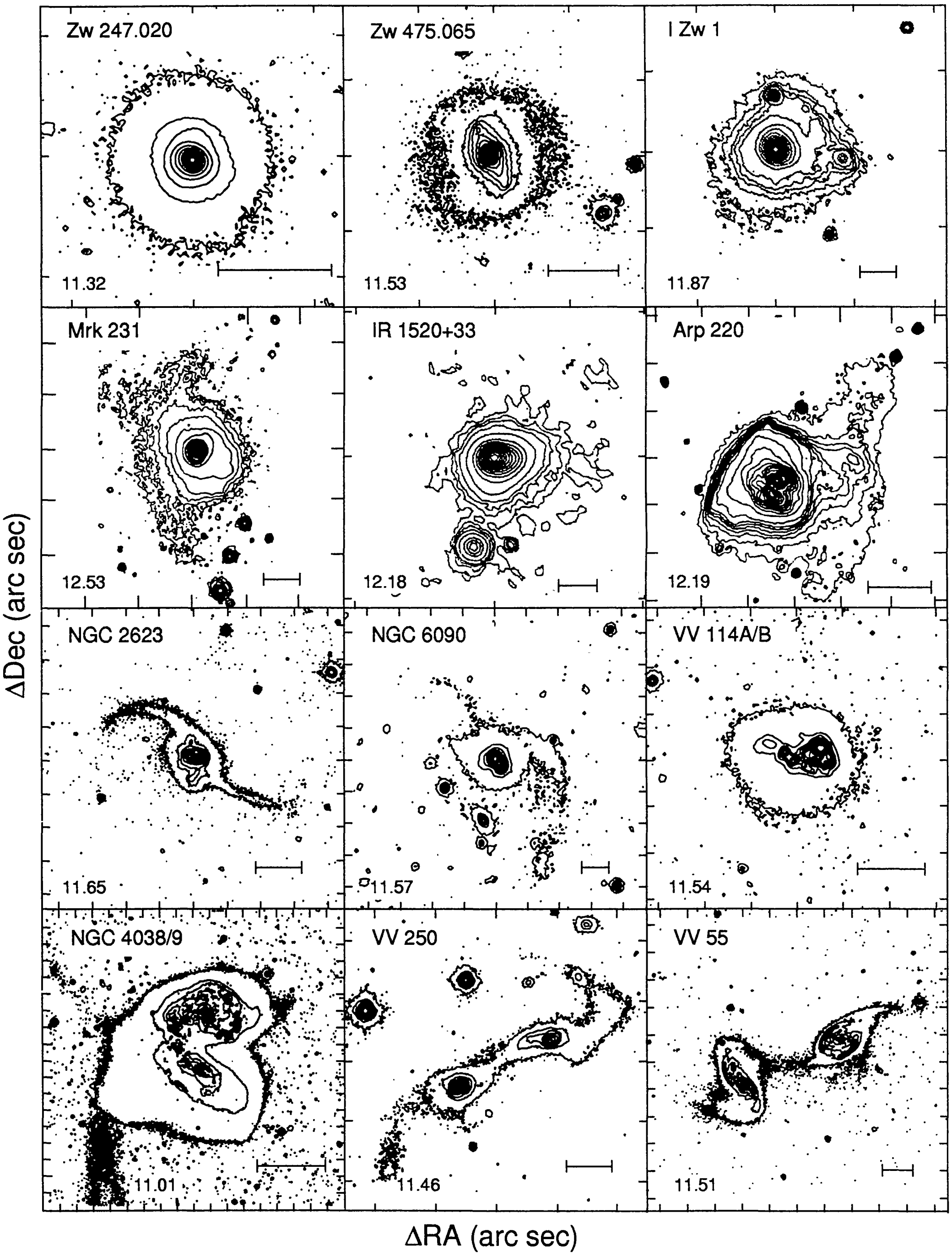



Fig. 1. *R*-band images of a subset of 12 LIGs selected from the *IRAS* Revised Bright Galaxy Sample (RBGS: Sanders et al. 1996) and a complete sample of 'warm' ULIGs (Sanders et al. 1988b). The scale bar represents 10 kpc, tick marks are at 20″ intervals, and the IR luminosity, log ($L_{ir}/L_{\odot}$), is indicated in the lower left corner of each panel. This subsample is chosen to illustrate the full range of morphologies and IR luminosities found in the complete sample of LIGs and 'warm' ULIGs —from the most luminous ULIGs which appear to contain dominant single nuclei (e.g., Mrk 231, I Zw 1), to lower luminosity sources that are either pairs of distinct, tidally distorted disks in the early stage of merger (bottom row), or apparently single objects with elliptical-like radial light profiles that may be the most advanced and relaxed mergers (e.g., Zw 247.020, Zw 475.056).

