THE "GREAT DEBATE": THE CASE FOR AGNS

On behalf of the "green team"

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Abstract. We summarize the evidence from multiwavelength observations that the dominant power source in the majority of ultraluminous infrared galaxies (ULIGs) may be an active galactic nucleus (AGN). In the broader context of the debate, we also show that — 1. ULIGs are indeed a key stage in the transformation of merging gas-rich disks into ellipticals, 2. ULIGs are plausibly the precursors of quasi-stellar objects (QSOs), and 3. ULIGs do appear to be local templates of the high luminosity tail of major gas-rich mergers at z $\sim$1–4.

1. Background

The nature of the dominant power source in ultraluminous infrared galaxies (hereafter ULIGs) has been the subject of intense debate, ever since their discovery in significant numbers by the all-sky survey carried out by the Infrared Astronomical Satellite (*IRAS*). The debate has intensified once again following recent mid- and far-infrared spectroscopic observations of ULIGs by the Infrared Space Observatory (*ISO*), and is the main theme of this workshop. The scientific organizing committee (SOC) asked the conference participants to form two teams (with meeting rooms in the "blue tower" and the "green tower") charged with marshaling the evidence in favor of starbursts and AGNs respectively, in preparation for ending the conference with a "Great Debate". This article presents the evidence assembled by the "green team" as to the fraction of the total bolometric luminosity of ULIGs that can reasonably be attributed to dust-enshrouded AGNs, and answers additional questions posed by the SOC on the relevance of ULIGs to galaxy transformations.

1.1. KEY TOPICS FOR THE DEBATE

The SOC proposed the following four topics for the debate:

(1) Most of $> 10^{12} L_{\odot}$ *ULIGs are predominantly powered by ?* *(heavily dust enshrouded AGN) or (circumnuclear starbursts)* *(2) ULIGs follow a merger sequence from colliding disk galaxies with large bulges to ellipticals.* *(3) ULIGs are precursors of QSOs.* *(4) ULIGs are local templates of the high luminosity tail of mergers at* $z = 1$*–*4.

Much of the Green Tower discussion was devoted to Topic 1, which most participants had thought to be the main theme of the Workshop. Much of our time was spent focusing on the nearest and best studied ULIGs, and on comparing the observational evidence from across the electromagnetic spectrum for and against the presence of a dominant AGN. Topic 3 seemed to blend naturally with the discussion of Topic 1.

Discussion of Topic 2 drew heavily on several large optical and near-infrared imaging studies of complete samples of low-z *IRAS* galaxies, while Topic 4 relied on more recent studies of a limited number of high-z *IRAS* sources and sources recently identified in deep submillimeter images obtained with the Submillimeter Common-User Bolometer Array (SCUBA: Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea.

2. Opening Remarks

The origin and evolution of ULIGs continues to be a subject of intense research, and one that has taken on renewed importance following new infrared/submillimeter results from *ISO* and SCUBA/JCMT, and from new X-ray observations with *ROSAT*, *ASCA*, and *BeppoSax*. Strong evolution in the space density of luminous infrared galaxies has been detected in the first deep mid-infrared surveys with ISOCAM (Taniguchi et al. 1997; Aussel et al. 1999) and deep far-infrared surveys with ISOPHOT (Kawara et al. 1998; Puget et al. 1999). Reports from the first deep submillimeter surveys with SCUBA on the JCMT (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999) show that the space density of ULIGs at high redshift ($z > 1$) appears be sufficient to account for nearly all of the far-infrared/submillimeter background radiation (e.g. Barger, Cowie, & Sanders 1999), and depending on their exact redshift distribution, produces an infrared luminosity density that exceeds that in the optical/UV by factors of 2–5 (e.g. models by Blain et al. 1999). In addition, the discovery that much of the X-ray background appears to be produced by a population of heavily obscured AGN (e.g. Fabian & Barcons 1992; Boyle et al. 1995; Almaini et al. 1998), objects which have been largely missed in optical surveys due to extremely heavy obscuration along the line of sight (e.g. $N_{\rm H} \gtrsim 10^{24-25}\,{\rm cm}^{-2}$: Maiolino et al. 1998) has clearly renewed interest in studies of infrared-selected AGN.

It seems clear that detailed observations of nearby ULIGs are a required first step in order to better understand these objects, and in particular to unravel the nature of the dominant energy source responsible for their enormous infrared luminosity. Given the evidence from millimeterwave interferometer observations which indicate large absorbing columns toward the nuclei of all ULIGs [typically $N({\rm H}_2) > 10^{24}\,{\rm cm}^{-2}$: e.g. Bryant & Scoville 1996), it has always seemed prudent to use a broad multiwavelength approach to study these sources, thus we welcome the new mid- and far-infrared *ISO* data as the latest tool in the study of ULIGs.

The four topics posed for the debate are answered in the order they were posed.

