

## THE COSMIC EVOLUTION OF LUMINOUS INFRARED GALAXIES: STRONG INTERACTIONS/MERGERS OF GAS-RICH DISKS

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### ABSTRACT

Deep surveys at mid-infrared through submillimeter wavelengths indicate that a substantial fraction of the total luminosity output from galaxies at high redshift ( $z > 1$ ) emerges at wavelengths  $30 - 300 \mu\text{m}$ . In addition, much of the star formation and AGN activity associated with galaxy building at these epochs appears to reside in a class of luminous infrared galaxies (LIGs), often so heavily enshrouded in dust that they appear as “blank-fields” in deep optical/UV surveys. Here we present an update on the state of our current knowledge of the cosmic evolution of LIGs from  $z = 0$  to  $z \sim 4$  based on the most recent data obtained from ongoing ground-based redshift surveys of sources detected in ISO and SCUBA deep fields. A scenario for the origin and evolution of LIGs in the local Universe ( $z < 0.3$ ), based on results from multiwavelength observations of several large complete samples of luminous IRAS galaxies, is then discussed.

*Key words* : galaxies: structure — galaxies: evolution — infrared: galaxies

### I. INTRODUCTION

The *Infrared Astronomy Satellite (IRAS)* All-Sky Survey (Neugebauer et al., 1984) provided the first unbiased survey of the sky at mid- and far-infrared wavelengths and gave us the first true census of the infrared emission properties of galaxies in the local Universe. In addition to showing that galaxies of all types and all spectral classification emit a significant fraction of their bolometric luminosity at infrared wavelengths, IRAS identified a substantial population of “infrared galaxies” the most extreme examples of which (e.g. Arp 220: Soifer et al., 1984b), could emit more than 99% of their total luminosity at infrared wavelengths (see Sanders & Mirabel 1996 for a more complete review). The “infrared galaxy” is an object with  $L(1 - 1000 \mu\text{m})/L(0.1 - 1 \mu\text{m}) > 1$  (see Soifer et al., 1984a). Throughout this review we adopt  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0$ .

#### (a) Luminous Infrared Galaxies (LIGs)

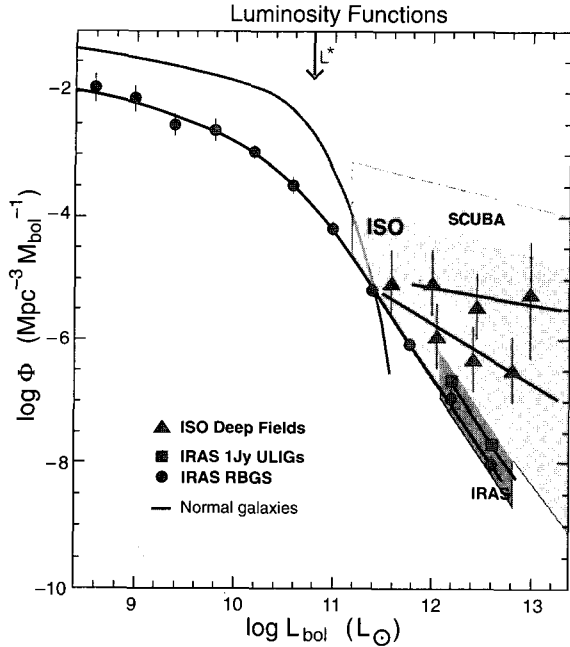
Although relatively rare in the local Universe ( $z < 0.1$ ) more recent mid- and far-infrared “deep field” observations by the *Infrared Space Observatory (ISO)*, and at submillimeter wavelengths with the Submillimeter Common User Bolometer Array (SCUBA: Holland et al., 1999) on the James Clerk Maxwell Telescope (JCMT) imply that the comoving space density of LIGs

( $L_{\text{ir}} > 10^{11} L_{\odot}$ ) increases dramatically over the redshift interval  $z \sim 0 - 1.5$ , and that the infrared luminosity output from LIGs at higher redshifts ( $z \sim 2 - 4$ ) may exceed the rest-frame optical/UV output from *all* galaxies by at least a factor  $\sim 3 - 5$ !

Much of the evidence for strong evolution in the LIG population has been assembled only recently, and is based on a relatively small number of deep-field surveys at several different infrared-submillimeter wavelengths. As will be described below, it is possible with only a few assumptions, to put together a consistent picture of the cosmic evolution of LIGs out to redshifts  $z \sim 3$ . However, a clearer understanding of the nature of individual sources, and in particular of the processes responsible for producing their intense infrared/submillimeter emission, will require more sensitive infrared observations from future space missions such as the Space Infrared Telescope Facility (SIRTF), the Japanese infrared observatory, ASTRO-F, and the Far-Infrared Space Telescope (FIRST/HERSCHEL) coupled with high angular resolution ground-based observations with submillimeter interferometers - e.g. the Smithsonian Submillimeter Array (SMA) and the Atacama Large Millimeter Array (ALMA).

### II. LUMINOSITY FUNCTIONS - EVIDENCE FOR STRONG COSMIC EVOLUTION OF LIGs

Figure 1 summarizes the current best estimates for the luminosity functions of infrared/submillimeter selected galaxies at redshifts  $z = 0$  out to  $z \sim 3$ . De-



**Fig. 1.**— The luminosity function (LF) for infrared selected galaxies. The thick solid line and filled circles represents the local LF of galaxies as determined using the 635 galaxies in the IRAS RBGS (Sanders et al., 2003), while the filled squares represent the LF of the 118 “local” ULIGs in the 1-Jy sample of Kim & Sanders (1998). The thin curve represents the Schechter function for normal optically selected galaxies in the local Universe (Schechter 1976). The shaded wedge labeled “SCUBA” represents the “best guess” LF of LIGs at redshifts  $z \sim 2-4$  (c.f. Lilly et al., 1999) as inferred from recent attempts to identify the submillimeter sources in the deep blank-field surveys with JCMT/SCUBA at  $850\mu\text{m}$  (e.g. Barger et al., 1999; Chapman et al., 2003). The shaded wedge labeled “ISO” represents the region that can be reasonably explored using data obtained from the ISOCAM and ISOPHOT deep-field surveys. Our preliminary results (Sanders et al., 2003) derived using redshifts recently obtained for a nearly complete sample ( $\sim 40$ ) of  $175\mu\text{m}$ -selected sources in the Lockman Hole (LH: Lockman et al., 1986) ISOPHOT deep fields (Kawara et al., 1998) are shown by triangles, where the sources were placed in two redshift bins  $\Delta z = 0.25-0.75$  and  $\Delta z = 0.75-1.5$ .

descriptions of the individual data sets are given below and in the figure caption.