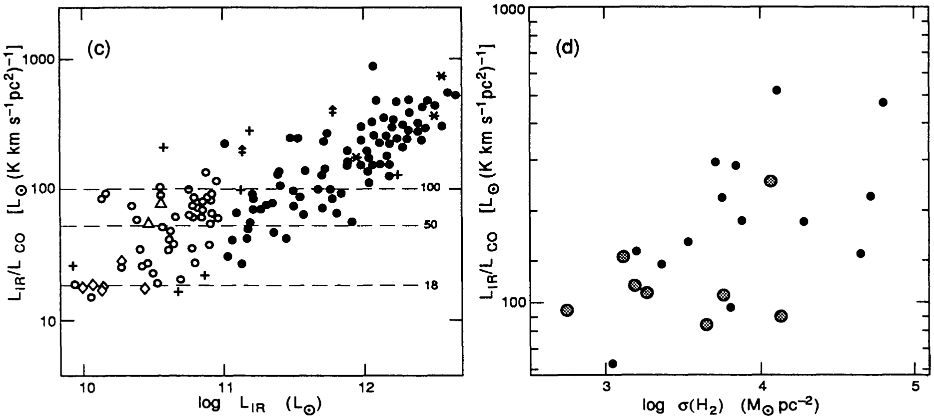


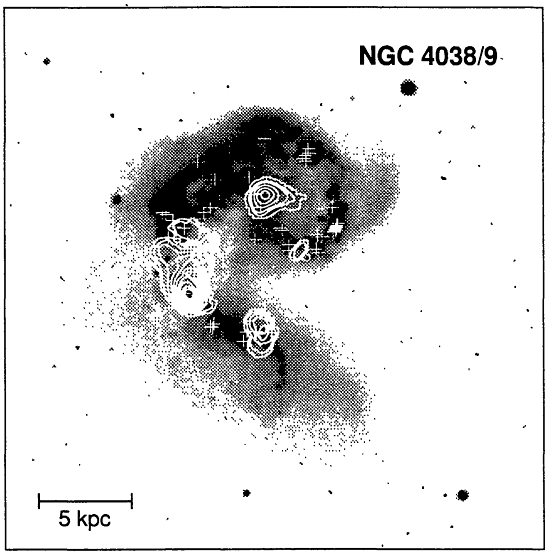

Fig. 2. (*a*) $L_{ir}/L'_{CO}$ vs $L_{ir}$. The dashed lines represent mean values for nearby 'normal' spirals ($L_{ir}/L'_{CO}$ ~18), nearby starburst galaxies ($L_{ir}/L'_{CO}$ ~50), and the most extreme star-forming GMC cores in the Milky Way ($L_{ir}/L'_{CO}$ ~100). Solid and open circles represent LIGs and lower luminosity BGS galaxies, respectively (see Sanders et al. 1991; Solomon et al. 1996). Open triangles refer specifically to the nearby starburst galaxies M82 and NGC 253, and open diamonds represent the Milky Way and 5 similar nearby spiral galaxies (see Sanders et al. 1991). Asterisks refer to optically selected QSOs that have been detected in CO: I Zw1 (Barvainis et al. 1989), Mrk 1014 (Sanders et al. 1988), 3C 48 (Scoville et al. 1993). The '+' signs represent powerful radio galaxies detected by *IRAS* (see Mazzarella et al. 1993; Evans 1996). (*b*) Correlation of the central concentration of molecular gas with the $L_{ir}/L'_{CO}$ ratio for LIGs in the *IRAS* BGS (Scoville et al. 1991; Bryant 1996). Small black and larger gray circles represent objects where the spatial resolution was sufficient to resolve circumnuclear regions of <1 kpc and 1–2 kpc diameter respectively.

