ULTRALUMINOUS INFRARED GALAXIES

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Abstract. At luminosities above $\sim 10^{11}\,L_{\odot}$, 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. At the highest luminosities, ultraluminous infrared galaxies (ULIGs: $L_{\rm ir} > 10^{12}\,L_{\odot}$), outnumber optically selected QSOs by a factor of ~ 1.5–2. All of the nearest ULIGs ($z < 0.1$) 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. ULIGs may represent a primary stage in the formation of massive black holes and elliptical galaxy cores. The intense circumnuclear starburst that accompanies the ULIG phase may also represent a primary stage in 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.

1. Introduction

One of the major results of the Infrared Astronomical Satellite (*IRAS*) all-sky survey was the identification of a class of luminous infrared galaxies (LIGs: $L_{\rm ir} > 10^{11}\ L_{\odot}$; $H_{\rm o} = 75\,{\rm km\ s^{-1}Mpc^{-1}}$, $q_{\rm o} = 0.5$)[1], objects that emit more energy in the far-infrared/submillimeter than at all other wavelengths combined. Redshift surveys of complete samples of *IRAS* galaxies now agree that infrared selected galaxies become the dominant population of extragalactic objects at bolometric luminosities above $\sim 4\,L^{*}$ (i.e. $L_{\rm bol} > 10^{11}\ L_{\odot}$). Reasonable assumptions about the lifetime of the infrared

[1] $L_{\rm ir} \equiv L(8\text{-}1000\mu{\rm m})$, computed from the observed infrared fluxes in all four *IRAS* bands according to the prescription in Perault (1987); see also Sanders & Mirabel (1996).

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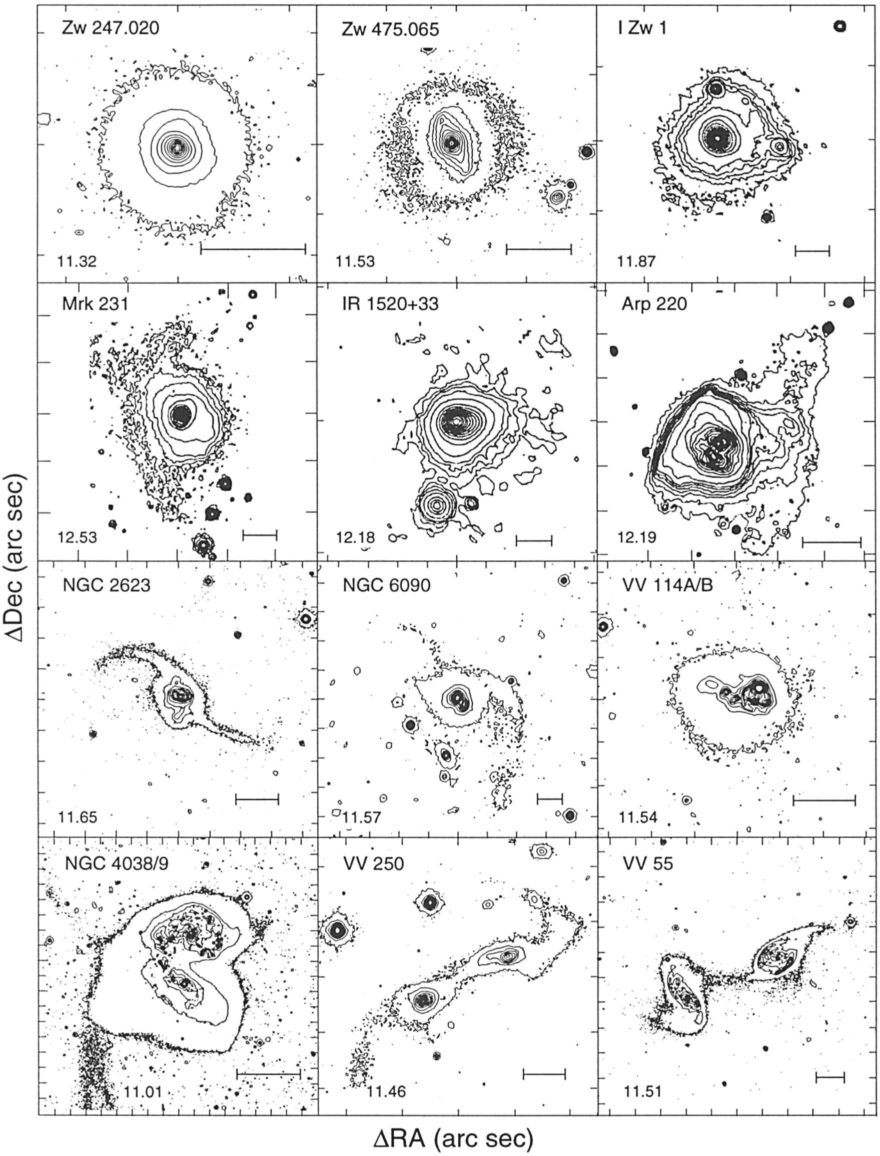