#### (a) The Local Universe ( $z = 0 - 0.3$ ): IRAS

One of the main extragalactic results from the IRAS All-Sky survey was the determination of the far-infrared galaxy luminosity function (LF) (e.g. Soifer et al., 1987; Soifer & Neugebauer 1991), which showed for the first time the existence of a *substantial population* of luminous infrared galaxies (LIGs) whose infrared luminosities,  $L_{\text{ir}}$ , exceed  $10^{11} L_{\odot}$ . The high luminosity tail of the infrared LF can be approximated by a power-law ( $\Phi \propto L_{\text{ir}}^{-2.35}$ ), which gives a space density for the most luminous infrared sources well in excess of predictions based on the optical LF (Schechter 1976: see also Figure 1). Soifer et al (1987) found that the

space density of LIGs was comparable to that of optically selected Seyfert galaxies in the luminosity range  $L \sim 10^{11} - 10^{12} L_{\odot}$ , while at the highest luminosities ( $L > 10^{12} L_{\odot}$ ) the space density of ULIGs was approximately a factor of 1.5–3 higher than that of the only other known objects with comparable bolometric luminosities – optically selected QSOs ( $M_B < -22.2$ : Schmidt & Green 1983).

#### (b) Intermediate Redshifts ( $z \sim 0.3 - 1.5$ ): ISO

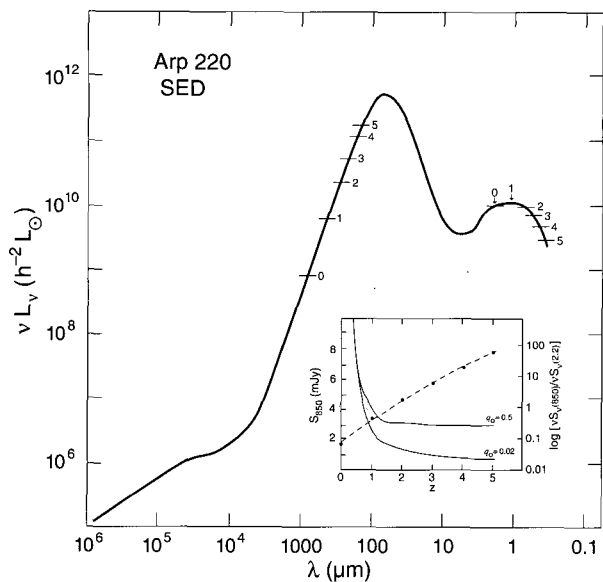
More sensitive surveys at infrared wavelengths, principally the mid- and far-infrared deep-fields observed by the *Infrared Space Observatory (ISO)* (Taniguchi et al., 1997; Kawara et al., 1998; Elbaz et al., 1999; Aussel et al., 1999) have provided dramatic evidence that the co-moving space density of the most luminous infrared sources increases rapidly with increasing redshift, rising by nearly a factor of  $\sim 10^3$  from  $z = 0$  out to  $z \sim 1$  (Sanders et al., 2003b).

Progress in identifying counterparts to the ISOPHOT sources has been slow, partly due to the amount of effort needed to “degitch” the ISOPHOT data, as well as the relatively large size of the ISOPHOT beam ( $45'' - 90''$ ). The development of efficient algorithms to “clean” the ISOPHOT data has led to more reliable source counts, and more accurate positions. The addition of VLA (20 cm continuum), optical (BVRIZ) and near-infrared (J,K) data has led to fairly reliable identifications of the optical counterparts to the brighter of the far-infrared sources, and we expect that identification of the fainter ISOPHOT sources will now proceed at a more rapid pace.

#### (c) High Redshifts ( $z \sim 1 - 4$ ): SCUBA

Near the end of the ISO mission, before ISOPHOT deep field data had been completely reduced, reports of the existence of a substantial population of faint submillimeter sources (which were being interpreted as LIGs at high redshifts) were made based on the first deep submillimeter surveys at  $850\mu\text{m}$  using the new SCUBA camera on the JCMT (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al., 1998; Lilly et al., 1999).

Figure 2 illustrates the basis for the interpretation of the faint submillimeter population as high-redshift (U)LIGs. Given the observed  $850\mu\text{m}$  fluxes in the range of 2–4 mJy, plus the “submillimeter excess” [i.e.  $\equiv \nu S_{\nu}(850\mu\text{m})/\nu S_{\nu}(2.2\mu\text{m})$ ] of these sources, which was typically  $> 1$ , it was relatively straightforward to show that they were most likely to be (U)LIGs at high redshift (i.e.  $z > 2$ ; see insert in Figure 3). It would be impossible to produce such a ratio from the SED of normal optically selected galaxies at any redshift, or even by the most extreme infrared selected galaxies at low redshift, but the observed ratios are almost exactly what would be expected for a ULIG at high redshift. It is the combination of a large negative K-correction in the submillimeter plus a relatively flat or positive



**Fig. 2.**— Observed radio-to-UV spectral energy distribution (SED) of the nearest ULIG, Arp 220 ( $z = 0.018$ ). Labeled tickmarks represent object rest-frame emission that will be shifted into the  $850 \mu\text{m}$  and  $2.2 \mu\text{m}$  observed frame for redshifts,  $z = 0 - 5$ . The insert shows the corresponding observed-frame  $850 \mu\text{m}$  flux and  $\nu S_\nu(850)/\nu S_\nu(2.2)$  ratio for Arp 220 at redshifts,  $z = 0 - 5$ .

K-correction in the near-infrared which naturally leads to values  $\nu S_\nu(850 \mu\text{m})/\nu S_\nu(2.2 \mu\text{m}) > 1$  for all ULIGs at  $z \geq 2$ .

The co-moving space density of these “SCUBA” galaxies was first estimated by Lilly et al. (1999) to be nearly a factor of  $10^3$  times higher than found for the local population of ULIGs as shown in Figure 1. Assuming that the mean redshift of the SCUBA population was  $\sim 2.5$  implied strong evolution, e.g. at least  $\Phi \propto (1+z)^{6-7}$  assuming pure number density evolution, which is in good agreement from what was found for the local population of ULIGs (Kim 1995; Kim & Sanders 1998). More recent estimates of the redshift distribution of these faint submillimeter sources (Barger et al., 1999; Chapman et al., 2003) suggests that their combined total infrared/submillimeter luminosity density *exceeds* that of the total UV/optical luminosity density from all galaxies at all redshifts  $z > 1.5$ , by a factor of  $\sim 5 - 10$  (Blain et al., 1999; Sanders 1999; Blain et al., 2002).