complete sample of the nearest and brightest LIGs. Attempts to characterize the nature of the luminosity sources in LIGs have, until recently, largely involved the analysis of long-slit optical spectra using several diagnostic emission line ratios (e.g., Veilleux & Osterbrock 1987). Analysis of the complete sample of LIGs in the *IRAS* Bright Galaxy Sample (BGS: Soifer et al. 1987, 1989) by Kim et al. (1995) and Veilleux et al. (1995) shows that the majority of objects appear to be powered by luminous starbursts, although a substantial fraction (~33%) of objects at all luminosities are classified as LINERs – objects where the gas excitation appears to be dominated by large scale shock heating, presumably due to supernovae explosions and powerful superwinds (e.g., Heckman et al. 1987; Armus et al. 1989). In contrast to the majority of LIGs at lower luminosities, a substantial fraction of all objects at the highest luminosities are Seyferts; the proportion of Seyferts increases systematically from a low of ~10% at $L_{ir} = 10^{11}$ $L_\odot$ to ~45% for ULIGs at $L_{ir} > 10^{12}$ $L_\odot$. Particularly important is a subsample of 'warm' ULIGs, those objects with $f_{25}/f_{60} > 0.2$ (e.g., de Grijp et al. 1986), that have been referred to as 'IR quasars' (Sanders et al. 1988b; Low et al. 1988). A substantial fraction of these objects have previously been classified as either optical QSOs or powerful radio galaxies suggesting that 'IR quasars' may represent an important evolutionary link between several classes of powerful AGN.

## 3. MOLECULAR GAS

Although nearly all LIGs appear to be strongly interacting/merger systems, the reverse of this statement is not true. Indeed, IR surveys of optically selected catalogs of interacting/merger galaxies, find only a relatively modest increase in mean IR activity (e.g., Lonsdale et al. 1984; Cutri & McAlary 1985; Mazzarella & Balzano 1986) for these samples as a whole when compared to normal isolated galaxies. However, as discovered by Joseph et al. (1984), all of these studies have found subsamples of optically selected mergers that exhibit extreme IR excess (e.g., Arp 220, NGC 6240). A key to understanding these results appears to be the total molecular gas content of the individual galaxies. It now seems clear that mergers involving either gas-poor ellipticals, or spirals where only one object is rich in molecular gas, are much less likely to evolve into LIGs. Mergers of relatively large, molecular gas-rich spirals appear to produce the majority of LIGs in the local Universe.

Millimeter-wave observations of IR galaxies have shown that all LIGs are rich in molecular gas, and that there is an increasing central concentration of this gas with increasing IR luminosity. Single-dish observations of CO(1→0) emission from the nearest LIGs (e.g., Young et al. 1984; Sanders & Mirabel 1985) found $H_2$ masses typically in the range $10^9 - 10^{10}$ $M_\odot$, assuming a constant proportionality between CO emission and $H_2$ mass,



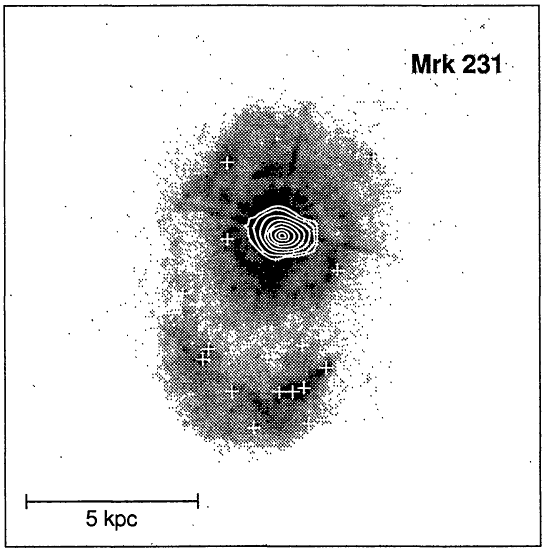




Fig. 3. *(left) The early-stage merger NGC 4038/9 ('The Antennae')* – a high contrast B-band image (UH2.2m, FOV = 260″×260″ – Hibbard et al. 1996) with positions of the most luminous star clusters as identified by Whitmore & Schweitzer (1995), superimposed ('+'). Also shown in contour form are the largest concentrations of dense molecular gas detected by the OVRO millimeterwave interferometer (Stanford et al. 1990). *(right) The advanced merger/ULIG/QSO Mrk 231 – HST B*-band image (FOV = 18″×18″) and identified stellar clusters ('+') from Surace et al. (1996). The prominent AGN appears to be observed through a hole in the massive molecular gas concentration as outlined by the contours of CO emission (Bryant & Scoville 1996).

