The Dynamics and Evolution of Luminous Galaxy Mergers: ISAAC Spectroscopy of ULIRGs

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Local ultraluminous galaxy mergers provide us with a quantitative observational means to track an important process for galaxy formation and evolution at high redshift. This article presents first results from a near-infrared spectroscopic study of a moderately large sample of local universe mergers that we have undertaken at the VLT with ISAAC. This study is providing compelling observational evidence that mergers of near-equal-mass, gas-rich galaxies can evolve into intermediate-mass elliptical galaxies after passing through an ultraluminous infrared phase.

The role of mergers in galaxy evolution

Galaxy merging is one of the main driving forces of galaxy evolution. In hierarchical CDM models of galaxy formation and evolution, merging leads to the formation of elliptical galaxies, triggers major starbursts, and accounts for the formation of supermassive black holes and quasars. Many studies have shown that the importance of mergers increases with redshift. Luminous, merger-induced starbursts and AGN at high redshift provide readily observable signposts for tracing out the main epoch of elliptical galaxy and quasar formation.

Before we can begin to assess quantitatively the physics of the merger process at high redshift and its link to the epoch of elliptical and QSO formation we need to first understand the details of galaxy merging and its relationship to starbursts and AGN in the nearby universe. The most violent local mergers and the probable analogus to luminous high-redshift mergers are the ultraluminous infrared galaxies (ULIRGs). Discovered 20 years ago with the IRAS satellite ULIRGs are now known to be mergers of gas-rich disc galaxies. They span the full range of merger states beyond the first encounter to complete coalescence (see Figure 1). They are amongst the most luminous objects in the local Universe, with both their luminosities ($L > 10^{12}\ L_\odot$ emerging mainly in the far-infrared) and their space densities similar to those of quasars. The near-infrared light distributions in many ULIRGs resemble those of elliptical galaxies. They also have large molecular gas concentrations in their central kpc regions (e.g. Downes and Solomon 1998) with densities comparable to stellar densities in ellipticals. These observational results have led several groups (e.g. Sanders et al. 1988) to posit that ULIRGs evolve into ellipticals through dissipative collapse triggered by a merger. In this scenario, the 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.

