The Latest Results from QUEST, the Quasar and ULIRG Evolution Study

Sylvain Veilleux$^{1,2}$

1 Department of Astronomy, University of Maryland, College Park, MD 20742 USA
2 Astroparticle Physics Laboratory, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771 USA
E-mail: veilleux@astro.umd.edu

Abstract. The latest results from our Quasar-ULIRG Evolution Study (QUEST) are described with an emphasis on the recent scientific breakthroughs on the issue of quasar feedback.

1. Introduction
Gas-rich galaxy merging at high redshifts may trigger major starbursts, lead to the formation of elliptical galaxies, and account for the growth of supermassive black holes (BHs; e.g., Sanders et al. 1988; Hopkins et al. 2009). This merger-driven evolutionary scenario starts with a completely obscured ultraluminous infrared galaxy (ULIRG). As the system evolves, the obscuring gas and dust is gradually dispersed, giving rise to dusty QSOs and finally to completely exposed QSOs. Powerful winds, driven by the central quasar or the surrounding starburst, have been invoked to stop the growth of both the BH and spheroidal component and explain the tight BH-spheroid mass relation (e.g., Murray et al. 2005). These winds are purported to quench star formation in the merger remnants (“negative mechanical feedback”), creating a population of red gas-poor ellipticals and explaining the bimodal color distribution observed in galaxy surveys.

Mergers are not the unique explanation for starbursts and quasars at high redshifts and the formation of elliptical galaxies. An increasingly popular alternative is the formation and growth of galaxies via cold gas accretion (e.g., Keres et al. 2005; Dekel & Birnboim 2006, 2008; Genzel et al. 2006, 2008; Dekel et al. 2009; Ceverino et al. 2010). However, these two different scenarios have several characteristics in common: (1) massive gas inflows to the center of the potential well, (2) formation of spheroids via violent relaxation and transformation of the accreted gas into new stars, (3) growth of the central black hole, and (4) the need for galactic winds to remove the left-over gas and produce the gas-poor elliptical galaxies observed in the local universe. Here we briefly review the observational evidence for processes (1)–(4), emphasizing the exciting new results relating to (4). We focus our discussion on the results from our own survey of local systems, QUEST, the Quasar-ULIRG Evolution Study. The ULIRG component of this survey focuses on the 1-Jy sample, a sample of $z < 0.3$ 118 ULIRGs selected at 60 $\mu$m from a redshift survey of the IRAS faint source catalog (Kim & Sanders 1998). The QSO component focuses on the Palomar-Green (PG) quasars of Schmidt & Green (1983). The QUEST sample of $\sim 40$ QSOs was carefully selected to match the redshifts of the QUEST set of ULIRGs and cover the full range in luminosity, infrared excess [$\log(L_{IR}/L_{BOL})$], and radio loudness of the PG QSOs.
2. Gas Inflows
There is now considerable indirect evidence that massive gas inflows have indeed taken place in galaxy mergers. In Rupke et al. (2008), we measured nuclear or near-nuclear oxygen abundances in a sample of 100 star-forming LIRGs and ULIRGs using new, previously published, and archival spectroscopy of strong emission lines (including [O II] λλ 3726, 3729) in galaxies with redshifts \(< z > \sim 0.1\). When compared to local emission-line galaxies of similar luminosity and mass (using the near-infrared luminosity-metallicity and mass-metallicity relations), we found that LIRGs and ULIRGs are oxygen underabundant by a factor of 2 on average. As a corollary, LIRGs and ULIRGs were also found to have smaller effective yields. We concluded that the observed underabundance results from the combination of a decrease of abundance with increasing radius in the progenitor galaxies and strong, interaction- or merger-induced gas inflow into the galaxy nucleus. This conclusion demonstrates that local abundance scaling relations are not universal, a fact that must be accounted for when interpreting abundances earlier in the universe’s history, when merger-induced star formation may be the dominant mode in massive systems. Kewley et al. (2006) came to a similar conclusion in their study of an optically selected sample of nearby interacting galaxies. Recent spatially-resolved spectroscopic studies of these objects, combined with numerical simulations, have confirmed the importance of gas inflows on the final distribution of metals in merger remnants (e.g., Rupke et al. 2010ab).