$M(H_2) \sim 4L'_{CO}$, based on Galactic CO observations of molecular clouds. Figure 2a summarizes more recent and complete CO observations of a large sample of LIGs illustrating the trend of increasing IR luminosity per unit mass of gas versus increasing $L_{ir}$. ULIGs have $L_{ir}/M(H_2)$ values *more extreme by factors of 2-10* than the most extreme star-forming molecular cloud cores found in the Milky Way (e.g., W51 IRS1, Sgr B2). The nature of the dominant luminosity source in ULIGs is currently a subject of great debate, with evidence both for and against either extremely energetic nuclear starbursts or AGN as the main energy source. Most likely both contribute substantially to the bolometric luminosity for the majority of LIGs in the range $L_{ir} \sim 10^{11.5} - 10^{11.9}\ L_\odot$, with AGN becoming progressively more important in the more luminous systems.

Figure 2b shows that the central concentration of molecular gas tends to increase with increasing $L_{ir}/L'_{CO}$ ratio. For advanced mergers, typically 40–100% of the total CO luminosity, or $M(H_2) = 1 - 3 \times 10^{10}\ M_\odot$, is contained in the central $r < 0.5 - 1$ kpc. These observations confirm theoretical models which show that gas is efficiently funneled into the merger nucleus during the merger of gas rich spirals (e.g., Barnes & Hernquist 1992). Such enormous central gas supplies are clearly an ideal breeding ground for powerful nuclear starbursts as well as potential sites for the formation of a self-gravitating accretion disk that would be required to fuel a powerful AGN. It is also interesting to note that the volume density of gas in the cores of these objects is similar to the mean stellar densities found in elliptical galaxy cores (Kormendy & Sanders 1992), which is evidence that these mergers may be in the process of forming an elliptical galaxy. The mean surface density in the central 1 kpc regions of ULIGs is in the range $\langle\sigma(H_2)\rangle = 2 - 7 \times 10^4\ M_\odot\ \mathrm{pc}^{-2}$, although the $H_2$ masses in these regions may be overestimated by a factor of 2–3 (Downes et al. 1993; Solomon et al. 1996). However, even allowing for such an overestimate, these values are 50–250 times larger than the mean surface density in the central 1 kpc of the Milky Way, and imply enormous mean optical depths ($A_V \sim 200 - 1000$ mag) along an average line of sight to the nucleus. These high column densities suggest that optical depths can be as large as unity at wavelengths out to $\sim 100\ \mu$m, and that these cores will also be optically thick even to hard X-Rays.

## 4. MASSIVE STAR CLUSTERS AND AGN

Perhaps the most exciting new discovery from observations of LIGs (and one with particular relevance to this conference) comes from images obtained with the *Hubble Space Telescope* (*HST*) that have succeeded

