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The hosts and environments of local ULIRGs and QSOs

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Abstract

This paper reviews the recent results from a comprehensive investigation of the most luminous mergers in the local universe, the ultra-luminous infrared galaxies (ULIRGs) and the quasars. First, the frequency of occurrence and importance of black hole driven nuclear activity in ULIRGs are discussed using the latest sets of optical, near-infrared, mid-infrared, and X-ray spectra on these objects. Obvious trends with luminosity, infrared color, and morphology are pointed out. Next, the host galaxy properties of ULIRGs are described in detail and then compared with local quasar hosts and inactive spheroids. A similar comparison is carried out for the environments of ULIRGs and local QSOs. By and large, the data are consistent with the scenario where ULIRGs are intermediate-mass elliptical galaxies in formation and in the process of becoming moderate-luminosity optical quasars. The powerful galactic winds detected in many ULIRGs may help shed any excess gas during this transformation. However, this evolutionary scenario does not seem to apply to all ULIRGs and quasars: Ultraluminous infrared mergers do not always result in a quasar, and low-luminosity quasars near the boundary with Seyferts do not all show signs of a recent major merger.

Keywords: Galaxies: active; Galaxies: interactions; Galaxies: Seyfert; Galaxies: starburst; Infrared: galaxies

Contents

1. Introduction

Galaxy merging is a key driving force of galaxy evolution. In hierarchical cold dark matter models of galaxy formation and evolution, merging leads to the formation of

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elliptical galaxies, triggers major starbursts, and may account for the growth of supermassive black holes and the formation of quasars (e.g., Kauffmann and Hehnelt, 2000). The importance of mergers increases with redshift (e.g., Zepf and Koo, 1989; Carlberg et al., 1994; Neuschaefer et al., 1997; Khochfar and Burkert, 2001). It is clear that dust-enshrouded starbursts and active galactic nuclei (AGN) play an extremely important role in the high-redshift Universe and are probably the dominant contributors to the far-infrared/submm and X-ray backgrounds, respectively (e.g., Pei et al., 1999; Miyaji et al., 2000). These luminous, merger-induced starbursts and AGN at high redshift thus provide readily observable signposts for tracing out the main epoch of elliptical galaxy and quasar formation if the above scenario is correct.

In order to assess quantitatively the physics of the merger process and its link to the epoch of elliptical and QSO formation at high redshift we must first understand the details of galaxy merging and its relationship to starbursts and AGN in the local universe. The most violent local mergers and the probable analogs to luminous high-redshift mergers are the ultraluminous infrared galaxies (ULIRGs). ULIRGs are advanced mergers of gas-rich, disk galaxies sampling the entire Toomre merger sequence beyond the first peri-passage (Veilleux et al., 2002; hereafter referred as VKS02 and discussed in more detail in Section 3). ULIRGs are among the most luminous objects in the local universe, with both their luminosities ($\geqslant 10^{12}$ $L_\odot$ emerging mainly in the far-IR) and space densities similar to those of quasars (e.g., Sanders and Mirabel, 1996). The near-infrared light distributions in many ULIRGs appear to fit a de Vaucouleurs law (Scoville et al., 2000; VKS02; see Section 3). ULIRGs have a large molecular gas concentration in their central kpc regions (e.g., Downes and Solomon, 1998) with densities comparable to stellar densities in ellipticals. These large central gas concentrations (and stars efficiently forming from them) may be the key ingredient for overcoming the fundamental phase space density constraints that would otherwise prevent formation of dense ellipticals from much lower density disk systems (Gunn, 1987; Hernquist et al., 1993). Kormendy and Sanders (1992) have proposed that ULIRGs evolve into ellipticals through merger induced dissipative collapse. In this scenario, these mergers first go through a luminous starburst phase, followed by a dust-enshrouded AGN phase, and finally evolve into optically bright, 'naked' QSOs once they either consume or shed their shells of gas and dust (Sanders et al., 1988a).