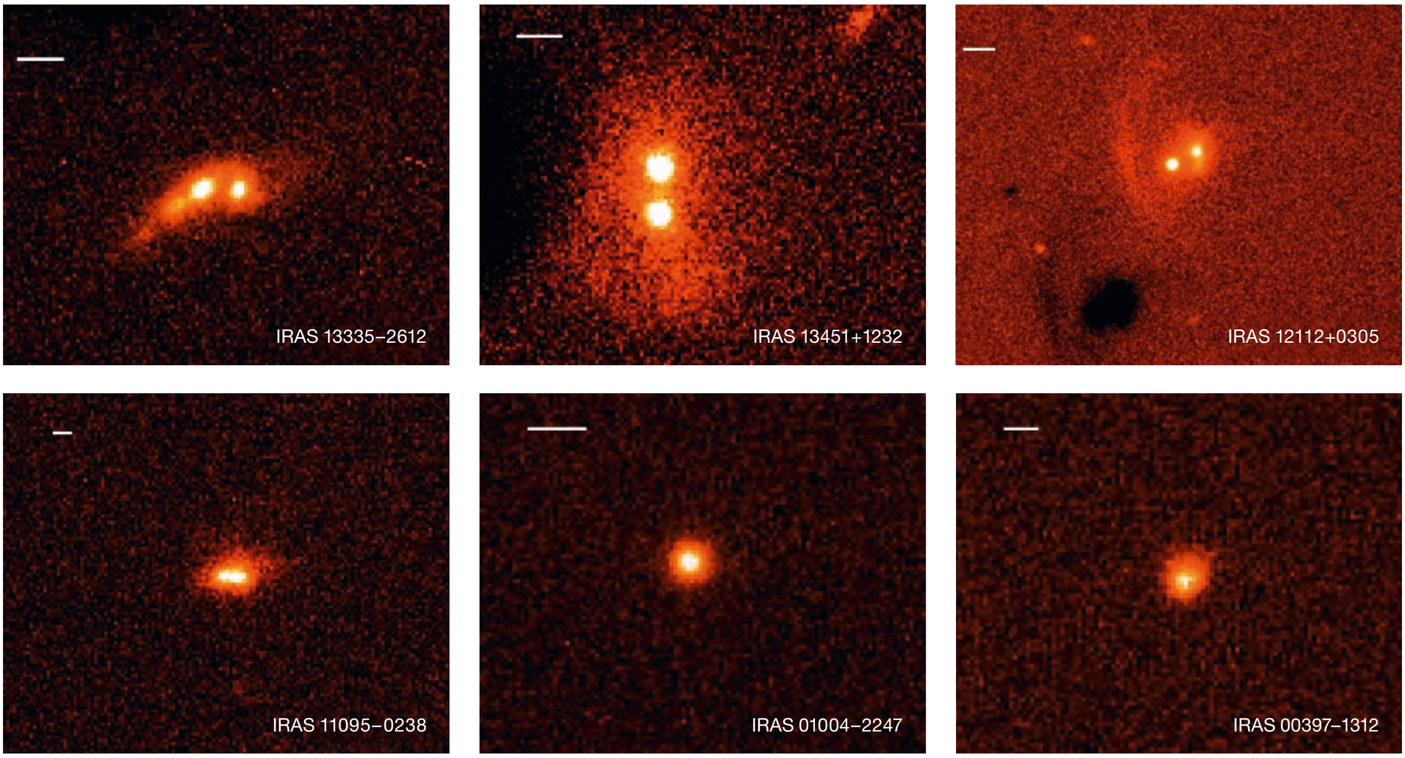
Numerical simulations undertaken by a number of groups also show that the violent merging of massive disc galaxies produces ULIRGs that evolve into spheroidal remnants with properties similar to those of elliptical galaxies (e.g. Barnes and Hernquist; Naab and Burkert 2003). The simulations trace the merging process from the initial encounter to final coalescence, when the merger remnant has settled into dynamical equilibrium. They predict that soon after the first encounter, the interstellar medium of the two galaxies is efficiently concentrated in the central few kiloparsecs on a dynamical timescale (a few tens of millions of years) due to large gravitational torques removing angular momentum from the gas. Equal-mass mergers of massive galaxies produce the highest central gas concentrations. Even in these most violent mergers, the kinematics of the system already reach their equilibrium values of rotation and dispersion by the time the two merger nuclei approach to within about one kiloparsec of each other, on a timescale of a few rotation periods (~ 10^8 yrs) (e.g. Bendo and Barnes 2000).

Therefore, the kinematic and structural properties of ULIRG mergers provide an excellent observational means to track the merging process, and to test how and on what timescales star formation and AGN activity are triggered. In order to trace the full potential evolutionary sequence of ULIRGs we have undertaken a spectroscopic programme with ISAAC of a flux-limited, moderately large sample of ULIRGs and a smaller sample of Palomar-Green QSOs. We were awarded 21 nights as a Large Programme, and during this time allocation we have been able to observe a total of 38 ULIRGs and 12 QSOs in a mixture of visitor and service mode. The three main goals of the programme are: (1) to investigate which merger progenitor configurations are likely to result in an ultraluminous infrared phase; (2) to establish an evolutionary connection between ultraluminous infrared galaxies and elliptical galaxies by comparing the dynamical properties of late-stage ULIRGs with those of elliptical galaxies; and (3) to investigate whether there is a fundamental link between ULIRGs and optically bright quasars by comparing the host and central massive black hole properties of late-merger-stage ULIRGs with those of a sample of optically selected QSOs and IR-excess QSOs in the same redshift and luminosity range. The rest of this article presents results that address the first two scientific goals. Our analysis of the QSOs is now in progress.

ISAAC – the ideal instrument to study merger evolution

To derive accurate kinematic properties from stellar absorption features, we needed high-quality, S/N of 30–50 on the continuum, near-IR spectroscopy of the sample sources. For the ULIRGs we selected sources for the study largely from the 1 Jy catalogue (Kim and Sanders 1998). The 1 Jy catalogue comprises a complete flux-limited (at 60 μm) sample of 118 ULIRGs compiled from a redshift survey of IRAS Faint Source Catalog objects.

Figure 1: The ISAAC *H*-band acquisition images for a selection of the programme sources, which show the variety of merging stages of the ULIRGs and also the excellent conditions at the VLT while the data were obtained. The horizontal bar in the upper left corner of each panel corresponds to 5 kpc at the redshift of the source.