Figure 1. R-band images of a subset of 12 LIGs selected from the *IRAS* Revised Bright Galaxy Sample (RBGS: Sanders et al. 1998) and a complete sample of "warm" ULIGs (Sanders et al. 1988b). The scale bar represents 10 kpc, tick marks are at 20″ intervals, and the infrared luminosity (log $L_{\rm ir}/L_\odot$) is indicated in the lower left corner of each panel. This subsample is chosen to illustrate the full range of morphologies and infrared 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). These ground-based data (typical seeing is 0.7″–1.2″) are currently being replaced with higher resolution *HST* and ground-based adaptive optics images at UV-to-nearIR wavelengths. As an example, see color plates 5-6 (pp. xxiii-xxiv) for new data on NGC 4038/39.

phase suggest that a *substantial fraction of all galaxies with* $L_B > 10^{10} L_\odot$ *may at some point in their lifetime pass through such a stage of intense infrared emission (Soifer et al 1987).* This review focuses on providing an up-to-date summary of the observed morphological properties of ULIGs[2], those infrared-selected objects which represent an extreme phase of nuclear activity in galaxies, equivalent to the bolometric luminosity of optically selected QSOs.

2. LIGs and ULIGs: A Merger Sequence

Ground-based optical and near-infrared imaging of complete samples of the brightest infrared galaxies clearly show that a substantial fraction of LIGs are strongly interacting or merging spirals, and that the higher the luminosity the more advanced is the merger. Millimeterwave observations of have shown these spirals to be rich in molecular gas – $M(H_2) \sim 10^9 - 3 \times 10^{10} M_\odot$ (e.g. Sanders et al. 1991) – and that there is an increasing central concentration of this gas with increasing infrared luminosity. The representative subsample of LIGs shown in Figure 1 illustrates the signs of strong interactions/mergers (tidal tails, double nuclei, etc.) that are revealed in deep optical images of nearby LIGs. Comparison of the images with numerical simulations (e.g. Barnes & Hernquist 1992; Mihos & Hernquist 1994) allows these objects to be placed in a rough time sequence.

3. ULIG Properties

TABLE 1. Properties of ULIGs

Property	Median	Min	Max
redshift	0.05	0.018	0.136
$\log L_{ir}$ $[L_\odot]$	12.2	12.0	12.65
$\log M(H_2)$ $[M_\odot]$	10.0	9.3	10.7
$M(H_2)$ at r <1kpc [%]	65	40	100
$\langle\sigma(H_2)\rangle$ at r <0.5kpc $[M_\odot pc^{-2}]$	4×10^4	1×10^4	1×10^5
$\langle\rho(H_2)\rangle$ at r <0.5kpc $[M_\odot pc^{-3}]$	3×10^2	1×10^2	1×10^3
$\langle A_V\rangle$ towards nucleus [mags]	800	400	2000
nuclear separation [kpc]	1.9	<0.02	9.3
tail length [kpc]	45	20	120
B-band luminosity $[L^*_B]$	2.5	1.1	4.4
K-band luminosity $[L^*_K]$	2.5	1.2	7.3

[2]Optical/near-IR spectroscopy of LIGs, and the nuclear gas and dust properties of ULIGs are discussed in conference papers by Veilleux and Scoville & Yun respectively.