Gradual changes in the far-infrared spectral energy distributions between 'cool' ULIRGs (*IRAS* 25-to-60 μm flux ratio, $f_{25}/f_{60} < 0.2$), 'warm' ULIRGs, and QSOs (Sanders et al., 1988b; Haas et al., 2003) bring qualitative support to an evolutionary connection between these various classes of objects, but key elements remain to be tested. This review attempts to summarize the latest results from our multiwavelength study of these objects. In Section 2, I discuss the important issue of nuclear activity in ULIRGs. In Section 3, the morphological properties of ULIRGs and quasars are compared and tested against the predictions of the merger-driven evolutionary scenario. The environments of ULIRGs and QSO are compared in Section 4 and found to be similar but not identical. Galactic winds in ULIRGs are discussed in Section 5; I argue that these winds constitute a key ingredient in this evolutionary picture. The main conclusions are summarized in Section 6.

2. Nuclear activity in ULIRGs

Considerable effort has been invested in recent years to determine the frequency of occurrence of AGN in ULIRGs and the importance of nuclear activity in powering the large infrared luminosities of these objects. Optical spectroscopy has for many years revealed a trend with infrared luminosity: only ~5% of all infrared galaxies with $\log[L_{\mathrm{IR}}/L_\odot] = 10 - 11$ show optical signs of Seyfert activity, while this fraction reaches ~50% among ULIRGs with $\log[L_{\mathrm{IR}}/L_\odot] \geqslant 12.3$ (e.g., Veilleux et al., 1995; Kim et al., 1998; Veilleux et al., 1999a; Kewley et al., 2001).

These numbers should be considered lower limits since emission from circumnuclear starbursts often dilutes the AGN emission-line signatures in ULIRGs. The effects of dilution were nicely demonstrated in a recent *HST*/STIS study of four 'warm' ULIRGs by Farrah et al. (2005). An AGN is detected in the *HST* data of each of these objects, while only two objects show signs of an AGN from the ground. The STIS spectra of one of these objects (F05189–2524) present the strongest high ionization lines ever observed in a galaxy.

So far, hard X-ray studies have had only moderate success detecting buried AGN in ULIRGs (e.g., Ptak et al., 2003; Franceschini et al., 2003). In a recent *CXO* study of 14 ULIRGs by our group (Teng et al., 2005), we found clear trends of increasing $L_{2-10\ \mathrm{keV}}/L_{\mathrm{FIR}}$ ratio with increasing *IRAS* 25-to-60 μm flux ratio (Fig. 1). But in most of these objects, our data are not of sufficiently good quality to distinguish between starburst emission and emission from a Compton-thick AGN. Observatories capable of probing energies above 10 keV, such as *Suzaku*, should be able in the near future to discriminate between these two possibilities.

Extinction due to dust is less important at long wavelengths, so not surprisingly this is where most of the progress in our understanding of the ULIRG power source has taken place in recent years. By and large, the results from near-infrared and mid-infrared spectroscopic studies of ULIRGs are consistent with those found at optical wavelengths. Near-infrared signatures of AGN are found in most optically-classified Seyfert ULIRGs, but not in LINER or HII ULIRGs (e.g., Veilleux et al., 1997, 1999b). Most ULIRGs with an optical (e.g., Hβ, Hα) or near-infrared (e.g., Paβ, Paα, Brγ) broad-line region are AGN dominated based on the value of the BLR-to-bolometric luminosity ratio, which is found to be typical of that of optical quasars. Similarly, one finds excellent agreement

