A HIGH RESOLUTION OPTICAL/NEAR-INFRARED STUDY OF THE EVOLUTIONARY LINK BETWEEN ULTRALUMINOUS INFRARED GALAXIES AND OPTICAL QSOS

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We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Astronomy.

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This work is dedicated to my wife Atiya who suffered through a full decade of my self-centered obsession with infrared galaxies.

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Abstract

The possible evolutionary connection between ultraluminous infrared galaxies (ULIGs: $L_{\rm bol} > 10^{12}$ L$_\odot$) and optically selected quasi-stellar objects (QSOs) was investigated. Three complete samples were examined: (1) "warm" ULIGs with mid-infrared colors characteristic of active galactic nuclei ($f_{25\mu\rm m}/f_{60\mu\rm m}$ >0.2), which appear to represent a critical transition phase between the second and third samples (2) "cool" ULIGs ($f_{25\mu\rm m}/f_{60\mu\rm m}$ <0.2) which appear to be the progenitors of warm ULIGs and which have many active star-formation characteristics, and (3) far-IR excess QSOs which have infrared to blue luminosity ratios at least as great as those of the "warm" ULIGs.

High spatial resolution observations (FWHM$\approx$ 0.3-0.8$''$) were made at wavelengths ranging from the near-ultraviolet (λ=3200Å) to near-infrared (λ=2.1μm). The following are the major findings: (1) all ULIGs have small scale structure in their central few kiloparsecs, (2) this structure is consistent in most cases with knots of powerful star formation which are insignificant in terms of their contribution to the high bolometric luminosity of the systems, (3) some of these knots have colors and luminosities consistent with QSO nuclei seen through patchy emission and extinction, (4) both ULIGs and QSOs have similar total mass host galaxies, (5) mergers are implicated in at least 22% of far-IR excess QSOs; 50% also have nuclear disturbances, and (6) there is evidence that the fraction of active nuclei detectable in the optical and near-infrared increases with the estimated dynamical age of the systems.

These results are consistent with the idea that at least *some* ($\approx$ 30%) QSOs like those examined here evolve via mergers from progenitors similar to the ULIGs, and that the ultimate fate of most ULIGs is to form systems similar in properties to optical QSOs. Implications for the evolution of active nuclei and clustered star formation in merging far-infrared active galaxies are discussed.

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Chapter 1

Introduction[1]

1.1. Historical Background

Over the past 30 years, our understanding of galaxy formation and the role of interactions between galaxies has undergone considerable change; galaxies are now understood to be dynamic, evolving entities, and that sometimes these interactions can be cataclysmic, violent events. Arp compiled his now famous "Atlas of Peculiar Galaxies" (Arp 1966), the vast majority of which are now understood to be interacting systems. Early n-body experiments (Toomre & Toomre 1972) showed how colliding spiral galaxies could be transformed in just the way seen in the Arp Atlas systems, and also that this could result in considerable changes in the circumnuclear environments of the merged galaxies, as large amount of gas would be funneled into the galaxy centers. Larson & Tinsley (1978) showed that the peculiar galaxies of the Arp Atlas showed evidence for having undergone a recent burst of star formation, and suggested that these bursts were due to galaxy interactions like those described by Toomre. All of these early works increasingly suggested that galaxy interactions, rather than being rare curiosities, might actually play an important role in galaxy formation and evolution.

The launch of the Infrared Astronomical Satellite (*IRAS*) in 1983 proved to be a major turning point in the study of galaxy interactions. One of the most important results of the IRAS mission was the discovery of a class of galaxies that emit the bulk of their luminosity in the far-infrared (Soifer et al. 1984, 1989). This far-infrared radiation appeared to be due to dust re-radiation of UV photons; in the majority of infrared luminous galaxies this dust appears to be heated by star-formation activity, a result expected from pre-*IRAS* studies. Initial studies of these galaxies indicated that a significant fraction of these galaxies appeared to be in groups or in morphologically disturbed systems indicative of galaxy interactions (Soifer et al. 1984). Although most studies to date have had relatively low resolution and short integration times, they have nonetheless generated considerable evidence that tidal interactions between galaxies in close association with each other are somehow associated with unusual infrared activity (Bushouse et al. 1988; Haynes & Herter 1988; Surace et al. 1994).