We have observed those sources with declinations < 25°, and with redshifts where the strong rest frame *H*-band stellar absorption lines lie in parts of the *H*- and *K*-band with high atmospheric transmission ($z < 0.13$ and $z > 0.20$). For these very dusty systems, observations in the near-infrared are superior to those in the optical for this purpose, since optical spectroscopy cannot penetrate to the centres of most ULIRGs. We chose to observe in the rest-frame *H*-band, where there are a host of stellar absorption features (e.g. CO $\Delta v = 3$ bands) and gas emission lines (e.g. [Fe II]) readily available. Such observations are only possible on 8-metre-class telescopes with sensitive IR spectrometers, since the strength of the absorption features is only a few per cent of the continuum. The VLT with ISAAC in its medium-resolution mode was a winning combination with which to carry out the programme.

We typically integrated for one hour on source per slit, and observed along at least two position angles per source. Our group had previously completed a smaller pilot study of about 15 ULIRGs (Genzel et al. 2001, and Tacconi et al. 2002), also largely with ISAAC on the VLT, and we have augmented the current programme sample with those sources as well. The total sample thus comprises 54 ULIRGs and 12 PG QSOs, and is the most complete and unbiased dynamical study of these systems to date. The sample covers the full range of the local ULIRG luminosity function, merger state and AGN activity. Our observations of these ULIRGs have yielded unprecedented, high-quality spectra, from which we have been able to derive stellar dynamical quantities (Figure 2). From the spectra we extract the stellar velocity dispersion, σ, and the rotational velocity, V_{rot}, for each source. We analyse the kinematic parameters together with structural quantities taken mostly from the 1 Jy sample photometric study of Veilleux et al (2002). Our group is also conducting an HST NICMOS imaging programme (PI Sylvain Veilleux) of many of the sample galaxies.

Dynamical evidence for major mergers

The present ULIRG sample contains 21 binary (early-stage merger) systems that we have observed to track the pre-coalescence merger phases, and to measure the mass ratios of these systems. For the binary ULIRGs we have measured the kinematic properties separately for each progenitor nucleus in the system. From the stellar dispersions and rotational velocities we compute the dynamical masses of the merging galaxies. We find that ultraluminous luminosities 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. Less frequently, we also find 3 : 1 mergers in our sample, but do not have a firm case where the dynamical mass ratio would indicate ULIRG activity being triggered in a minor merger. Mergers of mass ratio > 4 : 1 typically do not drive enough gas to the centre of the merger to generate ultraluminous luminosities. These results are in agreement with many merger models in the literature (e.g. Naab & Burkert 2003) that all predict that ultraluminous activity is efficiently triggered in a major merger of two massive, gas-rich galaxies.

