Probing for evolutionary links between local ULIRGs and QSOs using NIR spectroscopy

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Abstract

We present a study of the dynamical evolution of Ultraluminous Infrared Galaxies (ULIRGs), merging galaxies of infrared luminosity $> 10^{12} \ L_\odot$. During our Very Large Telescope large program, we have obtained ISAAC near-infrared, high-resolution spectra of 54 ULIRGs (at several merger phases) and 12 local Palomar-Green QSOs, to investigate whether ULIRGs go through a QSO phase during their evolution. One possible evolutionary scenario is that after nuclear coalescence, the black hole radiates close to Eddington to produce QSO luminosities. The mean stellar velocity dispersion that we measure from our spectra is similar ($\sim 160 \ km/s$) for 30 post-coalescence ULIRGs and 7 IR-bright QSOs. The black holes in both populations have masses of order $10^7 - 10^8 \ M_\odot$ (calculated from the relation to the host dispersion) and accrete at rates $> 0.5$ Eddington. Placing ULIRGs and IR-bright QSOs on the fundamental plane of early-type galaxies shows that they are located on a similar region (that of moderate-mass ellipticals), in contrast to giant ellipticals and radio-loud QSOs. While this preliminary comparison of the ULIRG and QSO host kinematical properties indicates that (some) ULIRGs may undergo a QSO phase in their evolutionary history before they settle down as ellipticals, further data on non-IR excess QSOs are necessary to test this scenario.

Key words: galaxies: formation, kinematics, & dynamics, infrared: galaxies
1. Introduction

In the local Universe, the best laboratories for studying violent merging events (considered key-mechanisms in driving galaxy evolution) are the ultraluminous infrared galaxies (ULIRGs). Several studies indicate that ULIRGs transform gas-rich disks into moderate mass ellipticals through merger-induced dissipative collapse (Kormendy & Sanders, 1992; Mihos & Hernquist, 1996). Photometric analysis of ultraluminous merger remnants by Veilleux et al. (2002) and Scoville et al. (2000) indicates that most of the sources are well-fit by an elliptical-like $r^{-1/4}$ light profile. Spectroscopic analysis by Genzel et al. (2001) and Tacconi et al. (2002) indicates that their stellar kinematics resemble those of dispersion-supported systems.

While the end products of galactic mergers can be considered understood, several details of the merging process (often related to the physics of the gas) are still very uncertain, even in the local Universe. A plethora of numerical models (Mihos & Hernquist, 1996; Springel et al., 2005) and observations (Sanders & Mirabel, 1996; Kim et al., 2002) indicates that major starburst episodes occur after the first galactic encounter and can be present after nuclear coalescence, before complete relaxation sets in. According to Di Matteo et al. (2005), the main accretion event happens after the coalescence. However, the relative contributions of starburst and AGN to the infrared (IR) emission during each phase of a gas-rich merger are still unclear. Whether ULIRGs may go through a QSO phase after the nuclear coalescence also needs to be confirmed.

One way to investigate the physical details of mergers is to determine the evolution of the ULIRG kinematic properties as a function of time. Hence, we obtained high-resolution, H- and K-band ISAAC spectroscopic data for 54 ULIRGs (spanning a wide range of merger phase) during our European Southern Observatory Very Large Telescope (VLT) large program (ID 171.B-0442). Of these sources (at $0.018 < z < 0.268$), 23 are binary (not fully merged) ULIRGs and 30 are (relaxed) remnants. We extract the stellar dispersion $\sigma$ and rotational $V_{\text{rot}}$ velocity from the CO rovibrational bandheads that appear in our spectra using the Fourier correlation quotient technique (Bender, 1990); this method provides the line-of-sight (LOS) broadening function with which a stellar template has to be convolved to produce the observed spectrum.

2. Dynamics of ultraluminous infrared mergers

2.1. Pre-coalescence phase: the conditions that trigger ultraluminous emission

We derive the kinematics of each individual component of the binary systems, to investigate the conditions under which ultraluminous infrared activity is triggered. From the stellar dispersion and rotational velocity, we compute the masses of the merging galaxies. We find that that ultraluminous luminosities are are mainly generated by almost equal-mass mergers; the average mass ratio of the binary ULIRGs is 1.5:1 and 68% of these sources are 1:1 encounters (Dasyra et al., 2005). Statistically, our result is in agreement with luminosity ratios inferred from imaging studies (e.g. Kim et al., 2002). In individual cases though, luminosity does not always accurately trace mass due to stellar population and extinction effects.