### III. ORIGIN AND EVOLUTION OF LIGs AND A POSSIBLE LINK BETWEEN ULIGs AND QSOs

Substantial progress has been made in understanding the processes which trigger the luminous infrared phase in galaxies (see Sanders & Mirabel 1996 for a more complete review). Recently completed surveys of complete samples of IRAS galaxies now clearly show

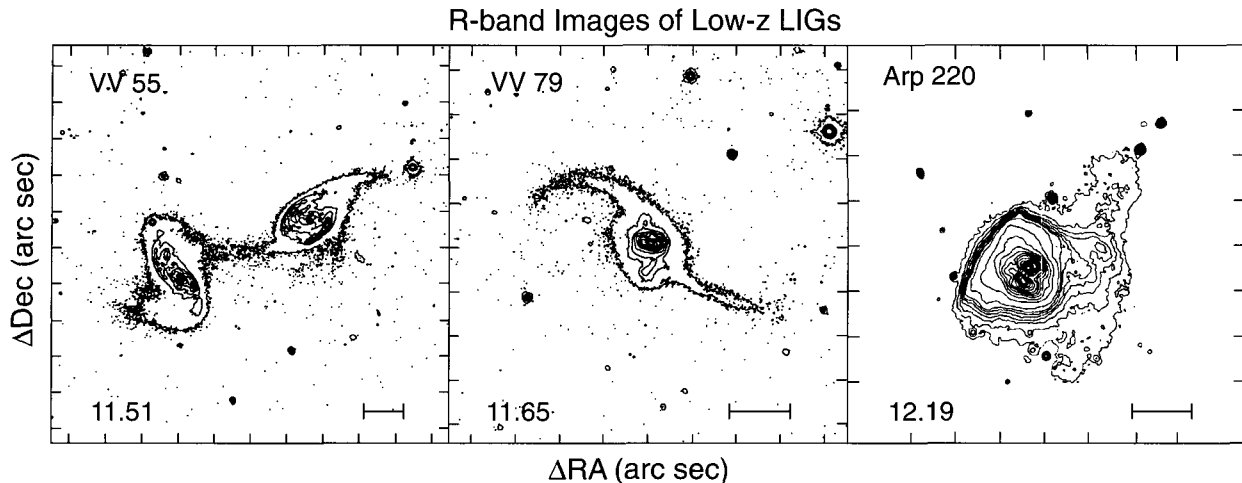
that strong interactions/mergers of gas-rich spirals are the trigger for the intense infrared emission (see Figure 3). Diskwide starbursts occur during the initial stages of the interaction. Much of the disk gas is then funneled toward the merger nuclei where it can trigger powerful circumnuclear starbursts and where it is also available for the building/fueling of massive black holes (MBH). While the azimuthally averaged radial profile of the merger remnant begins to assume an  $r^{1/4}$  power-law shape characteristic of elliptical galaxies (e.g. Figure 4), the dominant power source appears to shift from starburst to AGN (see Figure 5). As the enshrouded AGN begins to emerge from its dust cocoon the SED of the merger remnant exhibits the changes in shape illustrated in Figure 6 – from an SED with strong far-infrared excess to an SED dominated by an optical/UV “big-blue-bump”. The phases that have been identified in the transformation of LIGs  $\rightarrow$  ULIGs  $\rightarrow$  QSOs are described in greater detail below.

#### (a) The Paradigm: LIGs $\rightarrow$ “cool”-ULIGs $\rightarrow$ “warm”-ULIGs $\rightarrow$ IR-QSOs $\rightarrow$ opt-QSOs

There is an extensive literature on the properties of ULIGs and speculation on their origin and fate (see Joseph 2000; Sanders 2000). It is now fair to say that there is a strong consensus among all observers that nearly all ULIGs are triggered by the strong interaction/merger of gas-rich disks. Our own studies of the IRAS BGS and 1-Jy samples (Sanders et al., 1988a,b; Kim et al., 2002; Veilleux et al., 2002) indicate that the merger involves two large gas-rich spirals and that the ULIG phase occurs near the end-stage when the two disks overlap (with some observers suggesting that a small subset of ULIGs may be “group mergers” and/or more widely space doubles, e.g. Borne et al., 2000). Once the nuclei merge, ULIGs are much more likely to exhibit “warm” mid-infrared colors ( $f_{25}/f_{60} > 0.25$ ), followed by a transition to an optical QSO (i.e. the emergence of a “big-blue-bump”). There is an ongoing debate on whether all ULIGs follow this path, with a number of observers speculating that the “cold” ULIGs simply end in a superstarburst phase having little or nothing to do with QSOs (e.g. Genzel et al., 1998). However, most observers would also agree that the “warm” ULIGs, and perhaps the majority of the more luminous ULIGs (i.e.  $L_{\text{ir}} > 10^{12.4} L_\odot$ ) indeed may be the precursors of QSOs (Veilleux et al., 1995, 1997; Lutz et al., 1999).

Below we outline briefly the characteristics of objects that represent the five-stage sequence we (e.g. Sanders et al., 1988b) and others have proposed for the evolution of LIGs to optical QSOs.

1. *High Luminosity Infrared Galaxy* -  $\log(L_{\text{ir}}/L_\odot) = 11.3 - 12.0$ ; All of the objects from the RBGS in this luminosity range are found to be strongly interacting/merger pairs of gas-rich spirals (Ishida et al., 2003).



**Fig. 3.**— A representative sample of ground-based R-band images of LIGs (Mazzarella et al., 2003) from the IRAS RBGS (Sanders et al., 2003), illustrating the strong interactions/mergers that are characteristic of nearly all objects with  $L_{\text{ir}} > 10^{11.3} L_{\odot}$  (Ishida 2003). The scale bar represents 10 kpc; tick marks are at  $20''$  intervals, and  $\log(L_{\text{ir}}/L_{\odot})$  is indicated in the lower left of each panel.

Most of these systems are in a pre-merger phase with nuclear separations in the range 1–20 kpc. The trend is for the higher  $L_{\text{ir}}$  systems to be more advanced mergers (i.e. smaller mean nuclear separation).