ULIRGs evolve into intermediate-mass elliptical galaxies

We are investigating the relationship between ULIRGs and elliptical galaxies by

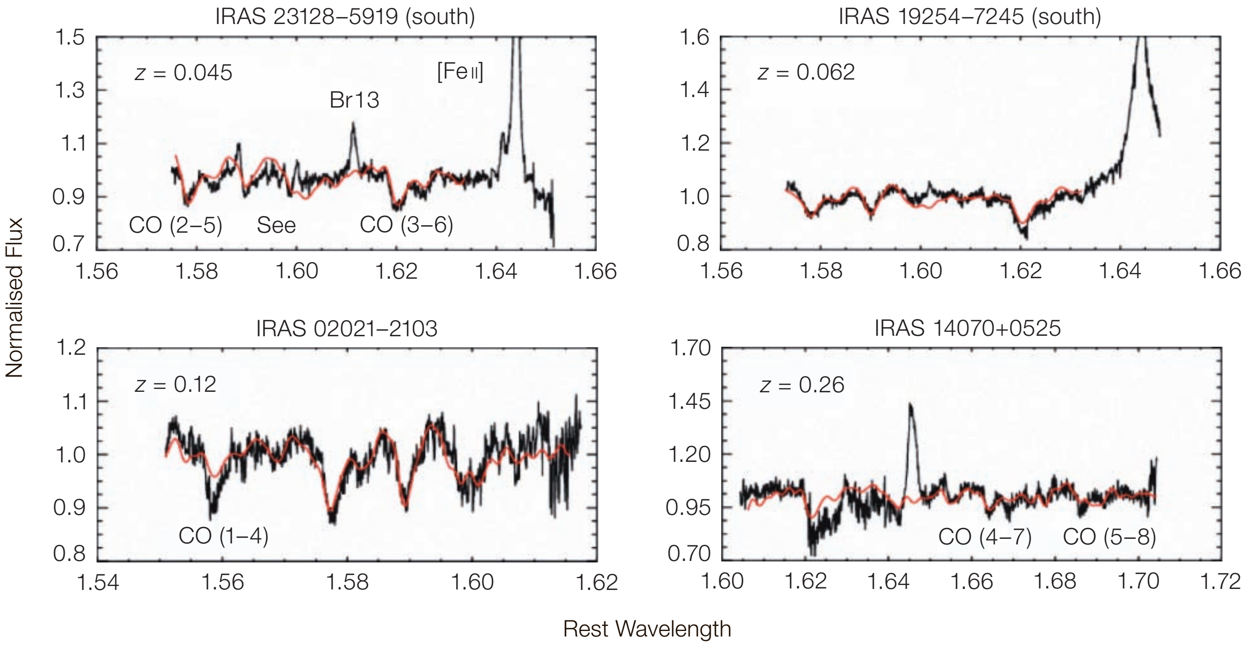


Figure 2: The normalised *H*-band spectra for a selection of the programme sources as a function of rest-wavelength. For comparison, the stellar templates, convolved with the Gaussian that best represents the broadening function (velocity dispersion) of the galaxy are over-plotted in red.

comparing the dynamical properties of the late merging stage ULIRGs (i.e. those coalesced into a single system) with those of representative samples of local elliptical galaxies. The mean stellar velocity dispersion of the fully coalesced, single nucleus ULIRGs is 157 (± 40) km s^{-1}. This mean dispersion is comparable or slightly lower than that of an L* elliptical galaxy (defined as $M_B \sim -20.4$ mag). The velocity dispersion distribution of the ULIRG sample, in fact, closely matches that of compact-core, discy-isophote elliptical galaxies with intermediate masses, and is very different from the (more massive) slowly-rotating/large-core/boxy-isophote ellipticals.

As a result of the virial theorem and common formation and evolution processes, dynamically hot systems (elliptical galaxies, lenticular galaxies, and spiral galaxy bulges) are all found in a well-defined plane of a space comprised of velocity dispersion (σ), effective radius (r_{eff}), and surface brightness with that radius (μ_{eff}). One particularly instructive way of investigating a possible evolutionary track of ULIRGs into elliptical galaxies, therefore, is to place both the ULIRG and elliptical samples on the same fundamental plane. Placing the young, infrared luminous merger systems in this space and comparing them to much older ellipticals is tricky, however, because of the influences of stellar evolution, extinction, and perhaps incomplete dynamical relaxation, all of which will strongly affect the central surface brightness and effective radii even if they are determined in the less extinguished near-infrared bands. To minimise these effects, we consider only the less evolution-sensitive, effective radius – host velocity dispersion (r_{eff}–σ) projection of the fundamental plane. We present this projection of the fundamental plane in Figure 3 for our ULIRG sample together with samples of giant (boxy-isophotal profile) ellipticals, moderate-mass (discy-isophotal profile) ellipticals (both from the work of Bender et al. 1992 and Faber et al. 1997), local cluster ellipticals (from Pahre 1999), and a small sample of luminous infrared galaxies (LIRGs; 10^{11} $L_\odot$ < L < 10^{12} $L_\odot$; from James et al. 1999 and Shier and Fisher 1998). The location of an elliptical galaxy along the fundamental plane is correlated with its luminosity (mass) and its dynamical and structural properties. The most massive ellipticals with boxy isophotes and large cores are found in the upper right of the diagram, while somewhat lower-luminosity, less massive ellipticals and lenticulars with discy isophotes are found in the central part of the plane. Figure 3 shows that most ULIRGs are remarkably close to or on the fundamental plane of early-type galaxies, strongly supporting the hypothesis that they will ultimately evolve into elliptical galaxies. As indicated by their moderate velocity dispersions and compact effective radii, the majority of the ULIRGs populate the region of the plane occupied by the intermediate-mass, discy-isophote elliptical galaxies. Although the late-merger-stage ULIRGs are dynamically hot systems (i.e. the velocity dispersion dominates the kinematics) the ULIRGs still show a significant rotational component in their stellar dynamics. We find a mean rotational to dispersion velocity ratio (v_{rot}/σ) of 0.6 for these late-stage ULIRGs. We again compare the ULIRGs to elliptical galaxies (see Figure 4), and find that ULIRGs have a v_{rot}/σ ratio comparable to what is found for intermediate-mass elliptical and lenticular galaxies. We conclude that there is strong dynamical evidence connecting late-stage local ULIRGs over the full range of the ULIRG luminosity function and intermediate-mass elliptical galaxies. Our previous pilot study (Genzel et al. 2001; Tacconi et al. 2002) showed a similar trend, although there we sampled only a small range of parameter space.