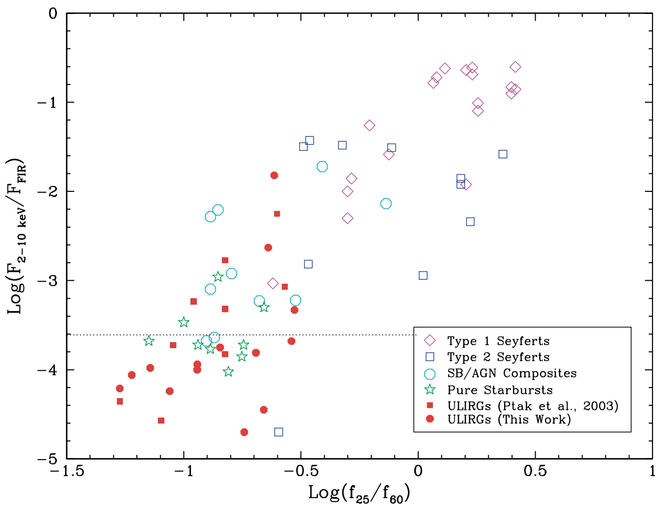

Fig. 1. Plot of $\log(f_{2\text{–}10\ \mathrm{keV}}/f_{\mathrm{FIR}})$ vs. *IRAS* $\log(f_{25}/f_{60})$ from Teng et al. (2005). All objects in the sample of Teng et al. (2005) are ULIRGs from the 1-Jy sample of Kim and Sanders (1998). The Seyfert 1 ULIRGs are distributed near the optical Seyferts, while the other ULIRGs are located among the starbursts and composites. Here we have only included the values for the Ptak et al. (2003) ULIRGs derived from their global spectra. The dotted line represents the average $\log(f_{2\text{–}10\ \mathrm{keV}}/f_{\mathrm{FIR}})$ values for the pure starbursts.

between the optical/near-infrared classification of ULIRGs and the classification based on the equivalent width of the mid-infrared PAH feature (Genzel et al., 1998; Lutz et al., 1998; Lutz et al., 1999; Tran et al., 2001). This indicates that strong AGN activity, once triggered, quickly breaks the obscuring screen at least in certain directions, thus becoming detectable over a wide wavelength range.

The advent of the *Spitzer Space Telescope* (*SST*) is adding considerably to our knowledge on these objects. IRS spectra have been published for only a few objects so far (e.g., Armus et al., 2004), but the analysis of IRS spectra on several more objects is in progress. Our group has been allocated 95.3 h to study 54 local ULIRGs and QSOs with IRS, but it is too early at this time to discuss the results from our analysis.

3. Host properties

It is important to compare the results discussed in the previous section with the host properties of ULIRGs and QSOs. If QSOs are indeed the end-products of ultraluminous infrared mergers, one should expect clear trends with morphology and expect the host luminosities/masses to be similar for both classes of objects.

3.1. Ground-based imaging study

In a first attempt to address these questions, we (VKS02) carried out a systematic R and K' imaging study of the *IRAS* 1 Jy sample of 118 ULIRGs. This large homogeneous sample allowed us for the first time to draw statistically meaningful conclusions; the problems of small sample size and/or inhomogeneous selection criteria have plagued many studies of luminous infrared galaxies in the past.

In VKS02, we find that all but one object in the 1-Jy sample show signs of a strong tidal interaction/merger. Multiple mergers involving more than two galaxies are seen in no more than 5 of the 118 (<5%) systems. None of the 1-Jy sources is in the first-approach stage of the interaction, and most (56%) of them harbor a single disturbed nucleus and are therefore in the later stages of a merger (see Fig. 2). Seyfert galaxies (especially those of type 1), warm ULIRGs ($f_{25}/f_{60} \geqslant 0.2$) and the more luminous systems ($>10^{12.5}\ L_{\odot}$) all show a strong tendency to be advanced mergers with a single nucleus.