2.1. WORKING DEFINITIONS

The following definitions have been in wide use, and are adopted for the purpose of this debate:

$L_{\rm ir}$:	$L(8 - 1000\,\mu m)$
ULIG:	$L_{\rm ir} \geq 10^{12}\,L_\odot$ [1]
"warm":	$f_{25}/f_{60} > 0.2$ (as originally defined by de Grijp et al. 1985; also Low et al. 1998, Sanders et al. 1988b)
AGN:	A compact nuclear region producing energy by non-stellar processes. Also, a strong "broad-line region" (BLR) with doppler motions $>$ 2000 km s^{-1} (HWHM) from gas in a region $<$ 1 pc in diameter.
RQQSO:	radio-quiet quasi-stellar object ($L_{20cm}/L_{1\mu m} \lesssim 10^{-5}$)

3. "Ultraluminous Galaxies: Monsters or Babies"

This was the advertised title of the Workshop, and with appropriate rewording, became the first topic for the debate:

Q1: Most of the $>10^{12}\,L_\odot$ ULIGs are predominantly powered by AGN ? or Starburst ?

[1] $L_{\rm ir} \geq 10^{12} L_\odot$ is equivalent to the minimum bolometric luminosity of a QSO, i.e. $M_{\rm B} < -22.3$ — which is equivalent to $M_{\rm B} < -23$ (Schmidt & Green 1983) corrected for $H_{\rm o} = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $q_{\rm o} = 0$ — and a bolometric correction for QSOs of $\sim 11.8 \times \nu L_\nu(0.43\,\mu{\rm m})$ (e.g. Elvis et al. 1994; see also Sanders & Mirabel 1996).

We define the words "most" and "predominantly" in the way that they have been used throughout this workshop, i.e. to mean "$> 50\,\%$".

From the beginning it seemed clear that the AGN camp could relatively easily reach a consensus on dominant AGNs for those ULIGs with "warm" mid-infrared colors, nearly all of which have Seyfert-like optical and/or near-infrared spectra, and for the most luminous ULIGs, i.e. the hyperluminous objects with $L_{\rm ir} > 10^{13}\,L_{\odot}$, where *all* of the currently identified objects indeed have "warm" colors and typically Seyfert 2 emission lines in direct optical emission (e.g. IRAS F09105+4108: Kleinmann & Keel 1987; IRAS F15307+3252: Cutri et al. 1994; IRAS F10214+4724: Rowan-Robinson et al. 1991), but have been shown to contain hidden broad line regions in polarized optical light (e.g. Hines et al. 1995), or in direct near-infrared emission (e.g. Veilleux, Sanders, & Kim 1997, 1999).

There was little or no agreement on the dominant energy source for the cooler ULIGs which make up the bulk of the ULIG population by number. As more complete multiwavelength data sets were assembled for individual objects, what was intriguing was the fact that for a significant fraction of the cool ULIGs, different wavelength data often gave contradictory results; for example relatively strong X-ray emission, or the clear presence of an AGN-like radio core, while mid-infrared and optical line diagnostics favored starbursts. What was also apparent was that previous statements about AGN-like properties of ULIGs often used as a benchmark objects which were radio-loud (e.g. 3C sources such as 3C 273) when referring to the mean radio and/or X-ray properties of AGN, despite the fact that the great majority of QSOs are *radio-quiet* and relatively X-ray week.

It was decided that the best way to attack Topic 1 was an in depth study of the five nearest ULIGs, objects for which a substantial body of high resolution, multiwavelength data already exists, and then to compare the properties of these objects with the mean properties of radio-quiet QSOs (RQQSOs). Figure 1 presents images of the 5 nearest ULIGs and Table 1 summarizes the large scale properties of each.

3.1. MULTIWAVELENGTH PROPERTIES OF THE NEAREST ULIGS

Table 2 lists the radio–to–X-ray properties of the five nearest ULIGs, including the latest high-resolution radio data from the VLA and VLBA and X-ray data from ASCA. In addition to the extensive notes included with Table 2, a brief summary of properties by wavelength band is given below.

3.1.1. *Radio*

One measure commonly used to distinguish starbursts from AGN is the FIR-to-radio correlation parameter q_o; starburst galaxies show a tight cor-