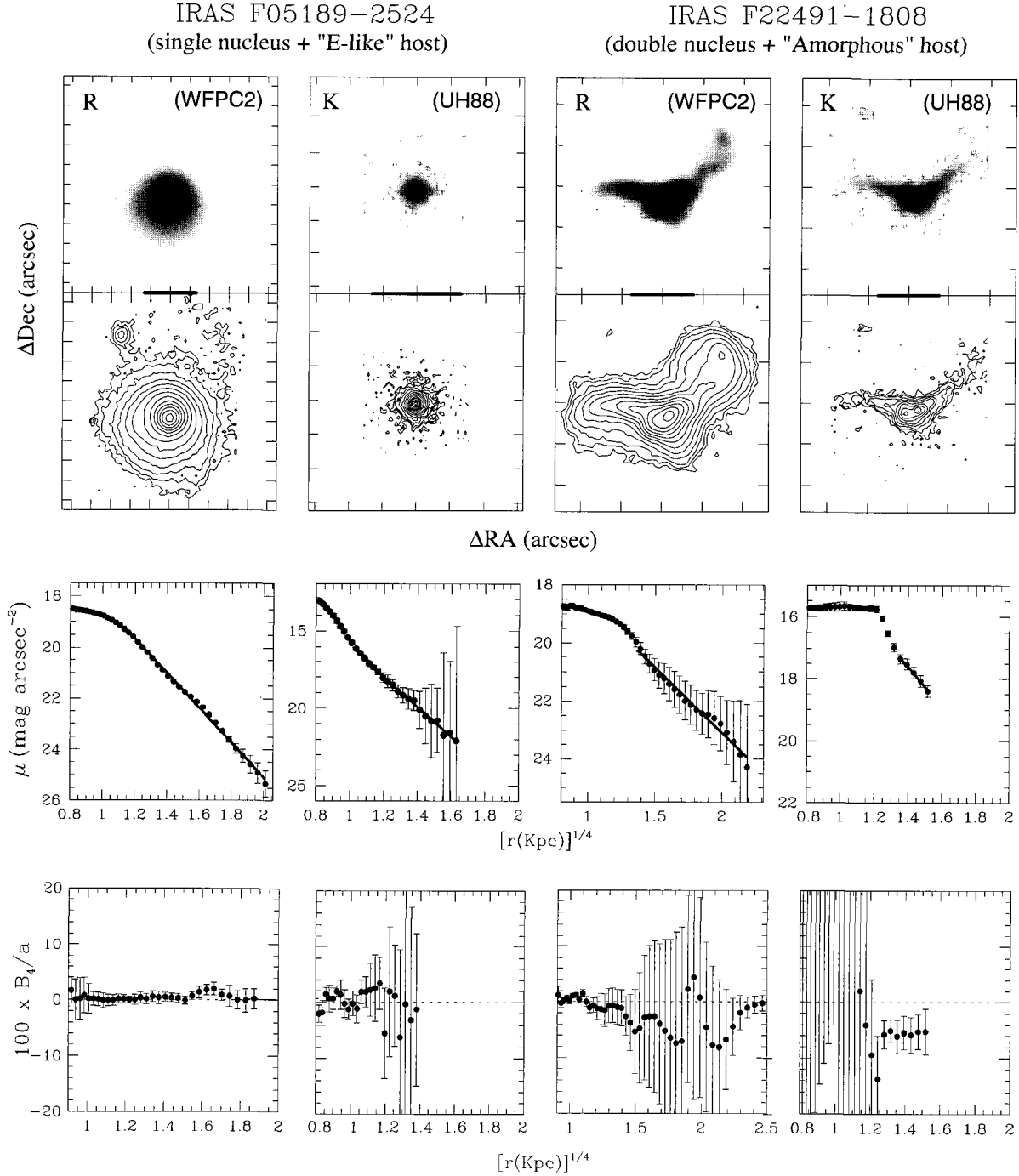
2. *“Cool” Ultraluminous Infrared Galaxy* -  $\log(L_{\text{ir}}/L_{\odot}) > 12.0$  and  $f_{25}/f_{60} < 0.25$ . Advanced merger systems where the mean nuclear separation is  $\sim 1.5$ –2 kpc. The bulk of the molecular gas originally distributed throughout the disks has been funneled into the inner few kpc and the bulk of the infrared luminosity is yet more compact. Optical spectra typically exhibit HII-like emission lines, but also show evidence of extremely large optical depths via a large Balmer decrement and heavily reddened continuum. Powerful superwinds are observed in nearly all cool ULIGs (Armus et al., 1987; Rupke et al., 2002). These objects have been the subject of intense debate concerning the nature of the dominant source of their intense infrared emission, e.g. super-starbursts versus dust-enshrouded AGN (e.g. Joseph 2000; Sanders 2000).

3. *“Warm” Ultraluminous Infrared Galaxy* -  $\log(L_{\text{ir}}/L_{\odot}) > 12.0$  and  $f_{25}/f_{60} > 0.25$ . Warm ULIGs represent  $\sim 15$ –20% of the  $60\mu\text{m}$ -selected ULIGs discovered by IRAS. The vast majority of these sources are single nucleus (i.e. post merger) systems, with Seyfert-like optical spectra. Warm ULIGs with Sy2 spectra in direct optical emission often show Sy1 lines in the near-infrared and almost always show evidence for hid-

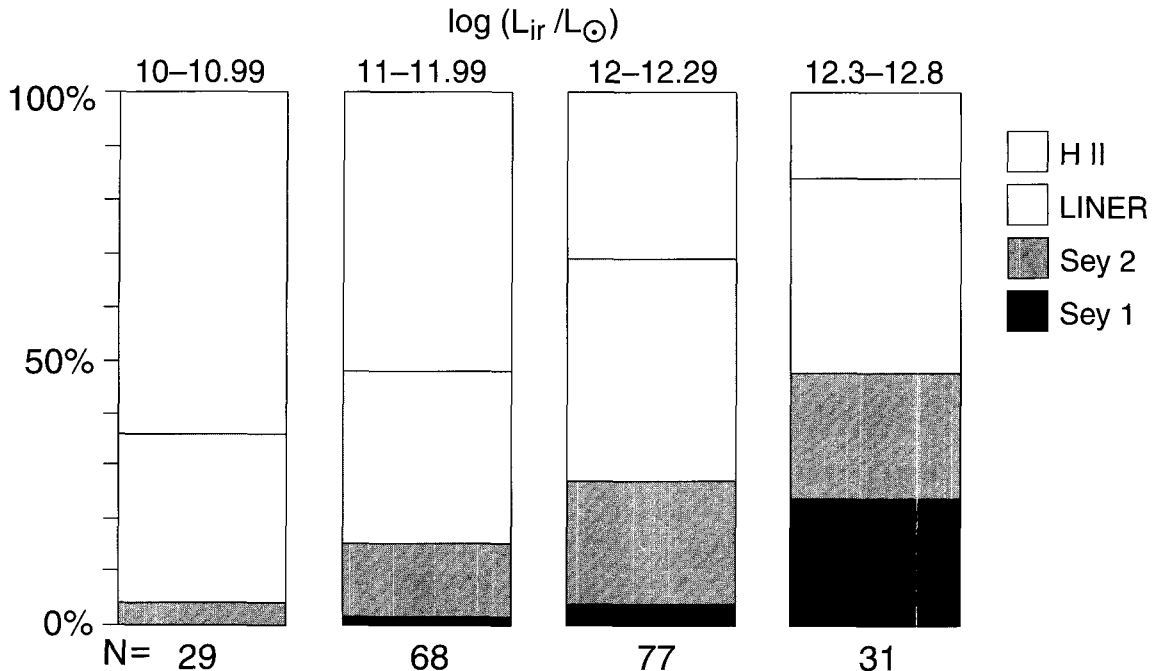
den Sy1 emission lines in polarized optical emission. Warm ULIGs typically are intrinsically powerful, but heavily absorbed, hard X-ray sources. There is general agreement that these objects harbor a powerful dust-enshrouded AGN. Given the relatively poor sensitivity of the mid-infrared IRAS and ISO detectors it is likely that SIRTf will discover a much larger population of warm ULIGs.