The individual galaxies in the binary systems of the 1-Jy sample show a broad distribution in host magnitudes (luminosities) with a mean of -21.02 ± 0.76 mag. $\left(0.85 \pm {0.86 \atop 0.43} L^*\right)$ at R and -23.98 ± 1.25 mag. $\left(0.90 \pm {1.94 \atop 0.61} L^*\right)$ at K', and a R- or K'-band luminosity ratio generally less than ~4. Single-nucleus ULIRGs also show a broad distribution in host magnitudes (luminosities) with an average of -21.77 ± 0.92 mag. $\left(1.69 \pm {2.25 \atop 0.97} L^*\right)$ at R and -25.03 ± 0.94 mag. $\left(2.36 \pm {3.24 \atop 1.38}\right)$ at K'. These distributions overlap considerably with those of quasars.

An analysis of the surface brightness profiles of the host galaxies in single-nucleus sources reveals that about 73% of the R and K' surface brightness profiles are fit adequately by an elliptical-like de Vaucouleurs law. These elliptical-like 1-Jy systems have luminosity and R-band axial ratio distributions that are similar to those of normal (inactive) intermediate-luminosity ellipticals and follow with some scatter the same $\mu_e - r_e$ relation, giving credence to the idea that some of these objects may eventually become intermediate-luminosity elliptical galaxies if they get rid of their excess gas or transform this gas into stars. These elliptical-like hosts are most common among merger remnants with Seyfert 1 nuclei (83%), Seyfert 2 optical characteristics (69%) or mid-infrared (*ISO*) AGN signatures (80%). The mean half-light radius of these ULIRGs is 4.80 ± 1.37 kpc at R and 3.48 ± 1.39 kpc at K', typical of intermediate-luminosity ellipticals. These values are in excellent agreement with the measurements of McLeod and McLeod (2001) and Surace et al. (2001) obtained for moderate-luminosity quasars but systematically lower than the measurements of Dunlop et al. (2003) obtained for higher luminosity quasars. I return to this point in Section 3.2.

In general, the results from VKS02 are consistent with the merger-driven evolutionary sequence ‘cool ULI-

RGs → warm ULIRGs → quasars.' However, many exceptions appear to exist to this simple picture (e.g., 46% of the 41 advanced mergers show no obvious signs of Seyfert activity).

3.2. Recent HST study

The removal of the central PSF emission associated with the AGN or nuclear starburst is an important source of errors in the analysis of the surface brightness profiles in the more nucleated systems of VSK02. In an effort to verify these results, we (Veilleux et al., 2006) have recently obtained and analyzed deep *NICMOS* H-band images of 26 highly nucleated 1-Jy ULIRGs and 7 IR-excess ($L_{IR}/L_{BOL} > 0.4$) PG QSOs.

A detailed two-dimensional analysis of the surface brightness distributions in these objects confirms that the great majority (81%) of the single-nucleus systems show a prominent early-type morphology. However, low-surface-brightness exponential disks are detected on large scale in at least 4 of these sources. The hosts of 'warm' ($f_{25}/f_{60} > 0.2$), AGN-like systems are of early type and have less pronounced merger-induced morphological anomalies than the hosts of cool systems with LINER or HII region-like nuclear optical spectral types (Fig. 3). The host sizes and luminosities of the 7 PG QSOs in our sample are statistically indistinguishable from those of the ULIRG hosts. In comparison, radio/X-ray luminous quasars, such as those studied by Dunlop et al. (2003), have hosts which are larger and more luminous.

As shown in Fig. 4, the hosts of ULIRGs and PG QSOs lie close to the locations of intermediate-size (~1–2 L^*) spheroids in the photometric projection of the fundamental plane of ellipticals, although there is a tendency in our sample for the ULIRGs with small hosts to be brighter than normal spheroids. Excess emission from a merger-triggered burst of star formation in the ULIRG/QSO hosts may be at the origin of this difference. Our results provide support for a possible merger-driven evolutionary connection between cool ULIRGs, warm ULIRGs, and PG QSOs. However, this sequence may break down at low luminosity since the lowest luminosity PG QSOs in our sample show distinct disk components which preclude major (1:1–2:1) mergers. The black hole masses derived from the galaxy host luminosities imply sub-Eddington accretion rates for all objects in the sample.