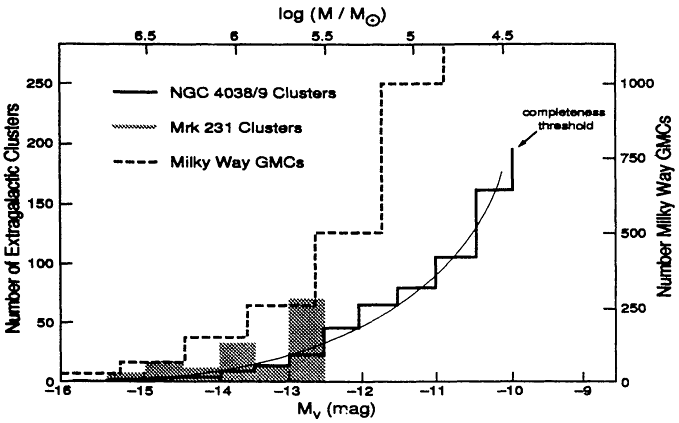



Fig. 4. The distribution of absolute magnitudes and the corresponding derived masses for the most luminous star clusters identified in the nearby LIG NGC 4038/9 (Whitmore & Schweitzer 1995), and for the clusters identified in the more distant and luminous ULIG Mrk 231 (Surace et al. 1996). The dashed histogram is the mass distribution of Giant Molecular Clouds (GMCs) in the Milky Way as determined from the Massachusetts-Stony Brook CO Survey (cf., Sanders et al. 1985; Solomon & Rivolo 1989). The thin curved line shows a power law fit to the clusters in NGC 4038/9, $\phi(L) \propto L^{-1.78}$, which is similar to the power-law slope for GMCs.

in detecting large numbers of newly formed putative star clusters distributed throughout the merger disks of these objects. Figure 3 shows two such examples; the relatively nearby 'early-stage' merger NGC 4038/9 ('The Antennae') and a more distant and much more luminous 'late-stage' merger – the ULIG/Infrared quasar Mrk 231. For nearly face-on systems such as these, the clusters appear to have dispersed their dusty cocoons, enough so that they are now clearly visible even at optical wavelengths. The identification by *HST* of young star clusters in several additional LIGs (e.g., Meurer et al. 1995; Holtzman et al. 1996) suggests that cluster formation may be quite widespread throughout much of the lifetime of the merger, and the recent identification of extremely massive circumnuclear star clusters plus a putative AGN in a complete sample of 'warm' ULIGs (Surace et al. 1996) suggests that both types of activity may be more closely related than previously assumed. Although sufficient data are not yet available to determine how star clusters are formed during mergers, one possible mechanism that has been suggested by Jog & Solomon (1992) and Jog & Das (1992) is the implosion of pre-existing GMCs due to overpressure from a hot and moderately dense atomic inter-cloud medium. If as predicted, such conditions result in an increase in the star formation efficiency of GMCs by at least a factor of 10, from typical values of 1–2% calculated for the ensemble average of Galactic GMCs to 10–20% for GMCs in LIGs, then a pre-existing GMC population as illustrated in Figure 4 for the Milky Way, may indeed provide the birth-sites for star clusters in mergers.

## 5. SUMMARY

Current observations of LIGs have clearly established the role of molecular gas-rich mergers as the trigger for the intense IR activity, and powerful starbursts appear to be a prominent source of luminosity in most of these systems. Future observations using large ground-based optical and near-IR telescopes in addition to *HST*, should have the sensitivity and resolution required to isolate and study the most massive individual star clusters and putative AGN that have already been identified. Millimeterwave and submillimeter interferometers should eventually be able to probe the dense circumnuclear gas at similar high resolution ($\lesssim$ 0.1arcs). Perhaps a better understanding of the cluster properties and the gas dynamics, in combination with current data on the kinematics of large scale tidal features (e.g., Hibbard & vanGorkom 1996) and output from new theoretical simulations (e.g., Barnes & Hernquist 1992; Mihos & Hernquist 1994), will allow us to establish a time sequence for the LIG phase, and thus lead to a better understanding of the ultimate fate of these objects.

This work was supported in part by NASA grant NAGW-3938, and through NASA grant number GO-05982.01-94A from the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract NAS 5-26555. I also thank Josh Barnes, Gabriela Canalizo, Jason Surace, and Bill Vacca for helpful discussions and comments while writing this review.