Some of these galaxies have luminosities similar to that of classical optically- selected quasars (i.e., $L_{\mathrm{bol}} > 10^{12}\ L_{\odot}$), and have been dubbed "ultraluminous infrared galaxies" (hereafter referred to as ULIGs). Sanders (1988a) found that the ULIGs show a distinct trend towards non-thermal, AGN-like spectra as opposed to lower luminosity systems; this result has been more precisely quantified by Kim (1995). This increasing Seyfert fraction, combined with the high space density of ULIGs relative to optical QSOs (Soifer et al. 1986) led to the suggestion that ULIGs were evolutionary predecessors of optically selected quasars (Sanders et al. 1988a). In this scenario, a merger between two gas-rich spiral disks leads to the formation and/or fueling of an active galactic nucleus (AGN); reprocessing of the AGN

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[1] This introductory chapter borrows heavily from the original proposal for this dissertation. As a result, it is written in such a way as to anticipate, but not know, the final conclusions.

light by dust in the merger core results in the ultraluminous infrared emission. Over time, powerful winds would blow away the shroud of reprocessing dust, enabling direct lines of sight to the central engine which would then have the appearance of an optical quasar.

Many additional studies have helped support this scenario. Sanders (1988b) used a far-infrared color criterion ($f_{25\mu\mathrm{m}}$ / $f_{60\mu\mathrm{m}} > 0.2$), known to select AGN-like systems (de Grijp et al. 1985), to select a complete sample of ULIGs with "warm" colors (the Warm Galaxy Sample, hereafter WGS). The WGS would therefore represent a transitional state between the BGS ULIGs and optically selected quasars. It was shown that these transition objects all exhibited evidence for an AGN in the form of Seyfert spectra, and that most appeared to have advanced interaction morphologies suggesting that they were more evolved forms of the BGS ULIGs. Observations by Heckman et al. (1990) provided evidence for the winds that would be needed to clear the dust away from the merger remnant. More recent work has shown that indeed most ULIGs do appear to be systems with disturbed morphologies indicative of current or past interactions (Clements et al. 1996, Murphy et al. 1996). Finally, much theoretical work, primarily in the form of n-body simulations, has continued to work out the expected details for the merger process (Barnes & Hernquist 1992 and references therein). For a detailed review of luminous and ultraluminous infrared galaxies, see Sanders & Mirabel (1996).

Optically selected quasars have also been found to have significant infrared activity. Neugebauer et al. (1984) found evidence that many of the quasars in the Palomar-Green Bright Quasar Sample (BQS) (Schmidt & Green 1983) were extended in the near-IR, a result recently confirmed by direct imaging (McLeod & Rieke 1995a,b). Sanders et al. (1989) found that the spectral energy distributions (SEDs) of PG QSOs were characterized not only by a blue peak but by a second infrared peak, which they concluded was due to reradiation by dust from a warped disk surrounding the quasar nucleus. Implicating dust in the SEDs of QSOs helped further claims of SED evolution between the dusty ULIGs and optically-selected QSOs. Other evidence has shown that some quasars lie in host galaxies that are similar to the merger remnants expected of evolved ULIG systems, and that mergers must play some role in the fueling of optical QSOs (Hutchings & Neff 1992, Stockton 1990 and references therein). Surprisingly, early *HST* results seemed to contradict the ground-based observations by failing to find the expected bright host galaxies (Bachall et al. 1995). The controversy continuing to surround the interpretation of the *HST* results have indicated that the space-based observations are not the panacea they might have been, and highlights the need for further ground- based follow-up work (McLeod & Rieke 1995, Neugebauer et al. 1995, Bahcall et al. 1997).