3. Formation of Spheroids
Our comprehensive ground- and space-based imaging and spectroscopic program of all ULIRGs and QSOs in the QUEST sample has demonstrated that ULIRGs are advanced mergers of gas-rich, disk galaxies sampling the entire Toomre merger sequence beyond the first peri-passage (Veilleux et al. 2002). The NIR light distributions and stellar kinematics in single-nucleus ULIRGs and QSOs are consistent with those of \(\sim 0.5−5L^*\) spheroids in formation (e.g., Veilleux et al. 2006, 2009; Dasyra et al. 2006ab, 2007). Numerous other studies have come to similar conclusions (e.g., Rothberg & Joseph 2006; Rothberg & Fischer 2010; Cales et al. 2011 among others).

A brief exercise in numerology provides some perspective on this result. The number density of local ULIRGs is \(\sim 2.5 \times 10^{-7} \text{ Mpc}^{-3}\). This is only \(\sim (1/7000) \times \) the number density of SDSS ellipticals. The obvious but long-standing question is whether there are enough “spheroids in formation” at high redshifts to account for all local ellipticals (e.g., Toomre 1977). Bright submm-selected galaxies (SMGs) may fit the bill. They show all of the tell-tale signs of high-z spheroids in formation: obvious mergers, rich in molecular gas, and intense ULIRG-like star formation rates (\(> 100 \text{ M}_\odot \text{ yr}^{-1}\); e.g., Greve et al. 2005; Tacconi et al. 2006, 2008). Located at \(z \sim 1−4\), they are \(\sim 2\) orders of magnitude more numerous than local ULIRGs. The expected number of SMG “descendants” is given by \(n(\text{SMGs}) \times \tau(\text{SMG era}) / \tau(\text{SMG lifetime})\), where \(n(\text{SMGs}) \sim 3 \times 10^{-5} \text{ Mpc}^{-3}\) is the number density of SMGs, \(\tau(\text{SMG era}) \sim 1500 \text{ Myr}\) is a rough estimate of the duration of the SMG era, and \(\tau(\text{SMG lifetime}) \sim 300 \text{ Myr}\) is the lifetime of individual SMGs. The expected number of descendants is thus similar to the number density of local ellipticals with \(L > L^*\). Their measured stellar masses also appear consistent with this idea (e.g., Borys et al. 2005), but they are denser and more compact than local massive ellipticals (e.g., Tacconi et al. 2008). Two possible solutions have been proposed for this discrepancy: (1) the end-result of SMGs are “puffed up” by subsequent dry major mergers and minor mergers. (2) The compactness observed by Tacconi et al. (2008) and others may be misleading: in reality perhaps there is a bright central starburst region dominating the surface brightness distribution, which is surrounded by a much larger, undetected halo of older stars dominating the overall mass distribution. This last possibility should be relatively easy to test with deeper rest-frame NIR observations of these objects.
4. Black Hole Growth

AGN have long been known to be present in ULIRGs (e.g., Sanders et al. 1988), in greater numbers than in LIRGs (e.g., Veilleux et al. 1995, 1999ab). However, the role they play in powering ULIRGs has been much harder to quantify, except in the few cases where a broad-line region is detected in the optical or near-infrared (these objects are invariably dominated by the AGN; e.g., Veilleux et al. 1997, 1999).

Dust obscuration remains a potential problem, so it is important to observe these objects at wavelengths where the AGN diagnostics are less affected by this dust: mid-to-far infrared, radio, and X-rays. Here we focus our discussion on the mid-infrared and X-ray results. This is not to say that the far-infrared is not potentially useful; on the contrary, Herschel data have already been used successfully to estimate the AGN contribution in some ULIRGs (e.g., van der Werf et al. 2010). However, whether these data can be used for accurate (±15%) estimates remain to be proven at this (admittedly early) stage of investigation. The reason to skip the radio (cm-wave) methods is different: the main problem here is the fact that this energy range is a minor contributor to the overall bolometric luminosity of ULIRGs, so one always needs to make the questionable assumption that results derived from the radio data apply to the mid-far infrared, where the bulk of the power is emitted.