4. *Infrared-excess QSO* - UV-excess, optically-selected QSO where the ratio of total infrared luminosity to the luminosity of the big-blue-bump (BBB) is more than 1.5 times the value of the mean for the bright PGQSO sample (i.e.  $L_{\text{ir}}/L_{\text{BBB}} > 0.4$ ; e.g. Sanders et al., 1989). Approximately 20–30% of PGQSOs are infrared-loud. Infrared-excess QSOs have recently been discovered to be rich in molecular gas with  $M(\text{H}_2)$  similar to that found in warm ULIGs (Evans et al., 2001). It is also possible that the “red AGN” ( $J - K > 2$ ) recently discovered in the 2MASS survey (Cutri et al., 2002) are also infrared-excess QSOs. If so, then the space density of infrared-excess QSOs could easily equal that of optically-selected QSOs.

5. *Infrared-normal QSO* - UV-excess, optically-selected QSO where the ratio of total infrared luminosity to the luminosity of the big-blue-bump (BBB) is less than 1.5 times the value of the mean for the bright PGQSO sample (i.e.  $L_{\text{ir}}/L_{\text{BBB}} < 0.4$ ; e.g. Sanders et al., 1989). Infrared-normal QSOs appear to have smaller masses of molecular gas than infrared-excess QSOs (Evans et al., 2001;



**Fig. 4.**— Example of the type of analysis that can now be done for many of the ULIGs in the RBGS and 1 Jy samples to test the hypothesis that the ULIGs are a transition stage in the formation of “E-type” galaxies during the merger of two gas-rich spiral disks. Rows 1 and 2 show HST/WFPC2 R-band and UH2.2m tip-tilt K-band images in grayscale and contour form respectively. North is to the top, and east is to the left, tick marks are at  $10''$  intervals, and the solid bar represents 10 kpc. Rows 3 and 4 show the 1-D radial variation of surface brightness and the parameter  $B_4/a$  as a function of  $r^{1/4}$ , respectively. The best  $r^{1/4}$  fit to the surface brightness profile (excluding the central  $1.5''$  radius of the image) is given by the straight line. (adapted from Sanders et al., 2000)



**Fig. 5.**— The optical spectral classification of infrared galaxies (from the IRAS RBGS and 1-Jy samples) versus infrared luminosity (Veilleux et al., 1999). These classifications were based on ground-based spectra covering the wavelength range  $\sim 3500\text{\AA}$ – $8800\text{\AA}$ , using a  $2''$  slit centered on the K-band “nucleus”.

Scoville et al., 2003).

During stages 2–5 above, the total bolometric luminosity of the system may change by only factors of a few, but the overall shape of the SED changes dramatically, particularly during the “warm” ULIG stage where a strong mid-infrared “bump” emerges as the peak of the SED shifts from the far-infrared (i.e. at  $\lambda \sim 50 - 100 \mu\text{m}$ ) to the optical/UV (i.e. at  $\lambda \sim 0.03 - 0.3 \mu\text{m}$ ). Characteristic SEDs for objects in each stage are illustrated in Figure 6.

#### i) A True Chronological Sequence?

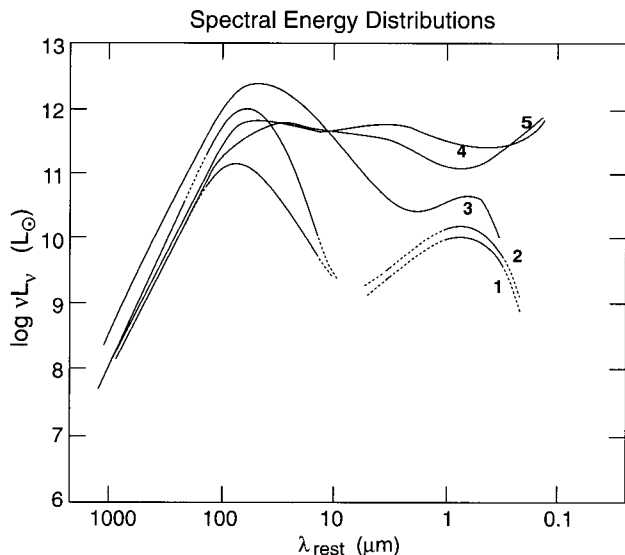
Despite the plausibility of the evolutionary sequence outlined above, the proposed scenario remains at best a good conjecture. While there is ample observational and theoretical evidence for the evolution of strongly-interacting/merger systems *prior* to the stage where the 2 nuclei merge (mostly through the relative separation of the 2 nuclei, the length of the still prominent tidal tails, etc. as compared with N-body simulations), there is much less evidence for the fate of the post-merger products, due largely to the rapidly fading strength of tidal debris, but also to the lack of good N-body simulations. A potential fruitful area of research would be to demonstrate that aging ULIGs do indeed show a substantial overlap in their observed properties with

those of the “infrared-excess” optically-selected QSOs.

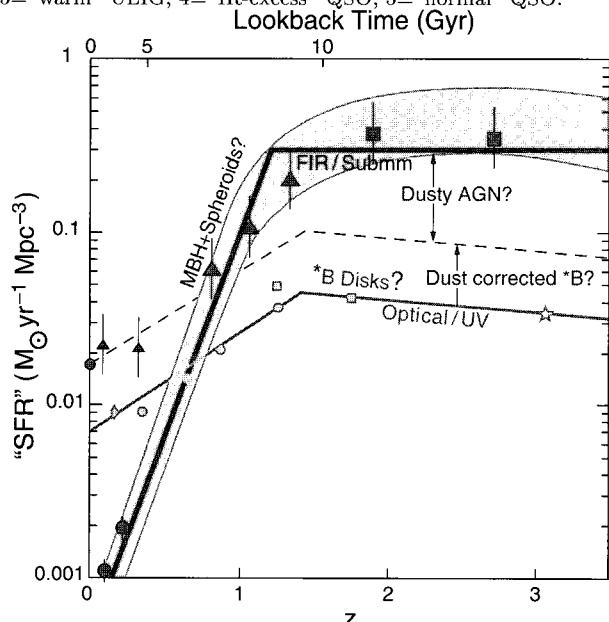
#### IV. THE COSMIC EVOLUTION OF SUPER-STARBURSTS AND AGN

The results of the previous section strongly suggest that nuclear super-starbursts and AGN may be intimately related, and that at least in the most luminous infrared sources, a substantial fraction of the observed infrared luminosity may be powered by the AGN rather than simply by star formation. One might then ask: What do the new ISOPHOT deep fields add to the current picture of the “star formation history” of the Universe often represented by the “Lilly-Madau Diagram” (Lilly et al., 1996; Madau et al., 1996) ?