Several problems remain to be solved in the hypothetical merger time sequence. While many ULIGs and QSO host galaxies appear to be mergers, it is not clear if this is true for *all* ULIGs (especially the WGS) and QSO hosts. QSO progenitors, like QSOs, must contain compact central engines; however, results are inconclusive on the presence of AGN in the ULIGs and many authors have argued that the high infrared luminosities of the ULIGs are actually due to star formation (Kim 1995; Leech et al. 1989; Lonsdale et al. 1995; Condon et al. 1991). Similarly, it is not clear if the observed QSO host galaxy properties are compatible with their being major mergers of spiral galaxies (McLeod & Rieke 1994a,b). Even if they are, it is not clear what fraction are the result of major mergers in light of the apparent diversity in QSO host environments (Bahcall et al. 1997). Finally, it has not been shown that the QSO mergers are actually older than ULIGs, thus establishing a time sequence, nor has it actually been shown that time evolution exists within the ULIGs themselves; some workers argue that the observed properties of ULIGs (particularly the apparent "warm" galaxy – AGN correlation) actually represent a range of properties, and not an evolutionary sequence.

1.2. The Need for High Spatial Resolution

At the distance of typical ULIGs (z=0.05-0.15), $1''$ corresponds to a physical scale of 1–3 kpc. Since it is expected that most of the activity occurs within the central few kiloparsecs (Carico et al. 1990), previous studies have been hampered by an inability to spatially resolve this nuclear activity. The resulting spatial confusion has prevented a detailed understanding of the star formation and possible AGN activity within the nuclei. Additionally, current observations have not been able to clearly resolve extended morphological features such as tidal tails, loops, and multiple nuclei. It is this shortcoming in resolution that this dissertation intends to address.

Astronomy in the late 1980s and early 1990s enjoyed a renaissance in high spatial resolution observing. Perhaps the most significant development was the launch of the Hubble Space Telescope (*HST*). Since ground-based observations are hampered by the intrinsic seeing of the atmosphere, the placement of an optical telescope in earth orbit immediately resulted in resolution improvements as high as 20× at optical wavelengths. Although initially plagued by defects in manufacture, the refurbished telescope currently provides (with WFPC2) spatial resolution with a degree of stability and sky coverage unmatchable from the ground.

However, the situation on the ground was also rapidly changing. It was recognized that a handful of ground-based sites such as Mauna Kea offered considerable improvements in both seeing and transparency (particularly in the near-infrared) over older sites, which led to their rapid development as new astronomical centers. Even at these sites, it became apparent that the telescopes themselves were major sources of image degradation (Roddier et al. 1990), and several facilities began vigorous programs to minimize telescope- based seeing defects (Pickles et al. 1994, Hawarden et al. 1994).

More important, however, was the development of adaptive optics. Spurred in part by the expense, delays, and difficulties in acquiring time associated with *HST* as well as the desire to improve already existing facilities, many groups pursued projects aimed at correcting for ground-based atmospheric distortions (see Beckers 1993 and references therein, Roddier et al. 1994, Rousset et al. 1994, Olivier et al. 1994). Unfortunately, most of these adaptive optics implementations were incapable of providing high order corrections with natural guide stars fainter than $m_{\rm V}$=15. However, lower- order tip/tilt corrections were possible; in the near-infrared on a small telescope like the UH 2.2m such corrections are capable of providing nearly all the resolution enhancement provided by a full adaptive optics system (Roddier et al. 1991).

Advances were also made in detector technology. In particular, major improvements were made in near-infrared detectors that made them much more similar in size, performance, and usability to optical charge-coupled devices (CCDs) (McLean 1994 and references therein, Hodapp et al. 1996). Between the time when data for this dissertation was initially taken and the time it was completed (a span of roughly 10 years), the imaging area of the near-infrared detectors used increased by nearly three-hundred fold. These developments vastly improved the efficiency of near-infrared observations, both by improving the quality of the raw data through better responsivity and lower dark current and through improved telescope efficiency due to the larger field of view with adequate spatial sampling. Similar improvements in the size and quantum efficiency of CCDs allowed observations to be extended to very short ($\lambda \approx 3000$Å) wavelengths, thus improving detectability of very blue emission like that expected from young stars.

1.3. Scientific Objectives

This dissertation is an attempt to examine whether or not an evolutionary connection exists between ultraluminous infrared galaxies and optically selected quasars. In order to this issue, several key points must be examined.