To investigate whether dynamical heating (mainly of the smaller companion) can skew our results, we re-ran the simulations of Naab & Burkert (2003) with an N-body-plus-SPH code after replacing 10% of the stellar mass with isothermal $(10^4 \text{ K})$ gas. Following the stellar dispersion as a function of time, we found that 3:1 mergers may appear to be 2:1 at nuclear separations as small as those we observe (7.2 kpc on average). Since only a minority of our sources belong to these merger
categories, our conclusions are stable against dynamical heating. Mergers of mass ratio >4:1 appear not to drive enough gas to the center of the merger to generate ultraluminous IR emission.

2.2. Post-coalescence phase: the evolution of the host properties and the end-products of ultraluminous mergers

By studying the kinematics of ULIRGs at merger phases that follow nuclear coalescence (remnants) and comparing them to the kinematics of the binary ULIRGs, we find that the mean stellar dispersion increases during the coalescence phase by 15 km s\(^{-1}\) (namely from 142 to 157 km s\(^{-1}\)). Although this increase is significant (within the 0.05 significance level of our Monte Carlo simulations), it constitutes only a lower limit on the dynamical heating that the merging galaxies undergo. This is primarily due to the fact that the ultraluminous phases are short compared to the total merger timescales (e.g. Mihos, 1999). The ratio between rotational and dispersion velocity of the ULIRG remnants, which equals 0.31 and increases to 0.62 when inclination effects are taken into account, indicates that the remnants are dispersion-supported systems, resembling ellipticals (Es). To investigate what type of ellipticals ultraluminous mergers will form, Genzel et al. (2001) suggested that ULIRGs need to be placed on the fundamental plane (FP) of early-type galaxies (Djorgovski & Davis, 1987). In Fig. 1 we present the effective radius-host dispersion (\(R_{\text{eff}} - \sigma\)) projection of the plane, constructed from our data for 54 ULIRGs (triangles). Giant (boxy-isophotal profile) Es are shown in boxes, moderate-mass (disky-isophotal profile) Es in filled circles, and further cluster Es in open circles (see caption for original references). Some luminous infrared galaxies (LIRGs; \(10^{11}L_\odot < L < 10^{12}L_\odot\)) are presented in diamonds. The fact that ULIRGs clearly populate the moderate-mass (\(\sim 10^{11}M_\odot\)) Es part of the FP suggests that these two populations are linked, while giant Es probably have a different formation history.

From the dispersion velocity of the stars in the bulge of our ULIRG remnants, we compute their BH mass \(M_{\text{BH}}\) using the \(M_{\text{BH}} - \sigma\) relation (e.g. Tremaine et al. 2002). To test whether the \(M_{\text{BH}} - \sigma\) relation can be applied at the late ultraluminous phases of a merger, we ran our simulations (presented in Sect. 2.1) and followed the host dispersion and the gas inflowing to the center of the simulation as a function of time. We found that by the time the nuclei coalesce, these quantities already scale linearly as long as the amount of gas that accretes onto the black hole from its surroundings (center of the simulation) is roughly constant with time (e.g. Di Matteo et al. 2005). The application of the \(M_{\text{BH}} - \sigma\) relation to the remnants yields black hole masses of the order \(10^7 - 10^8 M_\odot\).

The Eddington efficiency \(\eta_{\text{Edd}}\) (the ratio between the Eddington and the dynamical \(M_{\text{BH}}\)) of the ULIRG remnants is calculated by assigning 50% of the IR luminosity to the AGN. This statistical assumption follows Genzel et al. (1998), who found that some ULIRGs are largely starburst while others are AGN-powered, and may cause a few individual sources to accrete at super-Eddington rates. If we assign \(\eta_{\text{Edd}} = 1\) to these sources, the mean Eddington efficiency is 0.5. Such high \(\eta_{\text{Edd}}\) values may be an observational confirmation of the theoretical predictions of Springel et al. (2005) and Di Matteo et al. (2005). These authors suggest that after nuclear coalescence, the gas infall to the center of the system is so high that the AGN may accrete at near-Eddington rates.