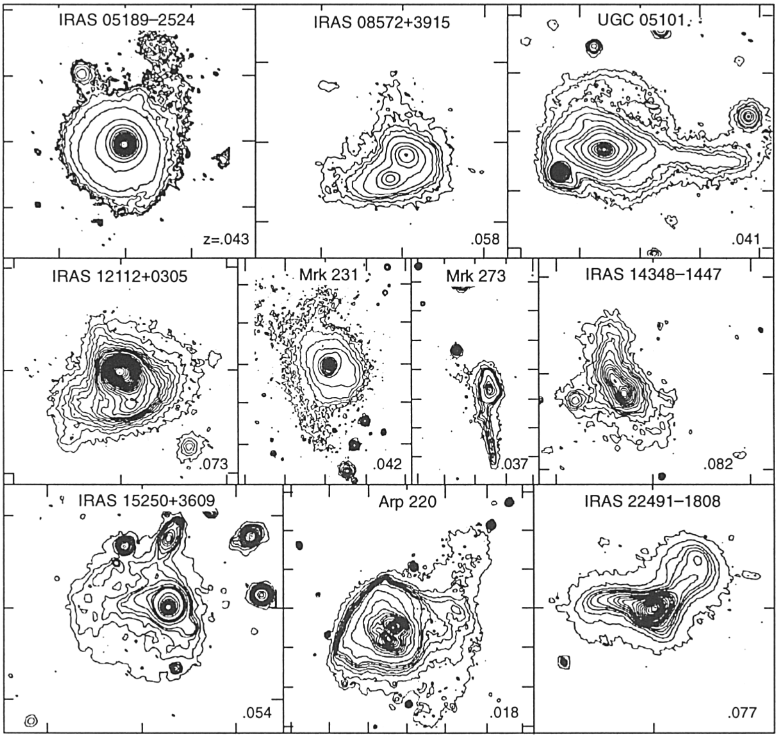

Figure 2. Optical (r-band) CCD images of the complete sample of 10 ULIGs from the original *IRAS* BGS (Sanders et al. 1988a). Tick marks are at 20″ intervals. Typical seeing for these ground-based images is ∼0.8″–1.5″.

Nearly all ULIGs appear to be late-stage mergers (e.g. Sanders et al 1988a,b; Melnick & Mirabel 1990; Kim 1995; Murphy et al. 1996; Clements et al. 1996). Figure 2 illustrates the largely overlapping disks that are seen in a *complete* sample of the nearest and best-studied ULIGs. The true extent of faint tidal features plus greater detail in the inner disks of these ULIGs is better revealed in the higher resolution ground-based images and *HST* images of ULIGs shown in color plates 7-8 (pp. xxv-xxiv). Table 1 summarizes properties of the complete sample of 20 ULIGs from the *IRAS* Bright Galaxy Samples (Soifer et al 1987; Sanders et al 1995). The mean lifetime for the ULIG phase, estimated from the observed mean separation and relative velocity of the merger nuclei, is $\sim 2 - 4 \times 10^8$ yrs.

4. The Nuclear Starburst-AGN Connection and Fate of ULIGs

The enormous central gas supplies present in ULIGs are clearly an ideal breeding ground for both powerful circumnuclear starbursts and AGN. In-

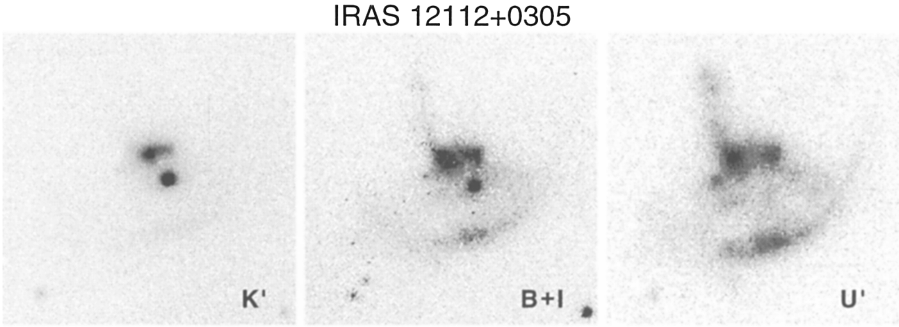

Figure 3. UV/Optical and near-infrared ground-based images of IRAS 12112+0305 (Surace 1998). The short wavelengths are dominated by knotty star formation, both in the central regions and along the extended tidal features. However most of the bolometric luminosity of this system appears to originate in the central knot (d <200 pc) that is completely obscured at U′, and that is either powered by an AGN, a superstarburst (which by itself would be much more powerful than the sum of the luminosity from all other starburst regions in this object), or a mixture of starburst and AGN.

deed those ULIGs that have been imaged with adaptive optics from the ground (see Fig. 3) or with *HST* (see Fig. 4) show evidence for a population of massive young ($\sim 10^7$ yrs) star clusters, although these clusters account for typically much less that half the ULIG bolometric luminosity (Surace & Sanders 1999). Most of the luminosity appears to be concentrated in one or two small (r <100 pc) regions centered on the putative nucleus (or nuclei) (e.g. Soifer, et al. 1998), and it is these compact regions which most likely harbor exotic superstarbursts, and/or a powerful AGN.

There is now substantial evidence that ULIGs are elliptical galaxies forming by merger-induced dissipative collapse (Kormendy & Sanders 1992), including $r^{1/4}$-law brightness profiles (e.g. Schweizer 1982; Wright et al. 1990; Kim 1995), newly-formed globular clusters (e.g. Fig. 4 and Surace et al. 1998), central gas densities ($\gtrsim 10^2\, M_\odot\, \mathrm{pc}^{-3}$ at $r \lesssim 0.5-1$ kpc: Scoville et al. 1991) that are as high as stellar mass densities in the cores of giant ellipticals, and powerful "superwinds" (Heckman et al. 1987; Armus et al. 1989) which will likely leave behind a largely dust free core. It seems reasonable to assume also, that this scenario might lead to a constant ratio of black hole mass to bulge mass in agreement with recent observational results (Kormendy & Richstone 1995; Magorrian et al. 1998).