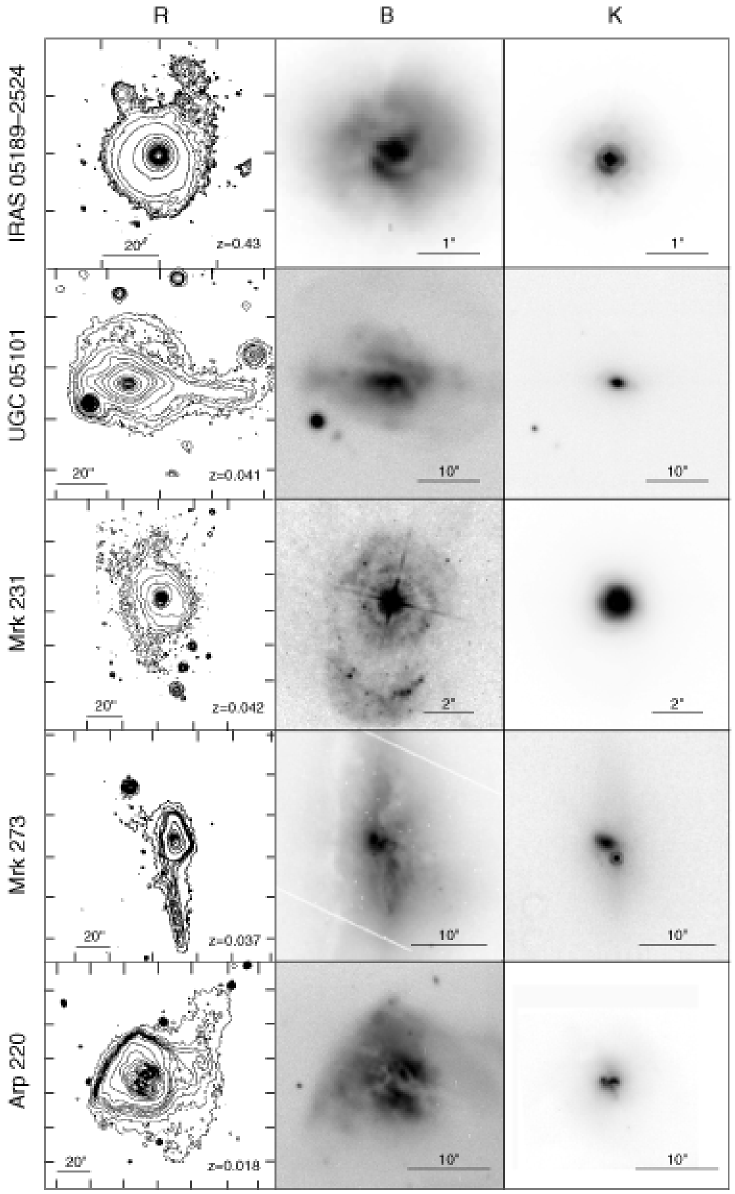

Figure 1. The five nearest ULIGs from the original *IRAS* BGS (Soifer et al. 1987). The large scale R-band images were obtained with the Palomar 5 m telescope (Sanders et al. 1988a,b,c). Tick marks represent intervals of 20″. The logarithmic stretch is designed to reveal both faint large scale features and bright nuclei. The optical (B-band) *HST* images are from Surace et al. (1998). The K-band images are from Surace et al. (1998) and Scoville et al. (1999). The plate scale for the B and K images is indicated in the lower right corner of each panel. The greyscale for the B and K images has been adjusted to show only the brightest features. For each object (row) all three wavelength panels (R,B,K) are centered at the same (R.A., Dec).

TABLE 1
GLOBAL PROPERTIES OF THE NEAREST ULIGS

Name	cz (km s^{-1})	log $L_{\rm ir}$ ($L_\odot$)	log M(H$_2$) ($M_\odot$)	Spectra (type)	Nucleus (morph)	Nucleus sep (pc)	K-profile (type)	Tails (kpc)
(1)	(2)	(3)	(4)	(5)	(6)		(7)	(8)
IRAS 05189−2524	12,801	12.10	10.3	S1	single	<80	E	20
UGC 05101	11,992	12.01	10.4	L	single	<80	E	40
Mrk 231	12,591	12.52	10.0	S1	single	<80	E	40
Mrk 273	11,332	12.10	10.2	S2	double	680	Am	55
Arp 220	5,546	12.15	10.3	L	double	340	E	25

[1] The 5 nearest ULIGs in the *IRAS* Bright Galaxy Survey (BGS: Soifer et al. 1987).
[2−3] Redshifts and luminosities are taken from the *IRAS* Revised Bright Galaxy Survey (RBGS: Sanders et al. 1999).
[4] H_2 masses are taken from Sanders, Scoville & Soifer (1991) and Solomon et al. (1997).
[5] Spectral types are taken from the optical/near-IR surveys of Veilleux et al. (1995), Veilleux, Kim, & Sanders (1999), and Veilleux, Sanders, & Kim (1997, 1999).
[6] Nuclear morphology, ('Single' or 'Double' at K-band), and nuclear separations, where the seeing limit (corresponding to typically ≤ 80 pc) is used to define 'Single' nuclei (see Figure 1).
[7] radial light profiles – 'E' = a deVaucouleurs-profile ($r^{1/4}$-law) is a good fit to the radial K-band profile over the range $\Delta r = 0.1 - 5$ kpc; 'AM' = amorphous, i.e. neither a $r^{1/4}$-law nor an exponential is a good fit to the radial K-band profile.
[8] mean tail lengths as measured from deep R-band images (see Figure 1).

relation around a value of $q_o = 2.34$ ($\sigma \sim 0.1$), while radio-loud AGN often have values as small as $q_o = 0$ to -1. The majority of ULIGs have values of q_o within the range $q_o = 2.0 - 2.6$, however *so do the majority of RQQSOs*, which presents a problem when using a global parameter such as q_o to distinguish starbursts from *radio-quiet* AGN.

A more direct method of distinguishing AGN from starbursts at radio wavelengths is to look for the presence or absence of a true high-brightness temperature AGN-like radio core. VLBA observations of RQQSOs find typical radio-AGN core fractions in the range of 20–50 % at 1.4 GHz (P. Barthel and H. Smith, private communication). Two of the five ULIGs in Table 2 (Mrk 231 and UGC 05101) have AGN-core strengths within this range; perhaps not surprisingly, these two objects also have the smallest q_o values.