Figure 7 shows a more current version of the “SFR vs.  $Z$ ” diagram which includes not only optical/UV data, but the new results obtained from deep sub-millimeter surveys at  $850 \mu\text{m}$  from the SCUBA deep fields. The observed optical/UV curve is based on the most recent high redshift optical data from Steidel et al. (1999), plus a correction to the low redshift UV data made by Cowie et al. (1999). Also shown is a reddening-corrected optical/UV curve based on models developed primarily for local starburst galaxies (e.g. Calzetti 1997; Meurer et al., 1997). The optical/UV data is assumed to come primarily from the formation of massive stars in starburst disks. The



**Fig. 6.**— Mean radio-to-optical SEDs (adapted from Sanders & Mirabel 1996) determined for objects in the *IRAS* RBGS, *IRAS* 1 Jy, and PGQSO samples. The numbers correspond to the five stage sequence described below: 1=LIG, 2=“cool” ULIG, 3=“warm” ULIG, 4=“IR-excess” QSO, 5=“normal” QSO.



**Fig. 7.**— Comparison of the luminosity density at submillimeter/far-infrared wavelengths from the *inferred* redshift distribution of SCUBA deep-field sources (shaded region) versus the *observed* luminosity density at optical/UV wavelengths (small symbols: adapted from Sanders 1999). The optical/UV data as well as a suggested upward correction of a factor of  $\sim 5$  (dashed line), are summarized by Steidel et al. (1999). The submillimeter curve (thick solid line) and measured redshifts (SCUBA - large squares; IRAS - large circles) are discussed in Blain et al. (1999), and Barger et al. (1999), respectively. What is most striking is the extremely strong evolution in the ULIG population that is implied at redshifts  $z = 0 - 1$ . The new ISO deep-field results are shown by the large triangles (Sanders et al., in preparation 2003).

far-infrared/submillimeter data is based on measured redshifts from an all-sky survey of *IRAS* LIGs at low- $z$  and on a relatively few identified redshifts for the faint SCUBA galaxies in the range  $z = 2-3$ . The shaded region and thick solid curve connecting the *IRAS* and SCUBA data points is largely based on model simulations using empirical far-infrared SEDs and fitting the constraints on the background imposed by the measured far-infrared/submillimeter extragalactic background light (EBL). For comparison purposes we have assumed that the far-infrared/submillimeter sources are powered by star-formation, although another equally plausible alternative is that they may represent powerful nuclear starbursts and the formation of MBH rather than starburst disks.

## V. FINAL REMARKS: THE PROMISE OF SIRTf, ASTRO-F, SOFIA, HERSCHEL, SMA, ALMA

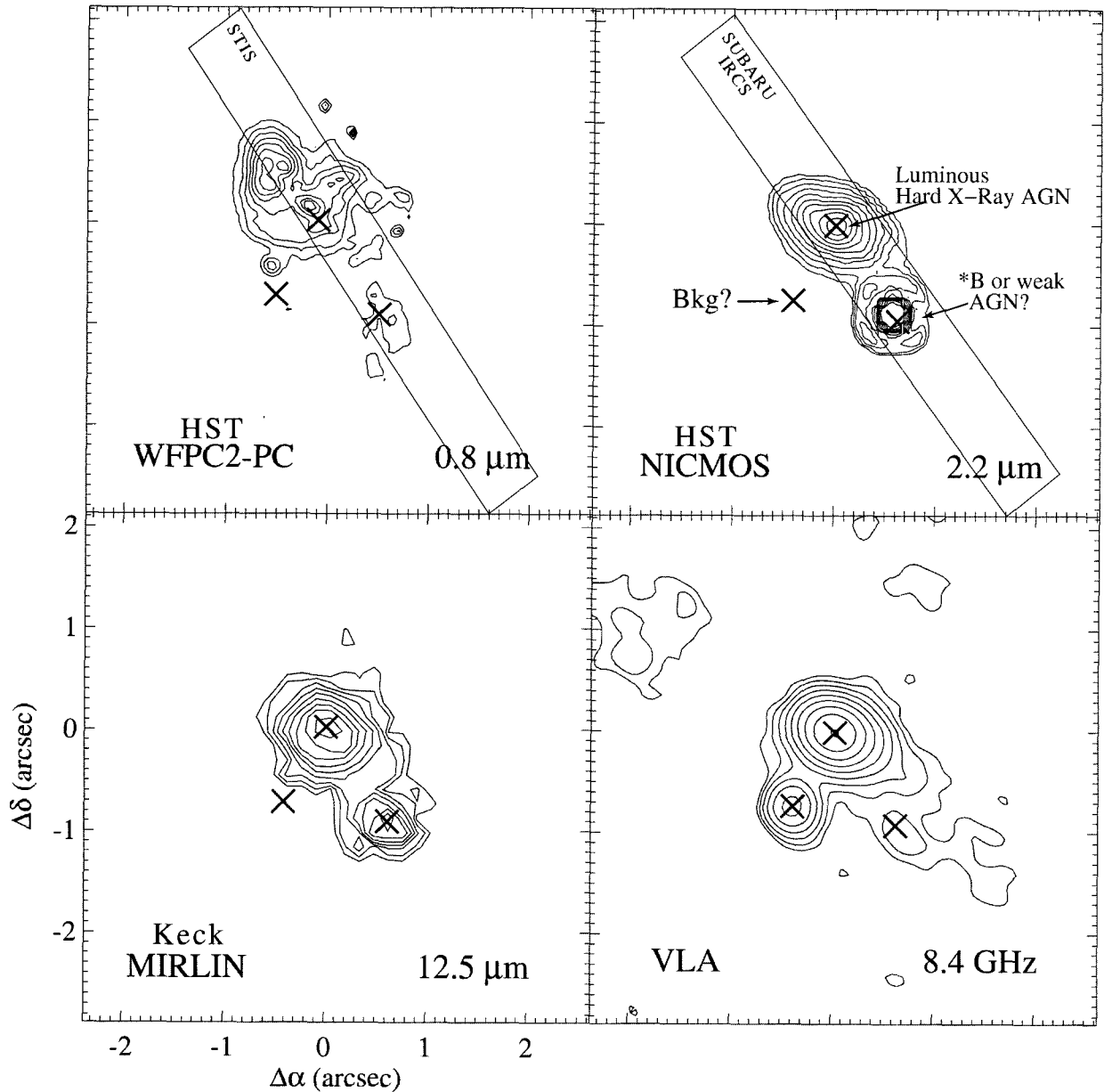
Although tremendous progress has recently been made in understanding the extragalactic infrared Universe, we are still limited in our detailed understanding of the infrared-galaxy population, largely due to the relatively poor sensitivity and resolution of previous far-infrared/submillimeter detectors. Although the size of the SIRTf and ASTRO-F primary mirrors are not much larger than *IRAS* and *ISO*, the increase in spatial sampling and the improved sensitivity and wavelength coverage of the SIRTf and ASTRO-F detectors will provide an orders of magnitude increase in the number of known distant infrared sources. It should be possible to measure the shape of the infrared galaxy luminosity function out to  $z > 1.5$ . The larger SOFIA and HERSCHEL apertures will enhance the sample sizes at larger redshifts, as well as begin to resolve individual sources at low to moderate redshifts. In addition, SOFIA and HERSCHEL will also provide important new far-infrared spectral line diagnostics that can be used to help distinguish between starburst and AGN.