The advent of Spitzer has revolutionized our understanding of (U)LIRGs and QSOs at mid-infrared wavelengths. In Schweitzer et al. (2006), we showed that starbursts are responsible for at least ~30%, but likely most, of the FIR luminosity of PG QSOs. We argued in Netzer et al. (2007) that both strong- and weak-FIR emitting sources have the same, or very similar, intrinsic AGN spectral energy distributions (SEDs). In Schweitzer et al. (2008), we found that emission from dust in the innermost part of the narrow-line region is needed in addition to the traditional obscuring torus in order to explain the silicate emission in these QSOs. In Veilleux et al. (2009b), the contribution of nuclear activity to the bolometric luminosity in the QUEST ULIRGs and QSOs was quantified using six independent methods that span a range in wavelength and give consistent results within ~±10%-15% on average. This agreement suggests that deeply buried active galactic nuclei (AGNs) invisible to the Spitzer InfraRed Spectrograph but bright in the far-infrared are not common in this sample. The average derived AGN contribution in ULIRGs was found to be ~35%-40%, ranging from ~15%-35% among “cool” \((f_{25}/f_{60} = 0.2)\) optically classified HII-like and LINER ULIRGs to ~50 and ~75% among warm Seyfert 2 and Seyfert 1 ULIRGs, respectively. This number exceeds ~80% in PG QSOs. ULIRGs fall in one of three distinct AGN classes: (1) objects with small extinctions and large polycyclic aromatic hydrocarbon (PAH) equivalent widths are highly starburst-dominated; (2) systems with large extinctions and modest PAH equivalent widths have larger AGN contributions, but still tend to be starburst-dominated; and (3) ULIRGs with both small extinctions and small PAH equivalent widths host AGN that are at least as powerful as the starbursts. The AGN contributions in class 2 ULIRGs are more uncertain than in the other objects. A morphological trend is seen along the sequence (1)-(2)-(3), in general agreement with the standard ULIRG-QSO evolution scenario and suggestive of a broad peak in extinction during the intermediate stages of merger evolution. However, the scatter in this sequence, including the presence of a significant number of AGN-dominated systems prior to coalescence and starburst-dominated but fully merged systems, implies that black hole accretion, in addition to depending on the merger phase, also has a strong chaotic/random component, as in local AGNs. See Armus et al. (2007), Farrah et al. (2007), Desai et al. (2007), and Petric et al. (2011) for more Spitzer results on (U)LIRGs.

More recently, we carried a similar analysis using new and archival Chandra and XMM-Newton X-ray data on 40 ULIRGs and 26 QSO from the QUEST sample (Teng & Veilleux 2010). A combination of traditional and hardness ratio spectral fitting methods was used to characterize the X-ray properties of these objects. The absorption-corrected 2-10 keV to bolometric luminosity ratios were used as a proxy for the fractional contribution of the AGN to
the bolometric luminosity of these systems. The results were in general agreement with those obtained in the mid-infrared with Spitzer: the likelihood for dominant nuclear activity increases along the merger sequence from “cool” ULIRGs, “warm” ULIRGs, infrared-bright QSOs, and infrared-faint QSOs. The starburst dominates the total power in ULIRGs prior to the merger, and this is followed by rapid black hole hole growth during and after coalescence. The main concern with using the X-rays to quantify the AGN contribution is that the 2-10 keV luminosity may not be adequately corrected for absorption. It is therefore crucial to look beyond 10 keV to search for, and quantify, highly absorbed AGN possibly lurking in some of these systems. The discovery of a Compton-thick AGN in the ULIRG/QSO Mrk 231 is a good case in point (Braito et al. 2004). An attempt was made with Suzaku to study local ULIRGs beyond 10 keV, but only one object was detected with any significance (Teng et al. 2009). More comprehensive studies will only be possible with the next generation of X-ray facilities (e.g., NuSTAR, Astro-H).