3. Dynamics of Palomar-Green QSO hosts and their relation to mergers

An evolutionary scenario for the late phases of gas-rich mergers, originally based on that of Sanders et al. (1988), is as follows: after coalescence, the IR emission arising from the nuclear starburst and AGN-surrounding dust is strong enough to reach QSO-like luminosities. However, as the dust and gas start clearing out from the nuclear region due to AGN winds and supernova feedback, the system goes through a short (up to \(10^8\) yrs) optically bright phase, before further accretion and star formation are finally prevented.
To test this scenario we obtained spectroscopic (VLT ISAAC-PI Tacconi, SPITZER IRS-PI Veilleux) and imaging (HST NICMOS-PI Veilleux) data for a (small) sample of Palomar-Green QSOs (Schmidt & Green, 1983) as part of our QUEST (QSO/ULIRG evolutionary study) project. The VLT sample consists of 12 sources, most of which are IR-bright (ratio of integrated IR to big blue bump luminosity > 0.46; Surace et al., 2001). If the above evolutionary scenario is realistic, the IR-bright sources are transitional objects between ULIRGs and (optically-selected) QSOs. The HST NICMOS imaging analysis of 7 IR-bright QSOs by Veilleux et al. (2006) indicates that their hosts have similar H-band host magnitudes to those of ULIRGs. In a similar vein, Canalizo & Stockton (2001) found that the (optical) spectra of most of their IR-bright QSOs (selected from the IRAS color-color diagrams) are well fitted by an old population and a recent ($\lesssim 3 \times 10^8$ yrs) strong starburst component.

From our high-resolution, largecollecting area data (obtained under excellent seeing conditions $\lesssim 0.5$), we succeeded in extracting host dispersions of local QSOs from NIR CO bandheads. The average dispersion of the IR-bright QSOs is (so far) similar to that of ULIRG remnants ($\sim 160$ km s$^{-1}$). Thus, their black hole and host masses are also of comparable size ($10^7-10^8$ and $10^{10}-10^{11}$ M$_\odot$ respectively). Since IR-bright QSOs have similar luminosities ($\gtrsim 10^{12}$ L$_\odot$) to ULIRGs, their accretion rates are also high ($\sim 0.5$ Eddington). For the few optically selected sources observed so far, the scatter in the dynamical properties is higher.

In one of the 12 QSOs targeted by our large program, PG1426+015, two nuclei separated by $\sim$4kpc appear in the acquisition image (also seen in HST NICMOS data; Schade et al., 2000). Our NIR spectroscopy indicates that the nuclei are at the same redshift. The optical spectrum of the bright component has very broad emission lines (Kaspi et al., 2000), verifying that the emission originating from this component can be attributed to an AGN. Calculation of the IR luminosity of the system (from IRAS fluxes) indicates that it is a LIRG. The spectra of the QSO and the secondary nucleus are presented in Fig. 2. The second nucleus does not show any indications of strong AGN continuum and resembles those of the binary ULIRGs; therefore we believe that it is starburst dominated. This system constitutes a good example of how mergers can simultaneously trigger strong accretion and starburst events. These findings contradict the aforementioned scenario in that the QSO phase is reached already before nuclear coalescence.

The IR-bright QSOs seem to differ from local QSOs that host even more massive black holes, such as the $0.1 < z < 0.25$ radio-loud (RL) sources or their radio-quiet optical counterparts (RQC) of Dunlop et al. (2003). The RL/RQC QSOs have black hole masses of order $10^8$ and $10^9$ M$_\odot$ that accrete on average at rates $\sim 0.05$ Eddington, and that are located in 5 times more massive and (K-band) luminous hosts. The positions of IR-bright and RL/RQC QSOs on the fundamental plane can be clearly distinguished (see Fig. 1); like giant Es vis-a-vis ULIRGs, the RL/RQC QSOs probably have a different formation history from the IR-bright population.

Our preliminary results seem to indicate evolutionary links between ULIRGs and IR-bright QSOs; however, the fact that some IR QSOs have prominent spiral hosts (Surace et al., 2001; Veilleux et al., 2006) implies that they may have a minor-merger origin (different from that of ULIRGs in terms of the mass ratio of the merging galaxies). Furthermore, IR-bright QSOs are only a small and not necessarily representative part of the PG population. We need to enrich our sample with optically selected QSOs in order to derive conclusions about the optically bright phase of this scenario.

4. Conclusions

From the high-resolution NIR spectroscopic data we have obtained for local ULIRGs and QSOs, we have found that

- For IR luminosity $> 10^{12}$ L$_\odot$ to be triggered during a gas-rich merger, encounters of comparable mass galaxies are (typically) required.
- Evolution (increase) of the host dispersion is ob-
served as the merger advances from pre- to post-coalescence.