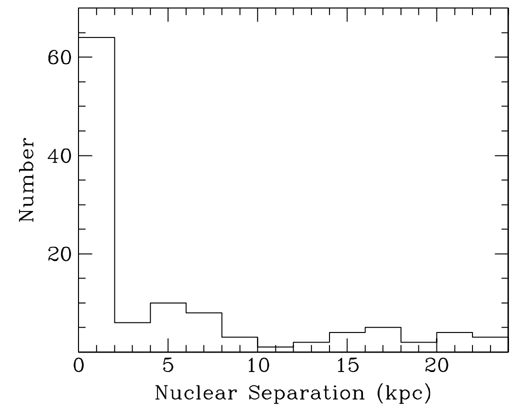

Fig. 2. Apparent nuclear separations in the 1-Jy sample of ULIRGs. The distribution is highly peaked at small values but also presents a significant tail at high values (taken from VKS02).

3.3. Host dynamical masses

VLT/Keck near-infrared stellar absorption spectroscopy has also been carried out to constrain the host dynamical mass for many of these ULIRGs and QSOs. The analysis of our VLT data on ULIRGs (Dasyra et al., 2006a,b) builds on the analyses of Genzel et al. (2001) and Tacconi et al. (2002). This portion of the work is discussed in more

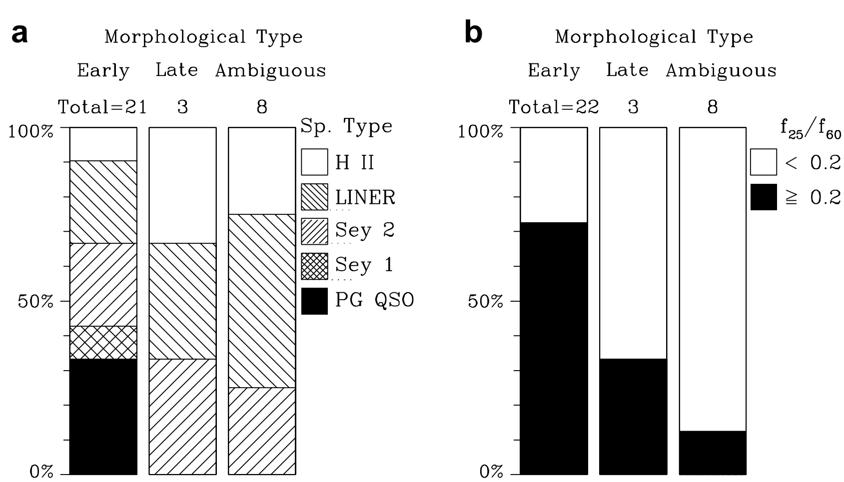

Fig. 3. Trends between the *dominant* morphological types (based on a decomposition that uses a single Sérsic galaxy component) and (a) optical spectral types, (b) *IRAS* 25-to-60 μm colors. There is one fewer object in panel (a) than in panel (b) because the optical spectral type of F02021–2103 is unknown. The hosts of warm, quasar-like objects all have a prominent early-type spheroidal component. F05189–2524 is the only Seyfert 2 ULIRG in the sample with a dominant late-type morphology (Veilleux et al., 2006).

