Two-dimensional structure and kinematics of a representative sample of low-z ULIRGs

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Abstract.
We present the optical INTEGRAL integral field spectroscopy data and Hubble Space Telescope archive images obtained for a representative sample of 22 local Ultraluminous Infrared Galaxies (ULIRGs $L_{IR} > 10^{12}L_\odot$). The sample has been designed for fulfilling a program aimed at studying the internal structure and kinematics of this type of galaxies. Taking advantage of the two-dimensional nature of the data, we study the structure of the stellar and ionized gas, the internal ionization state and the gas kinematics. In this contribution we present the sample and the most important results obtained so far.

1. Introduction
The relevance of galaxies with infrared excess was early highlighted by [14] and [22], and lately recognized by the observations of the IRAS satellite [27]. Among the sources that emit the bulk of their energy in the infrared, the Ultraluminous Infrared Galaxies (ULIRGs, $10^{12}L_\odot \leq L_{bol} \sim L_{IR}[8-1000\mu m] \leq 10^{13}L_\odot$), stand out as some of the brightest objects of the local Universe: they are as luminous as QSOs, and twice as numerous (see reviews in [13] and [25]). These interacting galaxies are mainly powered by strong merger-induced star formation (e.g. [15]), although the presence and importance of an AGN is still a matter of discussion. In fact, recent IR studies suggest that their contribution to the total energy of the system may be relevant only in 15%, 20% of cases (see [19] and [23]). The importance of ULIRGs has been highlighted in the last years, as they appear to be the low-z analogs to the population of star-forming luminous galaxies located at cosmological distances, such as Sub-mm galaxies ([26]) and LIRGs and ULIRGs detected by Spitzer [21]. Although a considerable effort is being dedicated to the study of these high-z galaxies, comprehensive analysis of the internal physics and kinematics of their local counterparts are necessary to obtain a global view of the big picture of galaxy evolution. Here we present some results for the first systematic study of a sample of local ULIRGs using optical INTEGRAL integral field spectroscopy (IFS) and Hubble Space Telescope (HST) high angular resolution images. This work compiles not only the previous results published by our group (see [7], [10] and references therein), but the analysis of 13 new unpublished galaxies. The present IFS data sample regions which are equivalent to the sizes that the instrument MIRI (Mid IR Instrument to be on board of the James Webb Space Telescope) will sample at redshifts of between 3–4. Throughout the paper we use $\Omega_\Lambda=0.7, \Omega_M=0.3,$ and $H_0=70$ km s$^{-1}$ Mpc$^{-1}$.
2. The Sample
The representative sample of local ULIRGs has been designed using the following criteriad to span different stages of the interaction process, (2) to sample the entire luminosity range, (3) to cover all types of nuclear activity, (4) to include only low-z objects. The selected galaxies cover the proposed criteria. They show a large variety of morphologies, that range from interacting discs with a projected nuclear separation of about 36 kpc, to close nuclei (or single nucleus) surrounded by a common envelope (see Fig.1). The luminosity range covered is $11.8 \leq \log (L_{IR}/L_\odot) \leq 12.6$, including two galaxies at the low luminosity end. To check how representative the sample of ULIRGs is in terms of luminosity, we have compared it with the IRAS Bright Galaxy Sample (BGS [24]), a complete flux-limited sample that covers the entire sky surveyed by IRAS at galactic latitudes of $|b| > 5^\circ$. From that comparison (García-Marín et al. 2008 in prep.), it is straight forward to conclude that the tendency of both samples, although not the same, is quite consistent. All the excitation mechanisms are well represented, with 27%, 32%, and 18% of the ULIRGs classified in the literature as HII, LINER and Seyfert galaxies, respectively. The remaining 23% represent objects with no clear or mixed classifications. The galaxies are located at distances between about 40 and 900 Mpc, meaning that the angular resolution ranges from 0.2 to 3.1 kpc arcsec$^{-1}$. Considering all these aspects, we conclude that our sample is essentially representative of the ULIRG class.

Finally, and in order to discriminate the morphological types, we separate the ULIRGs into two broad categories using the projected nuclear distance as a discriminator: (1) Pre-Coalescence Galaxies: those with a nuclear projected separation larger than 1.5 kpc. (2) Post-Coalescence Galaxies: those with a nuclear projected separation smaller or similar than 1.5 kpc. This criterion distributes uniformly the galaxies into the two categories (11 in each one) and well separates different merger stages of ULIRGs (early-late see Fig.1). Besides, theoretical models suggest that by the time the two nuclei have reached a separation of about 1 kpc, the stellar system has basically achieved its equilibrium, although their nuclei can be still separated structures (e.g., [17], [16], [5], [18]). However, it is important to bear in mind that we use the projected nuclear distances. Therefore, it may happen that some pre-coalescence galaxies are misclassified as post-coalescence due to projection effects.