- The merger remnants resemble moderate-mass ($\sim 10^{10}$-$10^{11} M_\odot$) ellipticals. The black holes they host are of the order $10^7$-$10^8 M_\odot$ and, on average, accrete at high Eddington rates ($\geq 0.5$).
- The IR bright QSO dispersions and black hole masses, being of the order $10^7$-$10^8 M_\odot$, resemble those of ULIRG remnants and indicate a possible link between the two populations. Our IR-bright sources differ from QSOs that host supermassive black holes and accrete at low rates.
- Imaging and spectroscopy of PG 1426+015 show that it is a binary system of nuclear separation $\sim 4$ kpc. Already at this early merger phase, one of the components is a powerful QSO (with strong dust continuum).

References

Bender, R. 1990, A&A, 229, 441
Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Canalizo, G., & Stockton, A. 2001, ApJ, 555, 719
Dasyra, K. M., Tacconi, L. J., Davies, R. I., Lutz, D., Genzel, R., T. Naab, Burkert, A., Veilleux, S. & Sanders, D. 2005, in press, astro-ph/0510670
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Dunlop, J. S, McLure, R. J., Kukula, M. J., Baum, S. A., O’Dea, C. P., & Hughes, D. H. 2003, MNRAS, 340, 1095
Faber, S. M., et al. 1997, AJ, 114, 1771
Genzel, R., et al. 1998, ApJ, 498, 579
Genzel, R., Tacconi, L. J., Rigopoulou, D., Lutz, D., & Tecza, M. 2001, ApJ, 563, 527
James, P., Bate, C., Wells, M., Wright, G., & Doyon, R. 1999, MNRAS, 309, 585
Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Januzi, B. T., & Giveon, U. 2000, ApJ, 533, 631
Kim, D.-C., Veilleux, S., & Sanders, D. B. 2002, ApJS, 143, 277
Kormendy, J., & Sanders, D. B. 1992, ApJ, 390L, 53
Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641
Mihos, J. C. 1999, Ap&SS, 266, 195
Naab, T., & Burkert, A. 2003, ApJ, 597, 893
Pahre, M. A. 1999, ApJS, 124, 127
Sanders, D., Soifer, B. T., Elias, J. H., Neugebauer, G., Matthews K. 1988, ApJ, 328, L35
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Schade, D. J., Boyle, B. J., & Letawsky, M. 2000, MNRAS, 315, 498
Schmidt, M. & Green, R. 1983, ApJ, 269, 352
Scoville, N. Z., Evans, A. S., Thompson, R., Rieke, M., Hines, D. C., Low, F. J., Dinshaw, N., Surace, J. A., & Armus, L. 2000 AJ, 119, 991
Shier, L. M., & Fischer, J. 1998, ApJ, 497, 163
Springel, V., di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776
Surace, J. A., Sanders, D. B., & Evans, A. S. 2001, AJ, 122, 2791
Tacconi, L. J., Genzel, R., Lutz, D., Rigopoulou, D., Baker, A. J., Iserlohe, C., & Tecza, M. 2002, ApJ, 580, 73
Tremaine, S., et al. 2002, ApJ, 574, 740
Veilleux, S., Kim D.-C., & Sanders, D. B. 2002, ApJS, 143, 315
Veilleux, S., Kim D.-C., Peng, C.Y., Ho, L. C., Tacconi, L. J., Dasyra, K. M., Genzel, R., Lutz, D., & Sanders, D. B. 2006, ApJ, submitted
Fig. 1. The fundamental plane of early-type galaxies ($e_{\text{eff}}-\sigma$ projection). The giant boxy and intermediate-mass disky Es (boxes and filled circles respectively) are from Bender et al. (1992) and Faber et al. (1997). Cluster Es (open circles) are taken from Pahre (1993) and LIRGs (diamonds) from Shier & Fischer (1998) and James et al. (1999). The ULIRGs and the IR-bright QSOs of our program appear as triangles and filled stars respectively. The RL/RQC QSOs of Dunlop et al. (2003) are open stars. Their black hole masses are converted into dispersions using the $M_{\text{BH}}-\sigma$ relation (Tremaine et al., 2002).

Fig. 2. PG 1426+015- On the left panel the acquisition image with the two nuclei is shown. On the right panel, the NIR spectra are presented; the on-source integration time on the QSO is $\sim 2$ times deeper than that on the secondary nucleus.