A somewhat unexpected finding is the detection with the VLA of large scale (i.e. 20–50 kpc) radio "plumes" in three of the five ULIGs (UGC 05101, Mrk 231, Mrk 273), similar to the bipolar plumes or extended jets seen in radio galaxies (M. Yun, this workshop) suggesting the presence of a powerful radio-AGN core in these objects.

TABLE 2
Multiwavelength Properties of the Nearest ULIGs

	Radio				Infrared				Optical		X-ray	
	VLA		VLBA		ISO		MKO		MKO-KPNO		ASCA	
Name	f_q^{-1}	Plumes	f_c	morp	$\frac{C^+}{C^+_{*B}}$	spec	BLR	$f_{\rm pol}$	spec	$\log\frac{C_R}{C_B}$	$\log\frac{L_X}{L_{\rm fir}}$	$\log L_{\rm HX}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
IRAS 05189−2524	52%	⋯	< 10%	⋯	0.25	⋯	S1	5%	S2	0.86	−1.82	43.9
UGC 05101	210%	yes	20%	AGN	⋯	*B	⋯	⋯	L	1.25	<−3.70	n/a
Mrk 231	468%	yes	30%	AGN	0.22	AGN	S1	10%	S1	0.95	−3.15	42.7
Mrk 273	121%	yes	12%	AGN/*B?	0.67	AGN	no	⋯	S2	1.10	−2.70	43.0
Arp 220	85%	no	3%	*B/RSN	0.17	*B	no	⋯	L	1.35	−4.40	n/a

[1] *IRAS* BGS source name
[2] comparison of observed radio-FIR ratio (corrected for free-free absorption) with "pure starburst" ratio: i.e. $100 \times 10^{2.34-q_o}$. The computed quantity $q_o \equiv q + (\alpha_o - \alpha) log(8.44/1.49)$ (Condon et al. 1991) is based on the observed value $q \equiv \log[(FIR/3.75 \times 10^{12} Hz)/S_{1.49\rm GHz}]$ where FIR is the sum of the 60 μm and 100 μm *IRAS* fluxes, and $q_o = 2.34$ and $\alpha_o = 0.7$ are the mean values for starburst galaxies (Condon, Anderson, & Helou 1991).
[3] large scale (25–50 kpc) 21cm AGN-like radio "plumes" detected (M. Yun, private communication)
[4] AGN-like radio core fraction at $\lambda = 3.6$ cm (Smith, Lonsdale, & Lonsdale 1998)
[5] radio core morphology at $\lambda = 3.6$ cm (Smith , Lonsdale, & Lonsdale 1998)
[6] relative strength of 158μm C^+ line compared to starburst mean (J. Fischer, private communication)
[7] mid-IR spectral type determined from relative strength of the 7.7 μm PAH feature (Genzel et al. 1998; Lutz et al., these proceedings)
[8] evidence for broad line region at Paα or Paβ, and/or strong evidence for [Si VI]λ1.962 emission (Veilleux, Sanders, & Kim 1997, 1999)
[9] percent polarization of BLR (D. Hines, private communication)
[10] optical spectral type (Veilleux et al. 1995; Veilleux, Kim, & Sanders 1999)
[11] continuum reddening measure, $\log C_{6565}/C_{4861}$ (Veilleux et al. 1995; Veilleux, Kim, & Sanders 1999)
[12] $\log[L(2-10\,\rm keV)/L(8-1000\,\mu m)]$
[13] $\log[L(5-10\,\rm keV)]$ ergs s^{-1}

3.1.2. *Mid-IR*

The mid-infrared (i.e. $\lambda \sim 5$–$50\,\mu$m) begins to directly probe the dominant peak of the spectral energy distributions (SEDs) of ULIGs. The most promising new diagnostic tool in this wavelength range is that provided by *ISO* spectroscopy. Genzel et al. (1998), Lutz et al. (1998), and Lutz et al. (these proceedings) argue that the strength of the 7.7 μm PAH line/continuum ratio can be used to determine the fraction of the infrared/submillimeter luminosity peak in SEDs that is due to a starburst and an AGN respectively. Using their arguments alone, two of the four ULIGs in Table 2 (Mrk 231, Mrk 273) owe $\gtrsim 50\,\%$ of their far-infrared/submillimeter luminosity to an AGN (e.g. Lutz et al., these proceedings). These authors also point out that there is evidence for "coexistence of central AGN and circumnuclear star formation in a significant fraction of (ULIGs)", and they note that "the mid-infrared emitting regions are highly obscured ($A_{\rm V} \sim 5-50$) for the screen case of $A_{\rm V} \sim 50-1000$ for the fully mixed case)." Large optical depths (i.e. $A_{\rm V} > 1000$) along the line of sight toward the nuclei of ULIGs are indeed suggested by millimeterwave interferometer measurements of molecular lines (e.g. Scoville et al. 1991; Downes & Solomon 1998; Sakamoto et al. 1999), as well as from the weakness of far-infrared spectral lines such as the 158 μm C^+ line (J. Fischer, these proceedings) which indicate optical depths of unity in ULIGs even at $\lambda \gtrsim 100\,\mu$m !