Figure 1. HST WFPC2/F814W archive images of the sample of galaxies. North is up, East to the left. The horizontal bar indicates 5 arcsec. The merger evolves from left to right, up to down. The thick orange line encompasses all pre-coalescence ULIRGs [11].
3. Observations, Data Reduction, and Data Analysis

IFS of the galaxy sample was obtained between 1998 and 2004 using INTEGRAL, a fiber-based optical integral field system [2] connected to the Wide Field Fibre Optic Spectrograph (WFYFOS; [6]) and mounted on the 4.2 m William Herschel Telescope. For the present project, three of the INTEGRAL configurations were used: the so-called standard bundles 1, 2, and 3 (SB1 with fiber diameter 0.45 arcsec and FoV 7.8 × 6.4 arcsec², SB2 with fiber diameter 0.9 arcsec and FoV 16.0 × 12.3 arcsec², and SB3 with fiber diameter 2.7 arcsec and FoV 33.6 × 29.4 arcsec²). The three bundles have a similar configuration in the focal plane. The majority of the fibers form a rectangular area centered on the object, whereas a subset of fibers that form an outer ring of 45 arcsec in radius is simultaneously used for measuring the sky. No lens array is coupled to the fibers, therefore there are inter-fiber gaps that cause small flux losses. In the majority (~75%) of cases the SB2 bundle was the preferred one: the fiber size is similar to the typical seeing of La Palma, and in general an entire ULIRG fits in the FoV. The spectra were taken with a 600 lines mm⁻¹ grating, providing an effective spectral resolution (FWHM) of approximately 6.0, 6.0, and 9.8 Å for the SB1, SB2 and SB3 bundles, respectively¹. The covered spectral range of interest was λ = 4500-7000 Å rest-frame.

The reduction and calibration of the IFS data were performed inside the IRAF² environment, and followed the standard procedures applied to this type of data (see [1] and references therein). The flux, centroid, and width of the emission lines of interest have been obtained fitting Gaussian functions to the observed emission-line profiles using the DIPSO package [12], inside the STARLINK environment³. Finally, to recover the structure of the stellar and ionized gas components as well as other emission lines features of the galaxy, a two-dimensional reconstruction of the spectral information was performed. Given that the INTEGRAL configuration does not provide a full spatial coverage of the galaxies, a Delaunay triangulation of a planar set of points has been applied using the free software IDA [9]. Complementary HST archive images have been used too. These data include the red (WFPC2-F814W for 100% of galaxies) and the near-IR (F160W-NICMOS for 60% of galaxies) continuum images. These filters are equivalent to the ground-based Johnson-Cousins filters I and H respectively [20]. The images were calibrated on the fly, with the best available reference files at the time of retrieval⁴.

4. Structure of the stellar and ionized gas components

In spite of the different angular resolution, the INTEGRAL-based continuum images of the galaxies obtained at wavelengths blueward of Hα and Hβ, recover the stellar structure observed in the high angular resolution HST images (9 times better than INTEGRAL, on average). This occurs even in the low-surface brightness structures, showing a good behavior that makes us confident that all the observed ionized gas structures are real. The outer external structures of the stellar continuum are an indication of the morphological type. In the pre-coalescence galaxies they trace the bridges, plumes and tails that connect the galaxies. In the post-coalescence ones they tend to trace outer envelopes that bear resemblance to that of a perturbed elliptical galaxy, and to show some late merger features. The structures of the stellar and ionized gas components present wavelength-dependent variations, due to the nature and spatial distribution of the ionization sources and the dust distribution (see Fig. 2). Especially in the early merger

¹ These values correspond to the old camera mounted on WYFFOS, that was used for the present observations. From August 2004 a new camera was commissioned for the instrument. See more details in http://www.iac.es/proyecto/integral
² The IRAF software is distributed by the National Optical Astronomy Observatory (NOAO), which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., in cooperation with the National Science Foundation.
³ See http://www.starlink.rl.ac.uk/.
⁴ More information about the data processing can be found at www.stsci.edu.
phases, it is common to find differences in the location of the continuum and the emission line maxima. Using this, it is possible to separate, up to distances of 10 kpc from the nucleus, the following mechanisms: (1) Extra-nuclear young star formation traced by Hα. (2) Shock-dominated regions and LINER activity traced by [O i]λ6300. (3) Presence of an AGN, traced by [O iii]λ5007.