The first is to determine whether or not merger activity exists in each of the samples. If mergers can be implicated in the formation history of both ULIGs and QSOs, this would be strong circumstantial evidence that they have had similar histories. Morphological diagnostics of merger activity (tidal tails, multiple nuclei, etc.) have already been identified in many of the ULIGs (Sanders et al. 1988ab, Murphy et al. 1996, Kim 1995, Surace 1993). It is likely that deep, high resolution imaging will show that all of the ULIGs are merger products. It is believed that the QSOs will also show some evidence for merger activity when similar observations are made of them.

Second, it is necessary to determine the age of any merger processes in each of the samples. This will be carried out by several means. The first is through observation of the merger morphologies of the systems. As the merger remnants age, we expect them to undergo morphological changes. For example, mean nuclear separations should decrease, tidal tails should expand and fade, and the extended envelope should become more relaxed. Second, current HST observations are revealing the presence of knots or clusters of star formation in many interacting galaxies (Whitmore & Schweizer 1995, Meurer et al. 1995). Assuming that these knots form as a result of the merger process, it should be possible to set an age for a given system by measuring the luminosities and colors of these knots, since these will evolve with time. Comparisons will be made to spectral synthesis starburst models, models of various emission mechanisms, and to empirical observations of other known starbursts. Because the spatial resolution will be high enough to spatially separate the starburst knots from the underlying galaxy, the burst age/strength degeneracy will be eliminated.

Third, the emission mechanisms present in the optical and near-infrared will be identified and characterized. In particular, since QSOs all contain a compact central source, we would expect their hypothetical progenitors, the ULIGs, to also contain compact central sources. A search will be made for evidence of an AGN in each of the ULIGs. Additionally, the nature of the compact star formation in the ULIGs will be examined with the particular question of determining their contribution to the high bolometric luminosity, possibly obviating the need for an AGN. This will be accomplished by a multi- wavelength high-resolution imaging campaign. Observations will include near-infrared, optical, and U' data. The many wavelengths will enable us to penetrate to varying degrees the heavy extinction seen in the IRAS galaxies. The resulting broad-band colors and high resolution maps of the nuclear morphology should be diagnostic of the different contributions of the (possibly starburst) stellar populations and AGN. We will attempt to show that the luminosity and colors of the QSO hosts are consistent with their being evolved versions of the ULIG hosts. Similarly we hope to show that the ULIGs have compact central engines which are consistent in terms of size, bolometric luminosity, and color with being heavily obscured QSO nuclei.

1.4. Sample Selection

Three complete samples have been chosen in order to test the possible connection between ultraluminous galaxies and optically selected QSOs. These samples are composed of the nearest examples of three presumably distinct evolutionary stages. All three samples lie in roughly the same region of the sky, as originally defined by the BGS: declination $\delta > -30$ °(in order to be visible from the northern hemisphere) and $|b| > 30$ °(in order to avoid confusion in the galactic plane, which is very severe in the far-infrared). All three samples are furthermore volume-limited with $z < 0.16$, for reasons discussed below.

1.4.1. "Warm" ULIGs

This sample was originally defined by Sanders et al. (1988b), and consists of all 12 ultraluminous galaxies characterized by having $f_{25\mu\mathrm{m}}/f_{60\mu\mathrm{m}} > 0.2$ and within the volume defined by $z<0.16$, corresponding to a 60 μm flux limit of 1.5 Jy. Since only a fraction (approximately 1/5) of ULIGS meet this "warmness" criterion (Kim 1995), this sample was naturally extended to higher redshifts and lower flux limits than the original BGS ULIG sample in order to get sufficient numbers of objects. This volume is also very near the completeness limit for ultraluminous galaxies in the deepest existing *IRAS*-based surveys, and is therefore a logical limiting volume. Finally, at these distances the physical spatial resolution obtainable may be enough to detect interesting features.

It is believed that these galaxies represent a transition state from the "cool" ULIGs to traditional optically selected QSOs (see §1.4.2–1.4.3); their properties are intermediate between the two other samples. Most have some evidence for merger activity and star formation like the greater body of ULIGs, but they also have evidence for compact nuclei (as seen in ground-based images) and Seyfert spectra similar to those of QSOs.