High spatial resolution measurements of ULIGs in the mid-infrared can potentially constrain the emitting size of the region responsible for the bulk of the mid-infrared luminosity in ULIGs. Soifer et al. (1999) report that the bulk of the mid-infrared emission ($\Delta\lambda \sim 10$–$25\,\mu$m) from Arp 220 comes from two very compact regions centered on the radio nuclei, each with diameter $\lesssim 200$ pc (FWHM). Both a very compact starburst and an AGN can be modeled to fit the data, however as pointed out by Soifer et al., it becomes difficult to hide a $10^{12}\,L_\odot$ starburst in regions this small.

3.1.3. *Near-IR*

Strong emission lines such as Paα and Paβ as well as high-excitation lines such as [Si VI] can potentially be used to distinguish starbursts from AGN. Even if the extinction is still two large along the line of sight to observe emission lines from the central source, there is the potential for observing scattered emission in polarized light. Two of the four ULIGs for which sensitive near-infrared spectra exist (IRAS 05189-2524, Mrk 231) show clear evidence for polarized Seyfert 1 emission lines and [Si VI] emission, further suggesting the presence of a strong AGN.

3.1.4. *Optical*

The use of standard line diagnostic diagrams (e.g. Veilleux & Osterbrock 1987) show that three of the five ULIGs have Seyfert spectra. Both ULIGs with Seyfert 1 optical and/or mid-infrared spectra have $L_{\rm BLR}/L_{bol}$ ratios nearly identical to the mean observed ratio for UV-excess QSOs, consistent with the hypothesis that the bulk of the bolometric luminosity in these infrared-dominated objects may indeed be due to a dust-enshrouded UV-excess QSO.

3.1.5. *X-ray*

Like the radio, the X-ray luminosity is but a small fraction of the total bolometric luminosity of all starbursts and most AGN, albeit usually a few orders of magnitude in $\nu L\nu$ larger than for the radio, but still several orders of magnitude less than the infrared luminosity of ULIGs. It is not clear that the observed X-ray spectrum can directly be related to the bolometric luminosity of ULIGs. However, by analogy with the mean X-ray properties of QSOs or starbursts, it may at least be possible to say whether a QSO-like X-ray nucleus is present.

The 2–10 keV luminosity of all five ULIGs in Table 2 is weak relative to the strong far-infrared emission (e.g. Nakagawa et al. 1999); however, *the X-ray luminosity of ULIGs is not weak in relation to RQQSOs when com-*

paring the X-ray luminosity to the luminosity in the optical (e.g. Ogasaka et al. 1997; Iwasawa 1999; Turner 1999). Strong absorption appears to affect both the optical/UV and soft X-rays in ULIGs, as might have been expected.

Absorption effects are minimized by considering only the hard X-ray emission, $L_{\rm HX} \equiv L(5-10\,{\rm keV})$, detected with *ASCA*. Three of the five ULIGs were detected in hard X-rays, all at a level consistent with the mean hard X-ray luminosity observed for RQQSOs [Note: Mrk 231 is compared here to the mean properties of BALQSOs which are somewhat weaker in their observed $L_{\rm HX}$ than other RQQSOs (Turner 1999).]

TABLE 3

COMPARISON OF ULIGS WITH MEAN PROPERTIES OF RADIO-QUIET QSOS

	Radio		Mid-IR	Near-IR/Optical		X-ray
Name	RG-plumes	AGN-core	PAH	$L_{\rm BLR}/L_{\rm bol}$	$P_{\rm BLR}$	log $L_{\rm HX}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
IRAS 05189-2524	…	< 25%	…	**100%**	**>50%**	**>50%**
UGC 05101	**Yes**	**>50%**	*B	no	n/a	<5%
Mrk 231	**Yes**	**>50%**	**AGN**	**100%**	**>50%**	**>50%**
Mrk 273	**Yes**	∼30%	**AGN**	no	n/a	>25%
Arp 220	NO	∼10%	*B	no	n/a	< 5%

[1] *IRAS* BGS source name
[2] VLA 20cm detection of large-scale (25-50kpc) AGN-like radio plumes (M. Yun, private communication)
[3] % AGN-like radio core fraction compared to mean value of ∼40% for RQQSOs (H. Smith, private communication)
[4] 7.7μm PAH line/continuum: $> 1 \equiv$*B; $< 1 \equiv$ AGN (Lutz et al., these proceedings)
[5] % $L_{\rm bol}$ of mean value for RQQSOs (Veilleux, Sanders, & Kim 1997, 1999)
[6] % BLR polarization compared to mean value for RQQSOs
[7] % $L(5-10$kev) compared to mean value for RQQSOs

3.1.6. *Summary: Comparison with RQQSOs*

Table 3 compares the properties of the five nearest ULIGs with the *mean* properties of RQQSOs, in order to try to answer the question — Is there evidence that > 50 % of the bolometric luminosity in > 50 % of ULIGs is due to an AGN ? Not surprisingly, perhaps, is that the two "warm" ULIGs (IRAS 05189−2524, Mrk 231) show substantial multiwavelength evidence for a dominant AGN, but equally important is the fact that one additional object, Mrk273, is predicted by the starburst camp to contain a dominant AGN (Lutz et al., these proceedings), and another, UGC 05101, shows substantial evidence at radio wavelengths for harboring a powerful AGN.