Figure 3. Average line ratios for the different regions (nuclear, circumnuclear, and external) defined in the morphologically evolved ULIRGs. The increasing value of the [O i]/Hα line ratio supports the assumption that LINER activity may be produced by shocks.

5. Two-dimensional Ionization State
The ionization state is derived using the BPT [3] diagrams (see [10]). Beside the classification of the individual spectral, and in order to obtain a generic view of the internal variation of the ionization state, the spectral information of each galaxy has been divided into three regions: the nuclear, circumnuclear (up to 2.5-3.0 kpc from the nucleus) and external (other) regions. The main results of the ionization analysis can be summarized as follows:

(1) About 80% of the studied galaxies have H1- or LINER-like nuclear classification, with approximately the same percentage of pre- and post-coalescence phases. The extra-nuclear
regions of a galaxy tend to show a similar classification than that of the nuclei. The presence of a Seyfert nucleus (in about 20% of galaxies) may lead to the detection of ionization cones and outer highly ionized clouds, whose observed excitation level may be higher than the nuclear one. (2) The azimuthally averaged excitation conditions of late merger ULIRGs present variations. The shock tracer [O I]/Hα shows an enhancement in the excitation towards the most external regions (see Fig. 4). This indicates an increasing importance of shocks towards the most external low surface brightness regions, in agreement with previous findings. The [N II]/Hα and [S II]/Hα line ratios (which are more sensitive to star formation), although increasing in most occasions, do not show a homogeneous behavior. This points towards variations in the physical conditions over the galaxy structure. (3) From comparison with models ([8] and [4]), we conclude that high-velocity shocks appear to be the primary mechanism responsible for the LINER-like ionization. The shock velocity varies from 150-200 km s\(^{-1}\) in the nuclei to 150-500 km s\(^{-1}\) in the most external low surface brightness regions. Photo-ionization by young stars (4-6 Myr) may be a secondary mechanism producing LINER-like excitation. (4) The integrated emission of ULIRGs shows excitation conditions that do not resemble those of the majority of local emission line galaxies. In fact, ULIRGs populate the extreme starburst, the highly excited and the transition regions. The differences measured between the nuclear and the integrated excitation states suggest that the classification of integrated high-\(z\) ULIRGs may vary with respect to the nuclear ones. For the diagnostic based on the [O I]/Hα line ratio, a systematic enhancement in the excitation from H II to LINER is detected when comparing the nuclear vs. integrated values.

Figure 4. From left to right, HST WFPC2/F814W, INTEGRAL Hα emission, velocity field and velocity dispersion. The white contours represent the red continuum. The horizontal bar indicates 5 kpc. The velocity field has a very perturbed structure, although in some cases there are hints for rotation (see for instance the nuclear regions of IRAS 08572+3915 and the global velocity field of IRAS 14060+2919). The distribution of the velocity dispersion is disordered too; the peak is not always associated with the nucleus, tracing tidal effects rather than mass concentrations.
6. Kinematics of the ULIRG sample

The 2D velocity fields of the warm-ionized Hα gas, that present velocity amplitudes of hundreds of km s$^{-1}$, are very complex and in general not consistent with those of purely rotating systems (see Fig. 4). Velocity gradients of up to about 80 km s$^{-1}$ kpc$^{-1}$ are measured in the tidal tails of several pre-coalescence galaxies. All these aspects point towards a tidally-driven kinematics, dominated by the merger process. However, in the early and late merger phases some galaxies present hints (i.e., large velocity amplitude, rotation-like structure, similar position of the photometric and kinematic position angle) for rotation in the global velocity fields. The velocity dispersion ($\sigma$) presents large nuclear values (order of 100-200 km s$^{-1}$). In about 80% of ULIRGs the location of the $\sigma$ peak is not coincident with the photometric nucleus, indicating either dynamically hot regions or that $\sigma$ is tracing tidally-induced flows rather than mass concentrations. For the studied ULIRGs, the $V/\sigma$ parameter ranges from about 0.4 to 2.5, that is, from pressure-supported galaxies to those where the velocity amplitude (mainly tidally-induced) dominates.

![Figure 5. Mass distribution of the sample.](image-url)

The dynamical masses derived from the nuclear $\sigma$ are $\leq m_*\text{ in 75\% of cases, and the mass ratio of the parent galaxies is in general between 1:1 and 3:1 (see Fig. 5).}

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