## REFERENCES

Armus, L., Heckman, T. M., & Miley, G. K. 1989, ApJ, 347, 727
Barnes, J. E., & Hernquist, L. 1992, ARA&A, 30, 705
Barvainis, R., Alloin, D., & Antonucci, R. 1989, ApJ, 337, L69
Bryant, P. M. 1996, Ph.D. Thesis, California Institute of Technology
Bryant, P. M., & Scoville, N. Z. 1996, ApJ, 457, 678
Clements, D. L., Sutherlard, W. J., McMahon, R. G., & Saunders, W. 1996, MNRAS, 279, 477
Cutri, R. M., & McAlary, C. W. 1985, ApJ, 296, 90
deGrijp, M. H. K., Miley, G. K., Lub, J., & deJong, T. 1985, Nature, 314, 240
Downes, D., Solomon, P. M., & Radford, S. J. E. 1993, ApJ, 414, L13
Evans, A. S. 1996, Ph.D. Thesis, University of Hawaii
Heckman, T. M., Armus, L., & Miley, G. K. 1987, AJ, 93, 276
Hibbard, J. E., Sanders, D. B., & Barnes, J. E. 1997, in preparation
Hibbard, J. E., & vanGorkom, J. H. 1996, AJ, 111, 655
Holzmann, J., et al. 1996, AJ, 112, 416
Jog, C. J., & Das, M. 1992, ApJ, 400 476
Jog, C. J., & Solomon, P. M. 1992, ApJ, 387, 152
Joseph, R. D., Meikle, W. P. S., Robertson, N. A., & Wright, G. S. 1984, MNRAS, 209, 111
Kim, D.-C. 1995, Ph.D. Thesis, University of Hawaii
Kim, D.-C., Sanders, D. B., Veilleux, S., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 129
Kormendy, J., & Sanders, D. B. 1992, ApJ, 390, L53
Lonsdale, C. J., Persson, S. E., & Matthews, K. 1984, ApJ, 287, 95
Low, F. J., Huchra, J. P., Kleinmann, S. G., & Cutri, R. M. 1988, ApJ, 327, L41
Mazzarella, J. M., & Balzano, V. A. 1986, ApJS, 62, 751
Mazzarella, J. M., Graham, J. R., Sanders, D. B., & Djorgovski, S. G. 1993, ApJ, 409, 170
Melnick, J., & Mirabel, I. F. 1990, A&A, 231, L9
Meurer, G., Heckman, T., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. 1995, ApJ, 110, 2665
Mihos, J. C., & Hernquist, L. 1994, ApJ, 431, L9
Murphy, T. W., Armus, L., Matthews, K., Soifer, B. T., Mazzarella, J. M., Shupe, D. L., Strauss, M. A., & Neugebauer, G. 1996, AJ, 111, 1025
Sanders, B. B., Mazzarella, J. M., Surace, J. A., Egami, E., Kim, D.-C., Soifer, B. T., Lipari, S., & Mirabel, I. F. 1996, ApJS, submitted (RBGS)
Sanders, D. B., & Mirabel, I. F. 1985, ApJ, 298, L31
____________. 1996, ARA&A, 34, 749
Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1988, ApJ, 335, L1
____________. 1991, ApJ, 370, 158
Sanders, D. B., Scoville, N. Z., & Solomon, P. M. 1985, ApJ, 289, 373
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988a, ApJ, 325, 74
Sanders, D. B., Soifer, B. T., Elias, J. H., Neugebauer, G., & Matthews, K. 1988b, ApJ, 328, L35
Scoville, N. Z., Padin, S., Sanders, D. B., Soifer, B. T., & Yun, M. S. 1993, ApJ, 415, L75
Scoville, N. Z., Sargent, A. I., Sanders, B. B., & Soifer, B. T. 1991 ApJ, 366, L5
Soifer, B. T., Sanders, D. B., Madore, B. F., Neugebauer, G., Danielson, G. E., Elias, J. H., Persson, C. J., & Rice, W. L. 1987, ApJ, 320, 238
Soifer, B. T., Boehmer, L., Neugebauer, G., & Sanders, D. B. 1989, AJ, 98, 766
Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1996, ApJ, in press
Solomon, P. M., & Rivolo, A. R. 1989, ApJ, 339, 919
Stanford, S. A., Sargent, A. I., Sanders, B. B., & Scoville, N. Z. 1990, ApJ, 349, 492
Surace, J. A. , Sanders, D. B., Vacca, W. D., Veilleux, S. V., & Mazzarella, J. M. 1996, ApJ, submitted
Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 171
Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
Whitmore, B. C., & Schweizer, F. 1995, AJ, 109, 960
Young, J. S., Kenney, J. D., Lord, S., & Schloerb, F. P. 1984, ApJ, 287, L65