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Integral field spectroscopy surveys of nearby spiral and U-LIRG galaxies

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Abstract

Here we describe the observations and preliminary results of the gas-phase analysis based on two ongoing, wide-field Integral Field Spectroscopy (IFS) surveys: the PPAK IFS Nearby Galaxies Survey (PINGS), targeting disc galaxies; and the VIMOS-IFU observations of low-z (Ultra)Luminous Infrared Galaxies (U-LIRGs), the local counterpart of massive, dusty high-z star-forming galaxies. We describe how these observations are allowing to discover and characterise abundance differentials between galactic substructures and differences depending on the morphologically/dynamically distinct types of objects, which in turn will allow us to interpret the gas-phase abundances of analogue high-z systems.

1 Introduction

The nebular emission arising from bright H II regions within actively star-forming galaxies has played an important role in our understanding of the chemical evolution in the universe. Metals are a fundamental parameter for cooling mechanisms in the intergalactic and interstellar medium (ISM), star formation, stellar physics, and planet formation. Measuring the chemical abundances in individual galaxies and galactic substructures, over a wide range of redshifts, is a crucial step to understanding the chemical evolution and nucleosynthesis at different epochs, since the heavy atomic nuclei trace the evolution of past and current stellar generations.

This evolution is dictated by a complex array of parameters, including the local initial gas composition, star formation history (SFH), gas infall and outflows, radial transport and mixing of gas within discs, stellar yields, and the initial mass function. Although it is difficult to disentangle the effects of the various contributors, determinations of current elemental abundances constrain the possible evolutionary histories of the existing stars and galaxies, and the interaction of galaxies with the intergalactic medium. The details of such a complex mechanism are still observationally not well established and theoretically not well developed, and threaten our understanding of galaxy evolution from the early universe to present day.

Rest-frame optical nebular emission lines have been –historically– the main tool at our disposal to the direct measurement of the gas-phase abundance at discrete spatial positions in low-z galaxies (e.g. [15, 10]). The relative strengths of these lines provide a diagnostic tool to identify both the abundance of heavy elements and the spectral shape of the ionizing flux distribution. The relevance of the study of the ISM in the local Universe cannot be underestimated, since the diagnostic tools developed to determine the abundance of heavy elements in the nearby Universe constitute the basis of the methods employed to derive abundances (and their relations with global galaxy parameters) in high-z galaxies (e.g. [14, 12]), objects that are typically characterised spectroscopically by their emission lines.

There have been several investigations of possible relationships between the global abundance properties of galaxies and their structural characteristics. However, the reduced number of galaxies studied in detail and the small number of H II regions studied per galaxy preclude definitive conclusions. Until recently, most of these measurements were made with single-aperture or long-slit spectrographs, resulting in samples of typically a dozen or fewer H II regions per galaxy or single spectra of large surveys samples like the Sloan Digital Sky Survey (SDSS). However, galaxies are complex systems not fully represented by a single spectrum or just broad band colours. Disk and spheroidal components are structurally and dynamically different entities with different SFH and chemical evolution, fact that has not been properly addressed until now.

The advent of Multi-Object Spectrometers (MOS) and Integral Field Spectroscopy (IFS) instruments with large fields of view (FOV) now offers us the opportunity to undertake a new generation of emission-line surveys, based on samples of scores to hundreds of H II regions and full two-dimensional (2D) coverage of the disks of nearby galaxies. This novel approach is being implemented in a new series of ambitious IFS surveys around the world, most notably the SAURON instrument [3], which has been extensively used to survey early type galaxies; the VENGA project [4] which plans to use the VIRUS-P instrument to carry out a spectroscopic mapping in a sample of nearby galaxies; the CALIFA survey (see [22]), and other high-z IFS surveys.

Here we describe two wide-field IFS surveys targeting a distinct sample of nearby objects: a) the PPAK IFS Nearby Galaxies Survey: PINGS ([18], focusing on spiral galaxies); and b) the VIMOS-VLT survey of (Ultra)luminous Infrared Galaxies (U-LIRGs [2]). We present the observations and preliminary results on the chemical abundance analysis, with an emphasis on the radial abundance gradients, the 2D distribution of the metal content in the galaxies, and differentials found between extra-nuclear and nuclear abundances, based on S/N-optimised integrated spectra.