What is perhaps most surprising is that Arp 220 appears to be alone in this small but well-studied group of the nearest ULIGs in it's absence of any clear signature of a dominant AGN. Rather than being the "rosetta-stone" for ULIGs, Arp 220 may simply be the nearest such object, and perhaps one of the most heavily obscured ULIGs as indicated by the extremely strong reddening in the optical and near-infrared, as well as evidence for extremely strong silicate absorption in the mid-infrared.

Have we shown that the answer to Topic 1 is "an AGN" ? If you take the five nearest ULIGs and adopt the bolometric luminosity indicator used by the starburst camp (i.e. the 7.7 μm/continuum ratio) plus the bolometric luminosity indicator used by the AGN camp (i.e. $L_{\rm BLR}/L_{\rm bol}$), then 4 of the 5 ULIGs in Table 3 are indeed dominated by an AGN. However, our decision to focus only on those objets that have been observed at the broadest range of wavelengths, and with the highest resolution and sensitivity that current X-ray satellites and radio interferometers can provide, has produced a sample too small to statistically prove that $> 50\,\%$ of *all* ULIGs are dominated by AGN, thus our answer to Topic 1 must be ...

A1: Possibly.
There is evidence from a detailed multiwavelength study of the 5 nearest ULIGs that $> 50\%$ of $L_{\rm bol}$ in $> 50\%$ of ULIGs is due to an heavily dust enshrouded AGN.

4. Merger Sequence

Q2: Do ULIGs follow a merger sequence from colliding disk galaxies with large bulges to ellipticals ?

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 (e.g. Joseph & Wright 1985; Sanders, Surace, & Ishida 1999; Mazzarella et al. 1999). Millimeter-wave observations of have shown these spirals to be rich in molecular gas – $M({\rm H_2}) \sim 10^9 - 3 \times 10^{10}\, M_\odot$ (e.g. Sanders et al. 1988a; Mirabel et al. 1990; Sanders, Scoville, & Soifer 1991) – and that there is an increasing central concentration of this gas with increasing infrared luminosity (Scoville et al. 1991; Downes & Solomon 1998). There is no clear evidence in favor of early

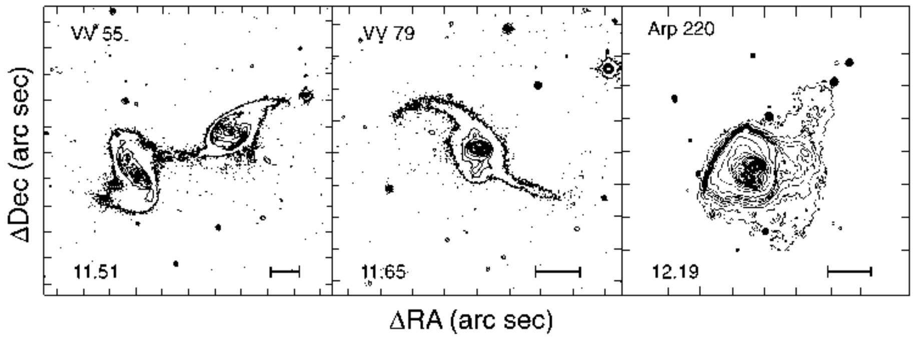

Figure 2. A subsample of R-band images (Mazzarella et al. 1999) of luminous infrared galaxies from the *IRAS* RBGS (Sanders et al. 1999) that illustrate the strong interactions/mergers that are characteristic of nearly all objects with $L_{\rm ir} > 10^{11.3}\,L_\odot$. The scale bar represents 10 kpc, 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.

versus late-type spirals, only that they both typically appear to be large (i.e. 0.5–2 L^*) and molecular gas-rich. The three LIGs shown in Figure 2 provide a coarse illustration of early, mid, and late type mergers commonly represented in the complete samples of LIGs. Comparison of these images with numerical simulations (e.g. Barnes & Hernquist 1992; Mihos & Hernquist 1994; C. Mihos, these proceedings) aids in allowing these objects to be placed in a rough time sequence.

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) . The large-scale ground-based images shown in the left panel of Figure 1 illustrate the largely overlapping disks that are seen in a *complete* sample of the nearest and best-studied ULIGs. Greater detail in the inner disks of these ULIGs is better revealed in the higher resolution ground-based images and *HST* images shown in the center and rightmost panels of Figure 1. The mean lifetime for the ULIG phase, estimated from the observed mean separation and relative velocity of the merger nuclei, is $\sim 1 - 2 \times 10^8$ yrs.

There is now substantial evidence that ULIGs are indeed elliptical galaxies forming by merger-induced dissipative collapse (e.g. summary by Kormendy & Sanders 1992), including $r^{1/4}$-law brightness profiles [e.g. Schweizer 1982; Joseph & Wright 1985; Wright et al. 1990 (see Figure 3); Kim 1995; Zheng et al. 1999), newly-formed globular clusters (e.g. Surace et al. 1998), central gas densities that are as high as stellar mass densities in the cores of giant ellipticals (e.g. $\gtrsim 10^2 M_\odot pc^{-3}$ at $r \lesssim 0.5 - 1$ kpc: Scoville et al. 1991; Downes & Solomon 1998), and powerful "superwinds" that will likely leave