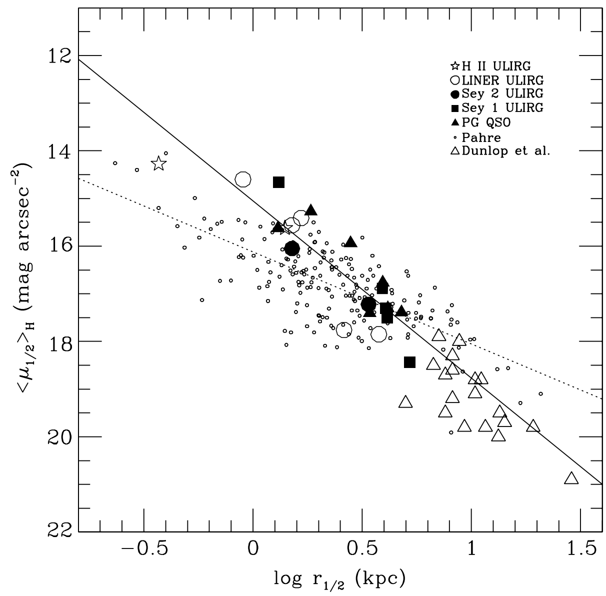

Fig. 4. Surface brightness versus half-light radius for the early-type host galaxies in the *HST* sample of Veilleux et al. (2006). The hosts of the 7 PG QSOs in our sample are statistically indistinguishable from the hosts of the 1-Jy ULIRGs. Both classes of objects fall near, but not quite on, the photometric fundamental plane relation of ellipticals as traced by the data of Pahre (1999, dashed line); the smaller objects in our sample tend to lie above this relation (the solid line is a linear fit through our data points). This excess H-band emission may be due to a merger-triggered burst of star formation. ULIRGs and PG QSOs populate the region of the photometric fundamental plane of intermediate-size ($\sim$1–2 L^*) elliptical/lenticular galaxies. In contrast, the hosts of the luminous quasars of Dunlop et al. (2003) are massive ellipticals which are significantly larger than the hosts of ULIRGs and PG QSOs. For this comparison, the R-band half-light radii tabulated in Dunlop et al. were taken at face value, and the surface brightnesses in that paper were shifted assuming R–H = 2.9, which is typical for early-type systems at $z \sim 0.2$ (see Veilleux et al., 2006 for more detail).

detail in the contribution by Dasyra to these proceedings. So here I only summarize the main conclusions. We find that the majority of ULIRGs are triggered by almost equal-mass major mergers of 1.5:1 average ratio, in agreement with VKS02. We also find that coalesced ULIRGs resemble intermediate mass ellipticals/lenticulars with moderate rotation, in their velocity dispersion distribution, their location in the fundamental plane (FP; e.g., Kormendy and Djorgovski, 1989) and their distribution of the ratio of rotation/velocity dispersion [$v_{\rm rot}$ $\sin(i)/\sigma$]. These results therefore suggest that ULIRGs form moderate mass ($m^* \sim 10^{11}$ $M_\odot$), but not giant (5–10×10^{11} $M_\odot$) ellipticals. These results are largely consistent with those from our imaging studies. Converting the host dispersion in fully coalesced ULIRGs into black hole mass with the aid of the $M_{\rm BH} - \sigma$ relation (e.g., Gebhardt et al., 2000) yields black hole mass estimates of the order 10^7–10^8 $M_\odot$. The accretion rate for sources after the nuclear coalescence is high 0.5–0.9, again similar to those derived by VKS02 and Veilleux et al. (2006). Our preliminary analysis of a dozen PG QSOs also shows agreement between the host mass (thus black hole mass) of PG QSOs and coalesced ULIRGs (Dasyra et al., 2006c).

4. Environment

Surprisingly very little is known quantitatively about the environment of ULIRG and how it compares with that of QSOs (e.g., Tacconi et al., 2002). If these two classes of objects are related, then their environments should be similar. Following the method outlined in Longair and Seldner (1979) and Yee and López-Cruz (1999), we find that the average cluster-galaxy correlation amplitude for 86 1-Jy ULIRGs is $\overline{B}_{\rm gc} = 106 \pm 21$ Mpc$^{1.77}$ (Zauderer et al., 2006). The results are shown in Fig. 5. The environment of most ULIRGs is similar to that of the field, although there appears to be a few exceptions. No obvious trends are seen with redshift, optical spectral type, infrared luminosity, or infrared color (f_{25}/f_{60}). We compare these results with those of local AGNs and QSOs at various redshifts. The 1-Jy ULIRGs show a broader range of environments than local Seyferts, which are exclusively found in the field (e.g., de Robertis et al., 1998a,b). The distribution of ULIRG $B_{\rm gc}$ values overlaps considerably with that of local QSOs (e.g., McLure and Dunlop, 2001), consistent with the scenario where ULIRGs are related to QSOs. However, a rigorous statistical analysis of the data indicates that these two samples are not drawn from the same parent population. The range of environments of ULIRGs is similar to that of QSOs, but the QSOs of McLure and Dunlop (2001) live on average in slightly richer environments than