2 The PPAK IFS Nearby Galaxies Survey: PINGS

The PPAK IFS Nearby Galaxies Survey (PINGS, [18]) consists in a wide-field 2D spectroscopic survey of a sample of nearby spiral galaxies in the optical wavelength range, using

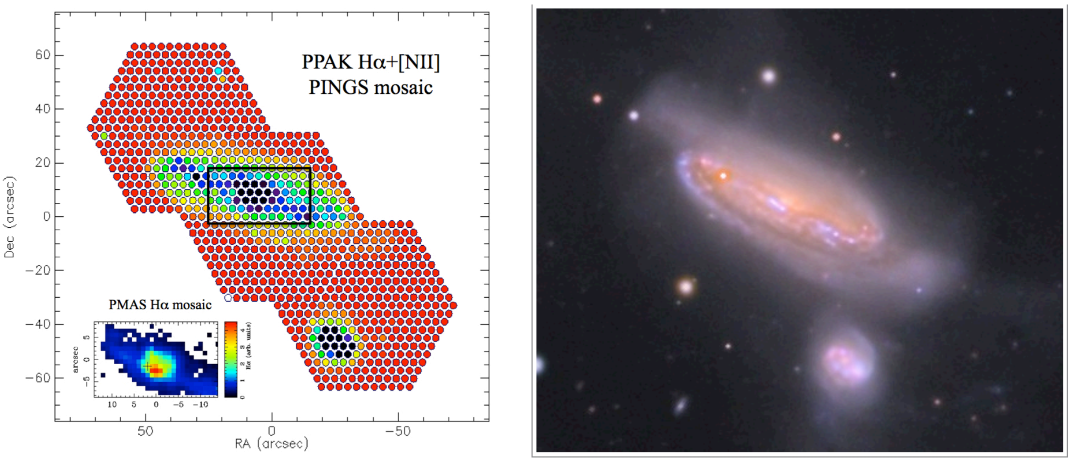

Figure 1: Example of an IFS mosaic observed by PINGS. *Left*: Hα+[N II] "narrow band image" of the PINGS mosaic containing the interactive galaxies NGC 7770 and NGC 7771. The inner-bottom panel shows a PMAS Hα emission line map of the centre of NGC 7771 (black rectangle in the large mosaic) after [1]. *Right*: Colour composite image of the NGC 7770, NGC 7771 interactive system (image by Kent Biggs).

the PMAS/PPAK spectrograph mounted at the 3.5 m telescope of the Centro Astronómico Hispano-Alemán at Calar Alto, Spain. This project represents the first attempt to obtain continuous coverage spectra of the whole surface of a galaxy in the nearby universe. The observations consisted of Integral Field Unit (IFU) spectroscopic mosaics for 17 galaxies within a maximum distance of 100 Mpc; the average distance of the sample being 28 Mpc (for H_0 = 73 km s^{-1} Mpc^{-1}). The sample includes normal, lopsided, interacting and barred spirals with a good range of galactic properties and star-forming environments with multi-wavelength public data (e.g. see Fig. 1). The spectroscopic mosaicking was acquired during a period of three years and the final data set comprises more than 50 000 individual spectra, covering in total an observed area of nearly 80 arcmin^2, an observed surface without precedents by an IFS study up to now. The observations are currently being supplemented with broad band and narrow band imaging for those objects without public available images in order to maximise the scientific and archival value of the dataset.

As part of the main data products, we have obtained for each IFS mosaic: a) complete pixel-resolved maps of the emission-line abundances based on a suite of strong-line diagnostics, incorporating absorption-corrected Hα, Hβ, [O II], [O III], [N II], and [S II] line ratios (e.g. see Fig. 2); b) local nebular reddening estimates based on the Balmer decrement; c) measurements of ionisation structure in H II regions and diffuse ionized gas (DIG) using the well-known and most updated forbidden-line diagnostics in the oxygen and nitrogen lines; d) rough fits to the stellar age mix from the stellar spectra of the galaxy sample [21].

With this approach we intend to obtain relations between the 2D distribution of gas metallicity and galaxy structure. The spatial study of abundance distributions is enabling us to detect features not previously observed by one-dimensional or single-aperture studies,