Future infrared space missions and more sensitive submillimeter surveys should succeed in identifying more distant ULIGs, thus allowing a direct test of whether the infrared luminosity function evolves as steeply as that of QSOs, and whether ULIGs were more numerous at $z \sim 1-4$ when it is presumed that most of the ellipticals were formed from mergers of spirals.

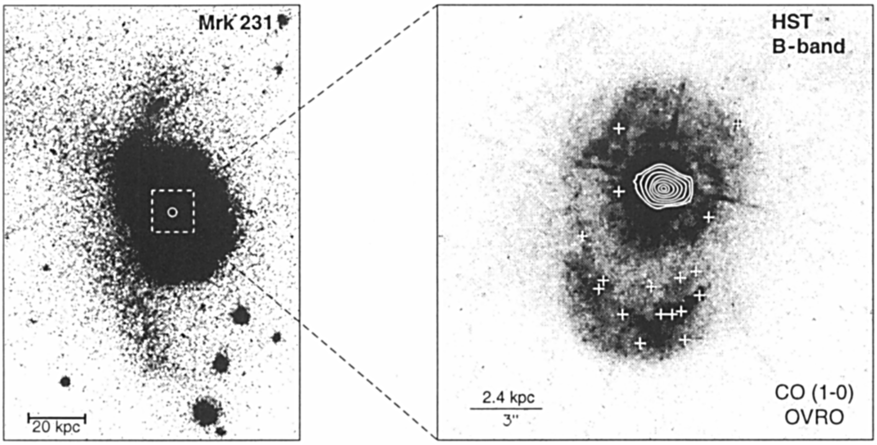

Figure 4. The advanced merger/ULIG/QSO Mrk 231 – Left panel: optical image (Sanders et al. 1987) and CO contour (Scoville et al. 1989). Right panel: *HST* B-band image and identified stellar clusters ('+') from Surace et al. (1998). The high resolution CO contours are from Bryant & Scoville (1996)

References

Armus, L., Heckman, T.M., & Miley, G.K. 1989, *ApJ*, **347**, 727
Barnes, J.E., & Hernquist, L. 1992, *ARAA*, **30**, 705
Bryant, P.M., & Scoville, N.Z. 1996, *ApJ*, 457, 678
Clements, D.L., et al. 1996, *MNRAS*, **279**, 459
Heckman, T.M., Armus, L., & Miley, G.K. 1987, *AJ*, **93**, 276
Kim, D.-C. 1995, Ph.D. Thesis, University of Hawaii
Kormendy, J., & Richstone, D. 1995, *ARAA*, **33**, 581
Kormendy, J., & Sanders, D.B. 1992, *ApJ*, **390**, L53
Magorrian, J., et al. 1998, *AJ*, **115**, 2285
Melnick, J., & Mirabel, I.F. 1990, *A&A*, **231**, L9
Mihos, J.C., & Hernquist, L. 1994, *ApJ*, **431**, L9
Murphy, T.W., et al. 1996, *A.J.*, **111**, 1025
Perault, M. 1987, Ph.D. Thesis, University of Paris
Sanders, D.B., & Mirabel, I.F. 1996, *ARAA*, **34**, 725
Sanders, D.B., Scoville, N.Z., & Soifer, B.T. 1991, *ApJ*, **370**, 158
Sanders, D.B., et al. 1987, *ApJ*, **312**, L5
Sanders, D.B., et al. 1988a, *ApJ*, **325**, 74
Sanders, D.B., et al. 1988b, *ApJ*, **328**, L35
Sanders, D.B., et al. 1995, *AJ*, **110**, 1993
Sanders, D.B., et al. 1998, *ApJS*, in preparation
Schweizer, F. 1982, *ApJ*, **252**, 455
Scoville, N.Z., et al. 1989, *ApJ*, **345**, L25
Scoville, N.Z., Sargent, A.I., Sanders, D.B., & Soifer, B.T. 1991, *ApJ*, **366**, L5
Soifer, B.T., et al. 1987, *ApJ*, **320**, 238
Soifer, B.T., et al. 1998, *ApJ*, submitted
Surace, J.A., & Sanders, D.B. 1999, *ApJ*, **512**, 162
Surace, J.A. 1998, PhD Thesis, University of Hawaii
Surace, J.A., et al. 1998, *ApJ*, **492**, 116
Wright, G.S., James, P.A., Joseph, R.D., & McLean, I.S. 1990, *Nature*, **344**, 417