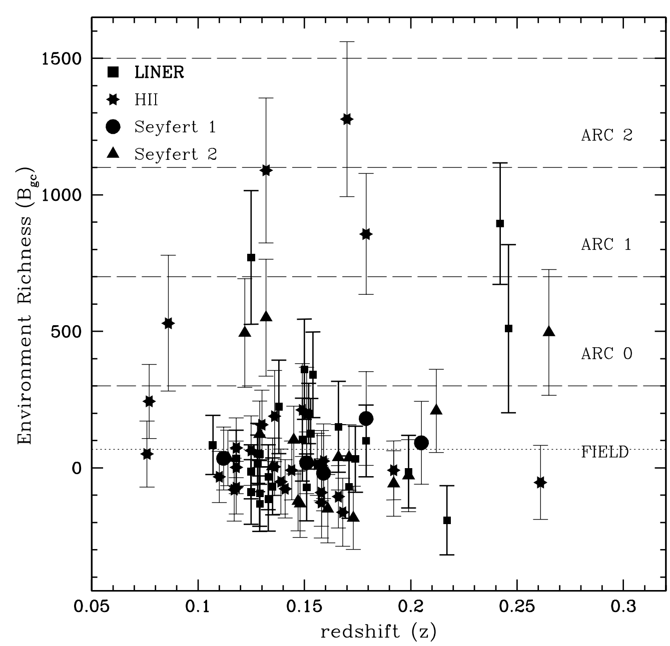

Fig. 5. Environment richness parameter, $B_{\rm gc}$, versus redshift for 86 1-Jy ULIRGs. There is no trend with redshift or optical spectral type. The horizontal dashed line corresponds to the average value for field galaxies. The corresponding Abell richness classes (ARC) are marked, following the binning of McLure and Dunlop (2001). Adapted from Zauderer et al. (2006).

ULIRGs. This may be due to the fact that the QSOs studied by Dunlop and collaborators have bigger and more luminous hosts than the 1-Jy ULIRGs (as discussed in Section 3).

5. Galactic winds

As shown in Fig. 6, the fraction of objects with detected (neutral Na ID-absorbing) winds increases with infrared luminositiy, reaching ~75% for ULIRGs (e.g., Rupke et al., 2002, 2005; Martin, 2005; see also review by Veilleux et al., 2005). The observed detection rate among ULIRGs is consistent with 100% once projection effects are taken into account. The projected 'maximum' velocities in the outflowing components average 300–400 km s^{-1}, and attain ~600 km s^{-1} (although 1100 km s^{-1} is seen in one object; Fig. 6). There is some indication of a trend of increasing outflow velocities with increasing SFR, particularly when the data from Schwartz and Martin (2004) on dwarf galaxies are included. The winds in ULIRGs entrain considerable neutral material (~10^8–10^{10} $M_\odot$ or ~10–1000 $M_\odot$ yr^{-1}) and are quite powerful (~10^{56}–10^{59} erg or 10^{41}–10^{44} erg s^{-1}). These winds may thus have a profound effect on the evolution of the ULIRGs. Recent numerical simulations of mergers with starburst- and AGN-driven feedback provide a nice theoretical framework for this picture (e.g., Hopkins et al., 2005; Croton et al., 2006).