Table 1.1. Warm ULIG Sample

Name	RA	DEC	z
	(J2000.0)		
I Zw 1	00:53:34.9	12:41:36.2	0.061
IRAS 01003−2238	01:02:49.8	−22:21:56.3	0.118
Mrk 1014	01:59:50.1	00:23:41.5	0.163
IRAS 05189−2524	05:21:01.5	−25:21:46.7	0.042
IRAS 07598+6508	08:04:30.5	64:59:52.8	0.149
IRAS 08572+3915	09:00:25.4	39:03:54.2	0.058
IRAS 12071−0444	12:09:45.1	−05:01:13.7	0.129
3C273	12:29:06.7	02:03:08.6	0.158
Mrk 231	12:56:14.2	56:52:26.1	0.042
Pks 1345+12	13:47:33.5	12:17:24.5	0.122
Mrk 463	13:56:02.7	18:22:18.3	0.051
IRAS 15206+3342	15:22:37.9	33:31:36.6	0.125

1.4.2. "Cool" ULIGs

We define "cool" ULIGs as the complementary set to the "warm" sample having $f_{25\mu m}/f_{60\mu m} < 0.2$ and which therefore would not be expected to have characteristics similar to AGN. This sample includes all 7 "cool" ULIGs from the original BGS, as well as 7 additional objects drawn from the IRAS 1 Jy ULIG survey (Kim 1995). The 7 BGS ULIGs are all fairly well studied, and hence form an important base group from which to extend this study. However, it was felt that since the "warm" sample extends to much higher redshift than the "cool" BGS ULIGs, this would necessarily bias the study towards finding more resolvable structure in the relatively nearby systems. Therefore, 7 additional higher redshift ULIGs were selected from the 1 Jy Survey such that the resulting "cool" sample has a redshift distribution similar to the "warm" sample. Additionally, it was intentionally biased towards being observable in the summer months, thus decreasing the crowding of the observing program in the winter and spring. Although this sample is technically incomplete, it must be stressed that no additional infrared, optical, or morphological criteria were applied in the selection of these 7 systems — only their location on the sky, which should be uncorrelated with their other properties, was considered.

1.4.3. Infrared-Excess Optically Selected QSOs

A complete comparison sample of QSOs was chosen from the optically selected Palomar-Green Bright Quasar Survey (PG-BQS; Schmidt & Green 1983) to lie in the same volume of space as the two ULIG samples ($z < 0.16$) and to have the same bolometric luminosity as the ultraluminous galaxies ($L_{\rm bol} > 10^{12}\ L_{\odot}$, which corresponds to $M_{\rm bol} < -22.18$ when adjusted to $H_0 = 75$ km s^{-1} Mpc $^{-1}$ (Schmidt & Green 1983)). Given that the space density of ULIGs is similar to that of optical QSOs, there are 32 PG QSOs within this volume. In

Table 1.2. Cool ULIG Sample

Name	RA	DEC	z	Log $\frac{L_{\rm ir}}{L_\odot}$
	(J2000.0)			
IRAS 00091−0738	00:11:43.2	−07:22:07.8	0.119	12.17
IRAS 01199−2307	01:22:21.4	−22:51:59.5	0.156	12.23
IRAS 03521+0028	03:54:42.1	00:37:05.9	0.152	12.44
UGC 5101	09:35:51.7	61:21:11.3	0.039	11.99
IRAS 12112+0305	12:13:46.1	02:48:41.4	0.072	12.24
Mrk 273	13:44:42.1	55:53:12.7	0.038	12.13
IRAS 14348−1447	14:37:38.7	−15:00:22.8	0.082	12.24
IRAS 15250+3609	15:26:59.4	35:58:37.5	0.055	11.99
Arp 220	15:34:57.3	23:30:11.9	0.018	12.17
IRAS 20414−1651	20:44:17.4	−16:40:13.7	0.086	12.12
IRAS 22206−2715	22:23:28.8	−27:00:03.3	0.131	12.15
IRAS 22491−1808	22:51:49.3	−17:52:23.5	0.078	12.08
IRAS 23233+0946	23:25:55.6	10:02:45.1	0.128	12.02
IRAS 23365+3604	23:39:01.3	36:21:09.8	0.064	12.10