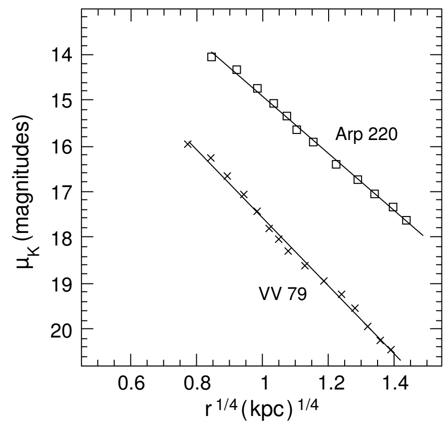

Figure 3. K-band radial surface brightness profiles (Wright et al. 1990) for two of the luminous infrared galaxies shown in Fig. 2 – VV 79 (NGC 2623), and Arp 220. The straight line represents a normalized $r^{1/4}$-law (deVaucouleurs) profile characteristic of elliptical galaxies. The inner gap corresponds to the lack of information at radii smaller than 1″ set by seeing. More recent higher resolution K-band imaging of these galaxies by NICMOS shows that a $r^{1/4}$-law continues to be a good representation of the K-band radial profile over the range 0.1–5 kpc (Scoville et al. 1999).

behind a largely dust free core (Heckman, Armus, & Miley 1987; Armus, Heckman, & Miley 1989).

A2: YES,

ULIGs appear to represent an advanced stage in the merger of two large spirals, where the merger remnant already has assumed a $r^{1/4}$-law profile,

but

there is no evidence that only early-type spirals are involved, only that both progenitors be molecular gas-rich.

5. Precursors of QSOs

Q3: Are ULIGs precursors of QSOs ?

If one chooses not to believe that ULIGs already harbor a dust enshrouded QSO (i.e. an UV-excess AGN with $M_{\rm B} < -22.3$), then is there

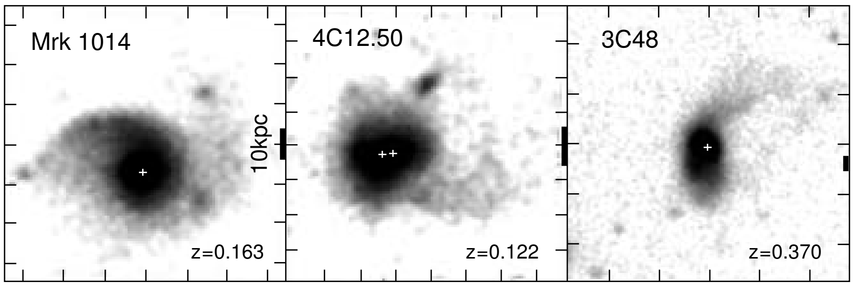

Figure 4. Optical images of infrared-excess, optically selected QSOs, powerful radio galaxies, and infrared selected QSOs (MacKenty & Stockton 1984; Kim 1995; Stockton & Ridgway 1991). The '+' sign indicates the position of putative optical nuclei. Tick marks are at 5″ intervals and the scale bar represents 10 kpc. All three objects exhibit strong nuclear concentrations of molecular gas, with typically $\sim 10^{10}\,M_\odot$ concentrated at galactocentric radii $\lesssim 1$ kpc (Sanders et al. 1988c; Mirabel, Sanders, & Kazès 1989; Scoville et al. 1989).

evidence that they will become QSOs ? It is probably a fair summary of the "Green Tower" view that at least 20–30 % of ULIGs (i.e. the "warm" objects) already harbor a bonifide QSO, and that a substantial fraction, if not all, of the cool ULIGs have the *potential* to eventually become QSOs.

Of course there is no reason to believe that all ULIGs, once unshrouded, will necessarily reach the optical/UV luminosity associated with QSOs – they may already have peaked in $L_{\rm bol}$ and/or some objects may simply be pure starbursts that for some reason never choose to build/fuel a massive black hole. However, recent studies of the host galaxies of QSOs provide new evidence for a plausible evolutionary connection between the ULIG phase and the optical/UV excess QSO phase. The mean and range of the H-band luminosity of QSO hosts, $L_{\rm H} \sim 1 - 4\,L^*$, reported by McLeod & Rieke (1994) and McLeod, Rieke, & Storrie-Lombardi (1999) are remarkably similar to the H-band luminosities of ULIGs (e.g. review by Sanders & Mirabel 1996). Also, it has been known for some time that QSO hosts often exhibit tidal features indicative of strong interactions/mergers [e.g. Stockton & MacKenty 1983: MacKenty & Stockton 1984 (see the left panel in Figure 4)], and more recent *HST* images of both radio-loud and radio-quiet QSOs show clear signs of large scale tidal debris, circumnuclear knots, bars and rings (e.g. McLure et al. 1999) similar to the inner structures seen in *HST* images of ULIGs (e.g. Surace et al. 1998). It is becoming easier to believe that QSO hosts are indeed slightly more evolved stages of ULIG mergers.

A3: YES,
there is good evidence that $\sim$20–30% of ULIGs are already dust-enshrouded QSOs,
but
it is not at all clear that all ULIGs will obtain the optical/UV luminosity corresponding to bonafide QSOs (i.e. $M_{\rm B} < -22.3$).

6. Local Templates of High-z Mergers

Q4: Are ULIGs local templates of the high luminosity tail of mergers at z = 1–4 ?