5. Galactic Winds

There is growing observational support for large-scale galactic winds: e.g., most galaxies with star formation rate (SFR) densities in excess of \( \sim 0.1 \, \text{M}_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) show signatures of outflows, both locally and at high redshifts (e.g., Veilleux et al. 2005). The local outflows are often spatially resolved, allowing determination of the mass outflow rates (\( \sim 0.1-5 \times \text{SFR} \)) and kinetic energies (\( \sim 10^{56-58} \) ergs in ULIRGs; Rupke et al. 2002, 2005abc; Martin 2005, 2006). These winds are primarily driven by the starburst rather than the AGN, except in late-stage mergers with quasar signatures where velocities \( \geq 1000 \, \text{km} \, \text{s}^{-1} \) (cf. 100-400 km s\(^{-1}\) in other systems) are sometimes observed (Rupke et al. 2005c; Krug et al. 2010).

In the past year, there have been three major scientific breakthroughs in this area of research:

- Our Herschel PACS GTO survey of ULIRGs (SHINING, PI Sturm) has revealed far-infrared (FIR) OH features with P-Cygni profiles indicative of massive molecular outflows in most (\( \sim 70\% \)) ULIRGs, including the closest quasar known, Mrk 231 (Fischer et al. 2010; Sturm et al. 2011; Fig. 1). In some of these objects the (terminal) outflow velocities exceed 1000 km s\(^{-1}\), and their outflow rates (up to \( \sim 1200 \, \text{M}_\odot \, \text{yr}^{-1} \)) are several times larger than their star formation rates. We compared the outflow signatures in different types of ULIRGs and in starburst galaxies to address the issue of the energy source (AGN or starburst) of these outflows. In Sturm et al. (2011), we reported preliminary evidence that ULIRGs with a higher AGN luminosity (and higher AGN contribution to \( L_{\text{IR}} \)) have higher terminal velocities and shorter gas depletion timescales. Taken at face value, the outflows in the observed ULIRGs are able to expel the cold gas reservoirs from the centers of these objects within \( \sim 10^6-10^8 \) years.

- Feruglio et al. (2010) used the IRAM PdB Interferometer to obtain a very deep map of the CO(1-0) transition in Mrk 231. Thanks to the wide band, broad wings were detected in the profile of the CO line, with velocities of up to 750 km s\(^{-1}\) and spatially resolved on kpc scale (Fig. 1). These broad CO wings trace a giant molecular outflow of about \( \sim 700 \, \text{M}_\odot \, \text{yr}^{-1} \), far larger than the on-going SFR (\( \sim 200 \, \text{M}_\odot \, \text{yr}^{-1} \)) in the host galaxy. Remarkably, this CO outflow coincides spatially with blueshifted optical Na ID \( 5890, 5896 \) Å absorption features (Rupke et al. 2005c).

- Our recent Gemini/IFU observations have revealed that the Na ID outflow in Mrk 231 is not only spatially resolved on kpc scale but also wide-angled, thus driven by a QSO wind rather than a jet (Rupke & Veilleux 2011; Fig. 2). In this paper, we showed that the nuclear region hosts an outflow with blueshifted velocities reaching 1100 km s\(^{-1}\), extending 2–3 kpc from the nucleus in all directions in the plane of the sky. A radio jet impacts the outflow north of the nucleus, accelerating it to even higher velocities (up to 1400 km s\(^{-1}\)). Finally, 3.5 kpc south of the nucleus, star formation is simultaneously powering an outflow that...
reaches more modest velocities of only $570 \, \text{km} \, \text{s}^{-1}$. Blueshifted ionized gas is also detected around the nucleus at lower velocities and smaller scales. The mass and energy flux from the outflow are $>2.5$ times the star formation rate and $>0.7\%$ of the active galactic nucleus luminosity. The former suggests strong negative feedback to star formation and the latter is consistent with the coupling efficiency required in the AGN feedback model of Hopkins & Elvis (2010). In other words, this powerful outflow may be the long-sought “smoking gun” of quasar mechanical feedback that clears out the neutral + molecular disk formed from dissipative collapse during the merger, resulting in red and dead elliptical galaxies without star formation activity.