order to pre-select for systems likely to be at a closer evolutionary stage to the ULIGs, an additional criterion was imposed such that they have infrared excesses ($L_{\rm ir}/L_{\rm blue}$) as great or greater than the "warm" system with the lowest such ratio (3c273; $L_{\rm ir}/L_{\rm blue} > 0.46$). Of the 18 such PG QSOs, 3 are also WGS ULIGs. Although many of these PG QSOs have been observed before (McLeod & Rieke 1995a,b, Hutchings & Neff 1992), there have been no systematic multiwavelength surveys made with the required depth or resolution to detect the features we are looking for.

In summary, there are 14 "cool" ULIGS, 12 "warm" ULIGS, and 18 infrared- excess PG QSOs. However, the PG QSOs and "warm" ULIGs overlap by 3. Most of this study will focus on the "warm" ULIGs, which are believed to represent the critical transition objects. The remaining two samples are primarily for comparison purposes.

1.5. Organization of Dissertation

This dissertation is organized into several chapters based on the three different samples and the types of data obtained. Following Chapter 1, the Introduction, will be a chapter discussing the warm ULIG sample and the optical data obtained for it with *HST*. The next chapter will deal with ground-based near-infrared imaging of the same sample. The next chapters will present results for the cool ULIG and PG QSO samples, respectively, using the techniques outlined in chapters 2 & 3. Chapter 6 will present the first U'-band imaging of these systems. The final chapter will synthesize the results of the previous chapters into a merger time sequence and discuss it's implications for ULIG evolution. Appendix A details an auxiliary study of widely separated interacting galaxy pairs using

Table 1.3. Infrared-Excess PG QSO Sample

Name	RA (J2000.0)	DEC (J2000.0)	z	$L_{\rm ir}/L_{\rm blue}$
PG 0007+106	00:10:31.0	10:58:29.5	0.089	0.48
I Zw 1	00:53:34.9	12:41:36.2	0.061	2.01
Mrk 1014	01:59:50.1	00:23:41.5	0.163	2.57
PG 0838+770	08:44:45.6	76:53:09.4	0.131	0.66
PG 1001+054	10:04:20.1	05:13:00.5	0.161	0.48
PG 1114+445	11:17:06.4	44:13:32.6	0.144	0.98
PG 1119+120	11:21:47.1	11:44:18.3	0.050	0.69
PG 1126−041	11:29:16.7	−04:24:07.6	0.060	0.79
PG 1202+281	12:04:42.2	27:54:11.4	0.165	1.04
3C273	12:29:06.7	02:03:08.6	0.158	0.46
PG 1229+204	12:32:03.6	20:09:29.2	0.064	0.54
PG 1351+640	13:53:15.8	63:45:44.8	0.088	0.81
PG 1402+261	14:05:16.2	25:55:33.7	0.164	0.55
PG 1411+442	14:13:48.4	44:00:13.6	0.090	0.69
PG 1415+451	14:17:00.6	44:56:06.4	0.114	0.73
PG 1440+356	14:42:07.5	35:26:22.9	0.079	0.83
PG 1613+658	16:13:57.2	65:43:09.6	0.129	1.25
PG 2130+099	21:32:27.8	10:08:19.5	0.062	0.52

IRAS data combined with high spatial resolution techniques in an attempt to clarify the starburst fueling timescale and its dependence on the galaxy merger progenitors. Appendix B discusses the deconvolution algorithms used in this thesis and their applicability under different circumstances to ground-based data. Finally, Appendix C will provide a detailed discussion of the techniques used to derive colors from spectral synthesis data and the detectors available at the Institute for Astronomy (IfA). As per departmental guidelines, each chapter is designed to be self-contained within the larger framework of the dissertation itself, and as such will feature its own brief introduction with relevant background material, a discussion of the data, conclusions, and references.

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