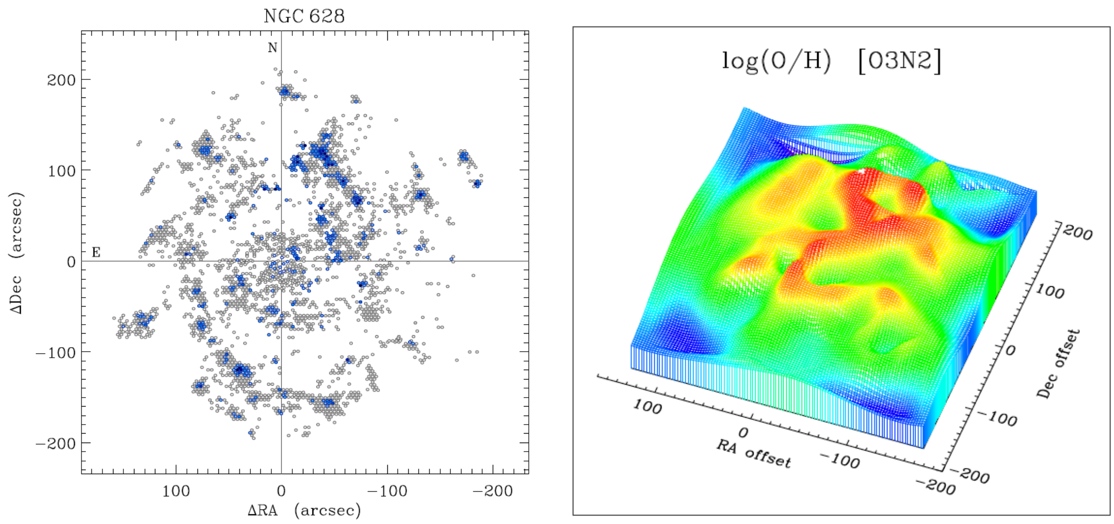

Figure 2: *Left*: Spatial map of the PINGS mosaic of NGC 628 showing those fibres for which nebular emission with high S/N is detected (grey), and those with enough emission lines for a complete chemical abundance analysis (blue). In the latter case, the colour intensity of each fibre has been scaled to the flux intensity of Hα for that particular spectrum. *Right*: 3D rendering of an interpolated grid of oxygen abundances derived from the IFS mosaic of NGC 628, showing a surface of iso-abundance contours obtained using the O3N2 metallicity calibrator.

i.e. inner and/or outer radial gradients, non-axially symmetric abundance distributions, shoulders or local perturbations of the abundance distribution, etc. The presence of these features would give us information about, e.g. anisotropic gas flows across the galaxies, the presence of galaxy environmental effects, or features currently predicted only by theory or inferred by a handful of observations (e.g. [23, 5]). Furthermore, the 2D line-ratio maps are allowing us to study the physical state and ionization mechanisms of the DIG.

Likewise, the nature of the scaling laws relating metallicity and star formation to other fundamental galaxy properties like luminosity, mass or surface brightness are being studied in detail. In most cases these relations were derived for integrated (or nuclear) properties of the galaxies, not for resolved structures. This aperture problem seems particularly relevant for metallicity since chemical abundance gradients appear to be present in most galaxies. The spatially resolved information provided by PINGS will bring light in this problem, allowing to properly study the metallicity scaling laws. This in turn has implications for broader problems within astrophysics, such as an improved understanding of how star formation proceeds at different masses, luminosities, metallicities and environments that might be of relevance at earlier epochs, and therefore, our confidence in the use of metallicity calibrators applied to high-z objects will be considerably enhanced.

Some of the preliminary results arising from these studies are the following: a) we found compelling evidence suggesting that, measurements of emission lines of classical H II regions are not only aperture, but spatial dependent, and therefore, the derived physical parameters