Ultimately we will need to rely heavily on the far-infrared/submillimeter interferometers SMA and ALMA in order to better understand the relative contributions of starbursts and AGN in producing the intense infrared emission in individual sources. Figure 8 illustrates the current problems with interpreting the nature of the far-infrared emission, even from the nuclear regions of relatively nearby ULIGs. The obscured high-luminosity AGN in the northeastern nucleus of Mrk 273 was only revealed through a combination of new high resolution hard X-ray data and mid-infrared imaging with the Keck 10m telescope.

## VI. ACKNOWLEDGEMENTS

I am grateful to the members of the Japan/Hawaii *ISO* Cosmology Key Project team for allowing me to summarize some of the preliminary follow-up observations of sources extracted from our ISOPHOT Deep

## Mrk 273



in

**Fig. 8.**— High spatial resolution HST images, recent mid-infrared Keck data (Soifer et al., 2000), and a VLA image (Condon et al., 1991) of the central region of the RBGS ULIG Mrk 273. These data show the wide variation of the ratio  $\nu f_\nu(\text{IR})/\nu f_\nu(\text{radio})$  for individual “knots” within the central regions of ULIGs, and they dramatically illustrate the necessity of obtaining multiwavelength images at comparable high resolution before attempting to use such ratios obtained from lower resolution data to characterize the nature of the luminosity source(s) responsible for the bulk of the luminosity from ULIGs. Mrk 273 has been classified as an AGN on the basis of mid-infrared line diagnostics using ISO spectra (e.g. Genzel et al., 1998), and using X-ray data (ASCA: e.g. Iwasawa 1999). Yet the northern source, until recently, appeared to be a super-starburst from recent VLBA data obtained by Carilli & Taylor (2000). However the high resolution Chandra observations recently published by Xia et al. (2002) now clearly reveals a compact, heavily obscured, hard X-ray nucleus coincident with the northern source. The absorption-corrected X-ray luminosity (0.1-10 keV) is  $L_X \sim 7 \times 10^{43} \text{ erg s}^{-1}$ , clearly establishes Mrk 273 as a Seyfert type 2 AGN.



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## REFERENCES

- Armus, L., Heckman, T.M., & Miley, G.K. 1987, Multi-color optical imaging of powerful far-infrared galaxies - more evidence for a link between galaxy mergers and far-infrared emission, *AJ*, 94, 831
- Aussel, H., Cesarsky, C.J., Elbaz, D. et al., 1999, ISOCAM observations of the Hubble Deep Field reduced with the PRETI method, *A&A*, 342, 313
- Barger, A.J., Cowie, L.L., Sanders, D.B. et al., 1998, Submillimeter-wavelength detection of dusty star-forming galaxies at high redshift, *Nature*, 394, 248
- Barger, A.J., Cowie, L.L., & Sanders, D.B. 1999, Resolving the submillimeter background: the 850 micron galaxy counts, *ApJL*, 518, L5
- Blain, A. W., Barnard, V. E., & Chapman, S. C., 2003, Submillimetre and far-infrared spectral energy distributions of galaxies: the luminosity-temperature relation and consequences for photometric redshifts, *MNRAS*, 338, 733
- Blain, A. W., Kneib, J.-P., Ivison, R.J. et al., 1999, Deep counts of submillimeter galaxies, *ApJL*, 512, L87
- Borne, K.D., Bushouse, H., Lucas, R.A. et al., 2000, Evidence for multiple mergers among ultraluminous infrared galaxies: remnants of compact groups ?, *ApJL*, 529, L77
- Calzetti, D., Reddening and star formation in starburst galaxies, 1997, *AJ*, 113, 162
- Carilli, C.L., & G.B. Taylor, 2000, The extreme compact starburst in Markarian 273, *ApJL*, 532, L95
- Chapman, S.C., Blain, A.W., Smail, I. et al., 2003, *Nature*, 422, 695
- Condon, J.J., Huang, Z.-P., Yin, Q.F. et al., 1991, Compact starbursts in ultraluminous infrared galaxies, *ApJ*, 378, 65
- Cowie, L.L., Songaila, A., & Barger, A.J. 1999, Evidence for a gradual decline in the universal rest-frame ultraviolet luminosity density for  $z < 1$ , *AJ*, 118, 603
- Cutri, R.M., Nelson, B.O., Francis, P.J. et al., 2002, The 2MASS red AGN survey, in *AGN Surveys*, eds R. Green, E. Khachikian & D. Sanders, (San Francisco, ASP), 127
- Elbaz, D., Cesarsky, C.J., Fadda, D. et al., 1999, Source counts from the 15 micron ISOCAM deep surveys, *A&A*, 351, L37
- Evans, A.S., Frayer, D.T., Surace, J.A. et al., 2001, Molecular gas in infrared-excess, optically selected quasars and the connection with infrared-luminous galaxies, *AJ*, 121, 1893
- Genzel, R., Lutz, D., Sturm, E. et al., 1998, What powers ultraluminous IRAS galaxies ?, *ApJ*, 498, 579
- Holland, W.S., Robson, E.I., Gear, W.K. et al., 1999, SCUBA: a Common-user Submillimetre Camera Operating on the James Clerk Maxwell Telescope, *MNRAS*, 303, 659
- Hughes, D., Serjeant, S., Dunlop, J. et al., 1998, High-redshift star formation in the Hubble Deep Field revealed by a submillimetre-wavelength survey, *Nature*, 394, 241
- Ishida, C.M., 2003, The link between interactions, infrared emission, and the transformation of galaxies: a detailed study of a complete sample of luminous infrared galaxies, Ph.D. Thesis, University of Hawaii
- Ishida, C.M., Sanders, D.B., Mazzarella, J.M. et al., 2003, B,V, and I-band imaging of a complete sample of luminous infrared galaxies. I. the atlas, *ApJS*, submitted
- Iwasawa, K., 1999, An X-ray investigation of powerful far-infrared galaxies, *MNRAS*, 302, 96
- Joseph, R.D., 2000 The great debate: starbursts as the energy source of ultraluminous infrared galaxies, in *Ultraluminous Galaxies: Monsters or babies ?*, *Ap&SS*, 266, 321
- Kawara, K., Sato, Y., Matsuhara, H. et al., 1998, ISO deep far-infrared survey in the "Lockman Hole". A search for obscured objects at high redshift. I. observations, *A&A*, 336, L9
- Kim, D.-C., 1995, The IRAS 1-jy survey of ultraluminous infrared galaxies, PhD Thesis, University of Hawaii
- Kim, D.-C. & Sanders, D.B., 1998, The IRAS 1-Jy survey of ultraluminous infrared galaxies. I. the sample and luminosity function, *ApJS*, 119, 41
- Kim, D.-C., Veilleux, S., & Sanders, D.B., 2002, Optical and near-infrared imaging of the IRAS 1-jy sample of ultraluminous infrared galaxies. I. the sample, *ApJS*, 143, 277
- Lilly, S.J., LeFèvre, Hammer, O. F. et al., 1996, The Canada-France Redshift Survey: the luminosity density and star formation history of the universe to  $z \sim 1$ , *ApJL*, 460, L1
- Lilly, S., Eales, S.A., Gear, W.K.P. et al., 1999, The Canada-United Kingdom deep submillimeter survey. II. first identifications, redshifts, and implications for galaxy evolution, *ApJ*, 518, 641
- Lockman, F.J., Jahoda, K., & McCammon, D. 1986, The structure of galactic HI in directions of low total column density, *ApJ*, 302, 432
- Lutz, D., Veilleux, S., Genzel, R., 1999, Mid-infrared and optical spectroscopy of ultraluminous infrared galaxies: a comparison, *ApJL*, 517, L13
- Madau, P., Ferguson, H.C., Dickinson, M. et al., 1996, High-redshift galaxies in the Hubble Deep Field: colour selection and star formation history to  $z \sim 4$ , *MNRAS*, 283, 1388
- Mazzarella, J.M., Sanders, D.B., Jensen, J. et al., 2003, Optical imaging of luminous infrared galaxies from the IRAS bright galaxy sample: The R,K atlas, *ApJS*, submitted
- Meurer, G.R., Heckman, T.M., Lehnert, M.D. et al., 1997, The panchromatic starburst intensity limit at low and high redshift, *AJ*, 114, 54
- Neugebauer, G., et al., 1984, The infrared astronomical satellite (IRAS) mission, *ApJL*, 287, L1
- Rupke, D.S., Veilleux, S., Sanders, D.B., 2002, Keck absorption line spectroscopy of galactic winds in ultraluminous infrared galaxies, *ApJ*, 570, 588