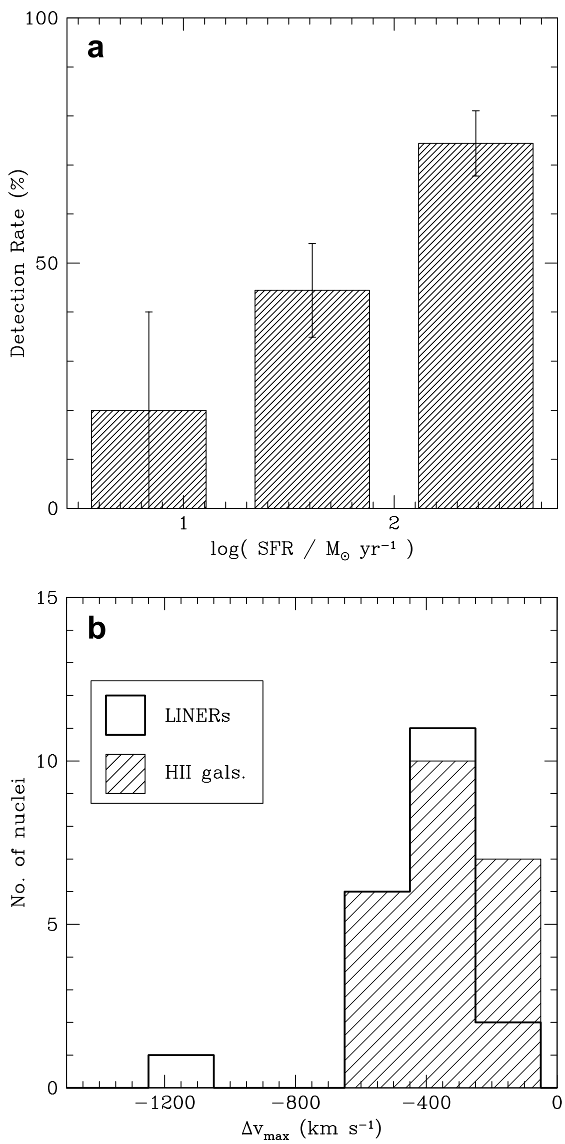

Fig. 6. (a) Detection rate of winds as a function of star formation rate. The last bin on the right corresponds roughly to ULIRGs. (b) Distribution of maximum outflow velocities among LINER ULIRGs (thick line) and H II region-like ULIRGs (hatched). Adapted from Rupke et al. (2005).

6. Summary

The main points of this review can be summarized as follows:

1. AGN is present and often dominant in >30% of all local ULIRGs and in >50% of local ULIRGs with log[L_{IR}/$L_\odot$] $\gtrsim$ 12.3. Optical, near-infrared, and mid-infrared diagnostics give consistent answers, but X-ray observations at $\lesssim$10 keV generally do not. *SST* data under analysis will revisit this important issue. Observations beyond 10 keV with *Suzaku* may also provide interesting constraints.
2. Warm AGN-like ULIRGs and QSOs have prominent spheroids, weaker tidal features, and stronger nuclei than cool LINER or H II ULIRGs. These warm systems are in the final stage of a merger. The luminosities, size, and stellar masses of PG QSOs coincide with those of elliptical-like 1-Jy ULIRGs.
3. Except for a few cases, the 1-Jy ULIRGs live in low-density environments. The environment richness parameter of ULIRGs resembles that of local QSOs although statistically they are not drawn from the same parent population.
4. Galactic winds are present in virtually all ULIRGs. The outflow velocities and the mass and energy injection rates are very significant, enough to affect the evolution of ULIRGs.

These results suggests that most ULIRGs are indeed intermediate-mass ellipticals in formation. Many of these objects may also be in the process of becoming optical quasars. However, this process is probably not 100% efficient: several late-merger ULIRGs do not show obvious signs of QSO activity. Moreover, low-luminosity QSOs often harbor exponential disks which preclude major (1:1–2:1) mergers; this suggests the existence of a luminosity threshold below which nuclear activity is not necessarily triggered through major mergers.

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