Our group is actively following up on these results using Herschel (guaranteed time key project SHINING and its OT1 and OT2 extensions), HST, Chandra, and a variety of ground-based facilities including Gemini and IRAM.

![Figure 1](Image)

**Figure 1.** (*Left box*) Powerful molecular outflows are detected in most ($\sim70\%$) local (U)LIRGs / FIR-bright QSOs with Herschel (from Sturm et al. 2011). The left panels show the maximum ($\approx$ terminal) outflow velocity as a function of SFR and AGN luminosity (asterisk = NGC 253; triangle = Arp 220). The upper right panel shows the ratio of mass outflow rate to SFR as a function of SFR, while the bottom right panel is the depletion time scale as a function of AGN luminosity. Note the possible trends of increasing outflow velocities and decreasing depletion time scales with increasing AGN luminosities, suggestive of increasing influence of QSO feedback.

(*Right box*) Continuum-subtracted spectrum of the CO(1–0) transition in Mrk 231 from Feruglio et al. (2010). Upper left panel shows the full flux scale, while upper right panel is an expanded flux scale to highlight the broad wings. The lower panels show the CO maps of the broad wings: beam profile on the left, the blue wing (from $-500$ to $-700 \, \text{km} \, \text{s}^{-1}$) in the middle, and red wing (from $500$ to $800 \, \text{km} \, \text{s}^{-1}$) on the right. The blue-wing emission is slightly extended. The mass outflow rate is $\sim700 \, \text{M}_\odot \, \text{yr}^{-1}$ or $\sim2.5 \times \text{SFR}$.

6. **Summary and Prospects**

The latest results from QUEST are:

1. Trends seen between merger phase, AGN fractional contribution to the bolometric luminosity and extinction are in general agreement with the standard ULIRG – QSO evolution scenario and suggestive of a broad peak in extinction during the intermediate stages of merger evolution.
Figure 2. (Left) HST / ACS continuum image of Mrk 231 in the 435W and 814W filters. The horizontal bar = 5 kpc (≈6'). The field of view of the Gemini/IFU data (6.3'' × 7.5'') of RV11 is overlaid as a box. Note the tidal arc ≈3.5 kpc (≈4'') south of the nucleus. (Middle) Hα emission, in logarithmic flux units. Bright features are unobscured HII regions, while fainter emission is likely shock-excited (elevated [N II]/Hα). The horizontal bar = 1 kpc (≈1.2''). Note the emission coincident with the tidal arc. (Right) Velocity field of the Na ID absorbing material in Mrk 231 relative to systemic. The spatial scale of this panel is in kpc and roughly matches that of the middle panel. A nuclear (blueshifted) outflow extends from the nucleus up to 2-3 kpc in all directions (as projected in the plane of the sky). The high velocities (≈1000 km s⁻¹) and derived large mass outflow rate (≥400 M⊙ yr⁻¹) suggest that the AGN powers the nuclear wind. The northern quadrant of the nuclear wind is further accelerated by the narrow radio jet (indicated by the two red lines). A lower-velocity starburst-driven outflow is present in the south, coincident with the tidal arc. (from Rupke & Veilleux 2011)

2. The scatter in this sequence implies that black hole accretion, in addition to depending on merger phase, also has a strong stochastic/random component.
3. Starburst-driven winds help clear dusty cocoons around most ULIRG merger remnants.
4. Powerful neutral/molecular quasar-driven winds are seen in a few nearby systems. They are capable of removing all of the gas in these systems in 10⁶–10⁸ yrs and therefore halting star formation activity on that same timescale.

The prospects are good to independently verify results #1 and #2 using Herschel and the soon-to-be-launched next generation of hard X-ray telescopes (e.g., NuSTAR, Astro-H). There is little doubt that Herschel and HST will provide important new constraints in the near future on #3 and #4. 3D data from 8-meter class telescopes, IRAM, and ALMA will provide the crucial spatial information needed to more accurately derive the important dynamical quantities of the neutral and molecular components of these outflows and evaluate the role they play on the overall evolution of the galaxy hosts. We all look forward to AHAR 2014 to discuss these new results!

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