- Sanders, D.B., 1999, A new view of galaxy evolution from submillimeter surveys with SCUBA, *Ap&SS*, 269-270, 381
- Sanders, D.B., 2000, The great debate: the case for AGNs, in *Ultraluminous Galaxies: Monsters or babies ?*, *Ap&SS*, 266, 331
- Sanders, D.B., Kim, D.-C., Mazzarella, J.M. et al., 2000c, The Hosts of ultraluminous infrared galaxies, in *Dynamics of Galaxies: From the Early Universe to the Present*, eds F. Combes et al., (San Francisco: ASP), 297
- Sanders, D.B., Mazzarella, J.M., Surace, J.A. et al., 2003a, The IRAS revised bright galaxy survey (RBGS), *AJ*, in press
- Sanders, D.B. & Mirabel, I.F., 1996, Luminous infrared galaxies, *ARA&A*, 34, 749
- Sanders, D.B., Phinney, E.S., Neugebauer, G. et al., 1989, Continuum energy distributions of quasars - shapes and origins, *ApJ*, 347, 29
- Sanders, D.B., Soifer, B.T., Elias, J.H. et al., 1988b, Warm ultraluminous infrared galaxies in the IRAS survey - the transition from galaxy to quasar ?, *ApJL*, 328, L35
- Sanders, D.B., Soifer, B.T., Madore, B.F. et al., 1988a, Ultraluminous infrared galaxies and the origin of quasars, *ApJ*, 325, 74
- Sanders, D.B., et al., 2003b, in preparation
- Sato, Y., Kawara, K., Cowie, L.L et al., 2001, *A&A*, submitted
- Schechter, P., An analytic expression for the luminosity function for galaxies, *ApJ*, 203, 297
- Schmidt, M. & Green, R.F., 1983, Quasar evolution derived from the Palomar Bright Quasar Survey and other complete quasar surveys, *ApJ*, 269, 352
- Scoville, N.Z., Frayer, D.T., Schinnerer, E. et al., 2003, *ApJL*, 585, L105
- Smail, I., Ivison, R.J. , & Blain, A.W. 1997, A deep submillimeter survey of lensing clusters: a new window on galaxy formation and evolution, *ApJL*, 490, L5
- Soifer, B.T., Helou, G., Lonsdale, C.J. et al., 1984b, The remarkable infrared galaxy Arp220 = IC4553, *ApJL*, 283, L1
- Soifer, B.T. & Neugebauer, G. 1991, The properties of infrared galaxies in the local universe, *AJ*, 101, 354
- Soifer, B.T., Neugebauer, G., Matthews, K. et al., 2000, High resolution mid-infrared imaging of ultraluminous infrared galaxies, *AJ*, 119, 509
- Soifer, B.T., Rowan-Robinson, M., Houck, J.R. et al., 1984a, Infrared galaxies in the IRAS minisurvey, *ApJL*, 278, L71
- Soifer, B.T., Sanders, D.B., Madore, B.F. et al., 1987, The IRAS bright galaxy sample. II - the sample and luminosity function, *ApJ*, 320, 238
- Steidel, C.C., Adelberger, K.L., Giavalisco, M. et al., 1999, Lyman-break galaxies at  $z > 4$  and the evolution of the ultraviolet luminosity density at high redshift, *ApJ*, 519, 1
- Taniguchi, Y., Cowie, L., Sato, Y. et al., 1997, ISOCAM 7 micron deep survey of the Lockman Hole: a mid-infrared search for primeval galaxies, *A&A*, 328, L9
- Veilleux, S., Kim, D.-C., Sanders, D.B. et al., 1995, Optical spectroscopy of luminous infrared galaxies. II. an analysis of the nuclear and long-slit spectra, *ApJS*, 98, 171
- Veilleux, S., Kim, D.-C., & Sanders, D.B., 2002, Optical and near-infrared imaging of the IRAS 1-Jy sample of ultraluminous infrared galaxies. II. the analysis, *ApJS*, 143, 315
- Veilleux, S., Sanders, D.B., & Kim, D.-C., 1997, A near-infrared search for hidden broad-line regions in ultraluminous infrared galaxies, *ApJ*, 484, 92
- Veilleux, S., Sanders, D.B., & Kim, D.-C., 1999, New results from a near-infrared search for hidden broad-line regions in ultraluminous infrared galaxies, *ApJ*, 522, 139
- Xia, X.-Y., Xue, S.J., Mao, S. et al., 2002, Chandra observations of Markarian 273: unveiling the central active galactic nucleus and the extended hot gas halo, *ApJ*, 564, 196