Ongoing work

The detailed results from the early-merging stage ULIRGs are presented in Dasyra et al. 2005, which has just been accepted by the Astrophysical Journal. A paper investigating the dynamical and black-hole properties of the late-merging-stage, single-nucleus systems in the sample is now in the final stage of completion. In the third part of the programme, we are investigating the possible evolutionary connection between ULIRGs and local QSOs, and we are currently analysing the ISAAC *H*-band spectroscopy of our sample of 12 Palomar-Green QSOs spanning the same redshift and luminosity range as the ULIRG sample.

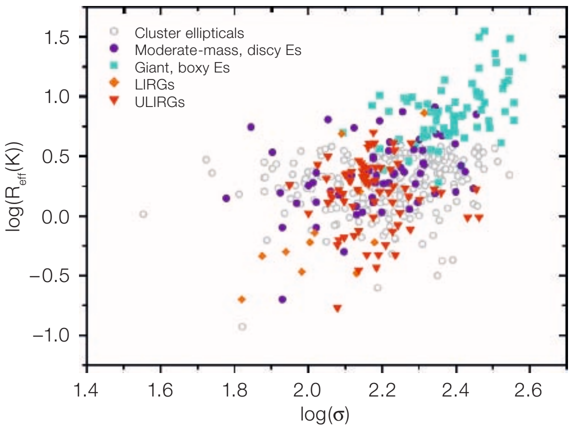


Figure 3: The dynamical projection (effective radius – velocity dispersion, $r_{eff}-\sigma$) of the fundamental plane for our sample of ULIRGs, compared with samples of elliptical galaxies and lower-luminosity infrared galaxies (LIRGs). See text for references.

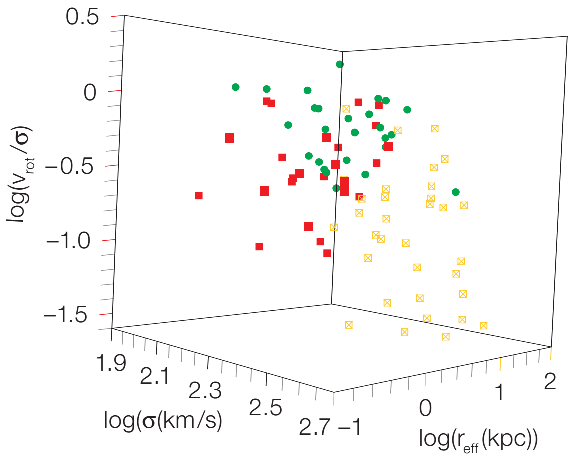


Figure 4: Here we show a three-dimensional plot ($\sigma-r_{eff}-v_{rot}/\sigma$), which indicates the distribution of the ratio of rotation-to-dispersion velocity for the fully coalesced ULIRGs and local elliptical galaxies. The ULIRGs are shown in red, intermediate-mass (discy) ellipticals in green and giant (boxy) ellipticals in gold. The elliptical galaxy properties are taken from Bender et al. (1992) and Faber et al. (1997).

Acknowledgements

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Supernova in NGC 1559

Colour-composite image of the spiral galaxy NGC 1559 in the Reticulum constellation, obtained with FORS1 on the VLT. NGC 1559 is located about 50 million light years away and is about seven times smaller than our Milky Way. The supernova SN 2005df, discovered on the night of August 4, 2005, is visible as the bright star just above the galaxy. SN 2005df has been further classified as a somewhat unusual type Ia supernova, caught probably 10 days before it reached its maximum brightness. Dietrich Baade, Ferdinando Patat (ESO), Lifan Wang (Lawrence Berkeley National Laboratory, USA), and their colleagues studied its polarisation properties and found that SN 2005df resembles closely SN 2001el, whose explosion was significantly asymmetric.

See ESO Press Photo 26/05 for more details.