[Note: We have interpreted this question as asking whether there is evidence that low-z ULIGs are templates of high-z ULIGs, leaving aside the larger question of how high-z ULIGs may be related to optically-selected high-z objects (e.g. Lyman-break galaxies).]

There is now substantial evidence to suggest that the space density of ULIGs evolves steeply with cosmic lookback time, and that ULIGs were much more common at redshifts $z \sim$1–4. In the mid- and far-infrared, the deepest surveys carried out by *IRAS* (e.g. Hacking & Houck 1987; Lonsdale & Hacking 1989; Gregorich et al. 1995; Kim & Sanders 1998), and more recently the deep surveys with *ISO* (e.g. Taniguchi et al. 1997; Kawara et al. 1998; Aussel et al. 1999; Puget et al. 1999) are consistent with number density evolution as steep as $(1+z)^5$ out to $z \sim$1. Within the past year, submillimeter surveys with SCUBA on the JCMT (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999) have revealed what appears to be a substantial population of high-z ULIGs (i.e. $z \sim$1–4) , that are plausibly the high-z extension of the low-z ULIGs detected by *IRAS*.

It is still too early to tell whether all of the high-z ULIGs detected by *ISO* and SCUBA have properties similar to local ULIGs. However, studies of the few high-z objects whose redshifts have been identified show that these sources may indeed resemble their lower redshift counterparts more closely than might at first have been assumed. The two best studied sources from the SCUBA sample of Smail et al. (1998) are illustrative. SMM J02399$-$0136 at $z \sim 2.8$, with $L_{\rm ir} \gtrsim 10^{13} L_\odot$, is morphologically compact with an optical classification as a narrow-line "type-2" AGN (Ivison et al. 1998; Ivison, these proceedings), and contains $\sim 10^{10.5} M_\odot$ of molecular gas (Frayer et al. 1998). SMM J14011+0252 at $z \sim 2.6$ with $L_{\rm ir} \sim 10^{12.3} L_\odot$ (Barger et al. 1999), is a strongly interacting/merger pair, with an H II-like optical spectrum and $\sim 10^{10.7} M_\odot$ of molecular gas (Frayer et al. 1999). These two sources fit into the pattern exhibited by ULIGs in the local Universe. In particular their molecular gas masses, optical luminosities, and optical morphologies are very similar to what is observed for local ULIGs [see Sanders & Mirabel (1996) for a review of local ULIGs].

A4: YES,

There is evidence that local ULIGs have properties (gas content, morphology, etc.) similar to the identified infrared luminous sources at $z = 1$–4,

but

there is no reason to believe that all high-z, high-$L_{\rm ir}$ sources are as homogeneous as the low-z ULIGs appear to be.

7. Concluding Remarks

The Scientific Organizing Committee is to be commended for expanding this debate to include a wider range of topics that are clearly important for the study of ULIGs. Both sides in the debate would likely agree that ULIGs represent an extremely important stage in galaxy transformations (e.g. through the building of ellipticals from merging spirals) and the accompanying metal enrichment of the intergalactic medium via nuclear superwinds. Both sides would probably also agree that research on local ULIGs has become even more important following the extremely exciting discoveries from *ISO* and SCUBA that suggest that the far-infrared/submillimeter background radiation (as measured by *COBE*) may indeed be resolved into a population of ULIGs at $z \sim 1-4$, and that the far-infrared/submillimeter luminosity from these high-z ULIGs may dominate that attributed to star formation as seen in the rest-frame optical/UV.

It also seems clear that most participants at this workshop believe that *both* starbursts and AGN are important at varying levels to the luminosity output of ULIGs, and that there is most likely an evolutionary connection between the fueling of starbursts and the fueling of AGN. Indeed, what better time to fuel both a circumnuclear starburst and an AGN than when dumping $\sim 10^{10}\, M_\odot$ of gas and dust into the central kiloparsec of a merger remnant. And if ULIGs indeed represent the building of massive bulges during the merger of gas-rich spirals, then the recent discovery that all massive ellipticals appear to contain massive black holes, where $M_{\rm MBH}$ is a constant fraction (i.e ~ 0.006) of $M_{\rm bulge}$ (e.g. Kormendy & Richstone 1995; Magorrian et al. 1998) also suggests that the building/fueling of a massive black hole is likely to be concurrent with the ULIG phase. And even if star formation is still favored as the dominant luminosity source in most ULIGs, members of the starburst camp might consider "affiliate membership" in the AGN camp simply by subscribing to the hypothesis that most ULIGs may eventually evolve into optically-selected UV-excess QSOs.

The majority of workshop participants on both sides of this debate seemed willing to accept the idea that "warm" ULIGs and those objects with the highest infrared luminosities (e.g. $\log\,[L_{\rm ir}/L_\odot] \gtrsim 12.6$) are most likely to be powered by a dominant AGN. Harder to accept was a dominant role for AGN in the lower luminosity, cooler ULIGs like Arp 220, but the fact that many Arp 220-like objects appear to have radio and hard X-ray properties similar to the mean properties of RQQSOs (e.g. Mrk 273, UGC 05101) suggests that dust obscuration could still mask a dominant AGN in the majority of these objects as well.

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