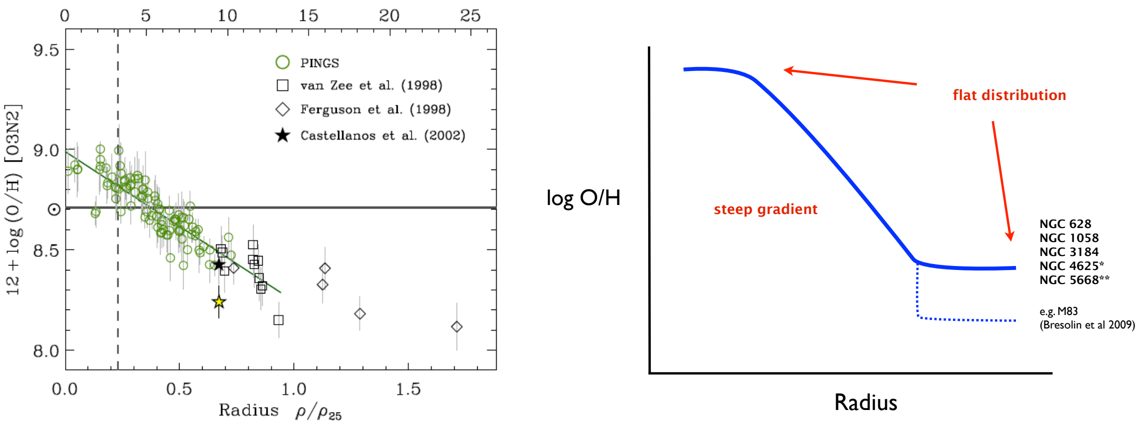

Figure 3: *Left*: Oxygen abundance vs. normalised radius (metallicity gradient) of NGC 628 based on HII regions selected within the FoV of the PINGS mosaic (green), and from the literature (black symbols), derived using the O3N2 calibrator. *Right*: Multi-modality of the abundance gradient inferred for a number of spiral galaxies in the PINGS sample (and in the literature), consistent with a flat-steep-flat behaviour with increasing galactocentric radii. In the case of M83, a discontinuity might also be present. *Notes*:*[11]; **Marino R. (PhD thesis).

and metallicity content may significantly depend on the morphology of the region, on the extraction aperture and on the S/N of the observed spectrum [18, 21]. b) We found observational evidence of non-linear multi-modal abundance gradients in normal spiral galaxies, consistent with a flattening in the innermost and outermost parts of the galactic discs, with important implications in terms of the chemical evolution of galaxies [19], see Fig. 3).

Such multi-modal gradients have been theoretically predicted, e.g. in the case of the inner plateau, this can be due to the influence of a non-axisymmetric gravitational field of spiral density waves [23], and in the case of the flattening at large galactocentric distances, the effect can be reproduced by "inside-out" scenarios of galaxy formation, in which the galaxy disk is built up via gas infall, and in which the timescale for the formation of the disk increases with galactocentric distance (e.g. [5], and references therein). Although previous observations showed complex non-linear behaviour in the radial distribution of oxygen for some spiral galaxies (e.g. [24]), the nearly 2D coverage of the PINGS mosaics allows to provide strong observational evidence of these effects, especially in the innermost regions of the galaxies where no spectroscopic studies were attempted before (e.g. NGC 628, NGC 3184, etc.).

In summary, most studies to date for obvious reasons have preferentially targeted the nebular emission of the brightest and highest surface brightness H II regions, but by targeting virtually every H II region within the galaxies discs, our IFS data is providing a much fuller and more objective sampling of the H II region population. In other words, similarly to SAURON for early-type galaxies, PINGS is providing the most detailed knowledge of star formation and gas chemistry across a late-type galaxy.

3 The metallicity structure of low-z (Ultra)Luminous Infrared Galaxies (U)LIRGs

As mentioned before, understanding the evolution of the metal enrichment over cosmic time is a core question in astrophysics. Nearby (Ultra)Luminous Infrared Galaxies (LIRGs: $L_{\rm IR} \equiv L[8\text{–}1000\,\mu{\rm m}] = 10^{11-12}\,{\rm L}_\odot$; ULIRGs: $L_{\rm IR} > 10^{12}\,{\rm L}_\odot$) are particularly interesting local objects in that respect. They constitute the local counterpart of massive, dusty high-z star-forming galaxies, for which higher S/N and better linear resolutions can be easily achieved (e.g. [16]). The observed properties of (U)LIRGs share many characteristics with populations of star-forming galaxies at high-z [8]). Therefore, the local (U)LIRGs population provides the opportunity to link the properties of those high-z sources with those we observe in the nearby universe.

The ISM of interacting U-LIRGs is frequently found in a kinematically extreme state, dominated by inflows, outflows, and turbulent motions (e.g. [26, 13]), which trigger an intense star formation, producing and redistributing metals at a prodigious rate, altering significantly the chemical states of the progenitor galaxies. Previous works have measured the metal content in low-z (U)LIRGs by using (long-slit or single-aperture) nuclear spectra for ~ 100 (U)LIRGs at $\langle z \rangle \sim 0.1$ [20]. These studies found that (U)LIRGs are under-abundant by a factor of two on average, when compared with local, non-interacting, emission line galaxies with modest star formation and similar luminosity and mass (using the near-IR L vs. Z relation), implying that local abundance scaling relations are not universal.

The SIRIUS project [2, 9, 1], is a long-term programme aimed at studying the internal structure and kinematics of a representative sample of low-z (U)LIRGs, using a variety of optical and near-infrared IFS facilities (INTEGRAL+WYFFOS & PMAS in the northern hemisphere and VIMOS-VLT & SINFONI in the southern one). As part of this project, we are characterising the nebular properties of the VIMOS-VLT sample, which contains a total of 42 systems with a mean redshift of 0.02, covering different morphological classes (spirals, early interactions, advance mergers and post-mergers). The purpose is to exploit the power of IFS observations by obtaining S/N-optimised, velocity-field corrected, integrated spectra of the sources, in order to study how the global nebular chemical abundance and ionization properties compare to the resolved cases (by applying empirical calibrations as those employed in high-z studies, e.g. [17], see Fig. 4), as well as trying to assess the contribution of the nuclear region and/or diffuse medium to the integrated spectra (which is especially relevant in the studies of similar non-resolved high-z systems). The results of these investigations will hopefullt allow us to contribute in the study of the chemical evolution among IR populations.

4 Conclusions

A good deal of our current understanding of the Universe is due to large surveys, either in the imaging or in the spectroscopic domain. However, those surveys conceived to provide spectral information (such as SDSS or zCOSMOS) are generally limited to one spectrum per galaxy, often with aperture losses that are difficult to control, leading to very different linear

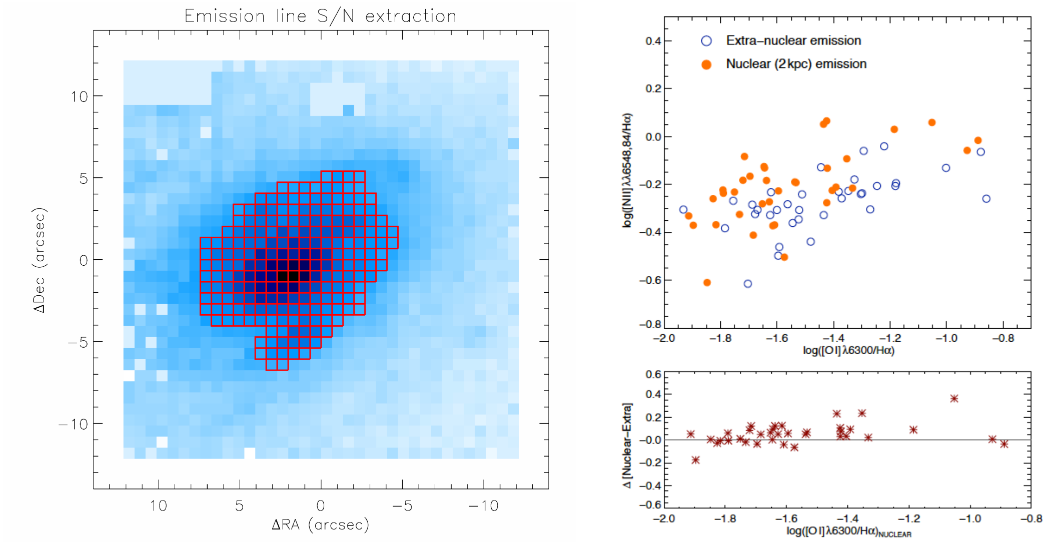

Figure 4: *Left*: VIMOS Hα "narrow band image" of the LIRG IRAS F12115-4656 after [2]. The red squares indicate the selected spaxels (after a S/N optimisation scheme) used to to obtain an integrated spectrum. *Right*: [N II]/Hα vs. [O I]/Hα diagnostic diagram for the integrated emission of the nuclear and extra-nuclear regions of the VIMOS-(U)LIRGs sample, showing the relative differences between the two populations.

scales at different redshifts. The SAURON, SIRIUS, VENGA, PINGS and CALIFA projects represent a milestone in terms of the new generation IFS surveys, considering that before their advent, the imaging-spectroscopy technique was not considered to be implemented in large samples, i.e. in a *survey mode*.

Nearby galaxies offer the unique opportunity to study the SFH-ISM coupling on a spatially resolved basis, over large dynamic ranges in gas density and pressure, metallicity, dust content, and other physically relevant parameters of gas and dust. Therefore, the ongoing (and the upcoming) wide-field, nearby IFS surveys represent a powerful tool for studying effectively not only every H II region within the whole surface area of a galaxy (alleviating the aperture problem), but also those regions where diffuse emission is present and –as very important by-product– a complete 2D picture of the underlying stellar populations of a galaxy. These projects will provide the largest and most comprehensive IFS survey of galaxies, which will allow the community to address several fundamental issues in galactic structure and evolution. The future on this field looks very promising, and it will hopefully help to bring new insights into the physical processes at play in star formation and galaxy evolution.

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