THE CALIFA SURVEY: A PANORAMIC VIEW ON GALAXY PROPERTIES

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ABSTRACT

We present here a brief summary of the status of the on-going CALIFA survey. We have just started the last semester of observing (Spring 2015). So far, we have gathered IFU data of more than 600 galaxies, ~85% of them corresponding to the main CALIFA sample (516 objects). We give an overview of some of the main science results that have been published by the CALIFA team during the last four years. In particular, we emphasise the results regarding the properties of the ionized gas in galaxies and the gradients in oxygen abundance, as well as the evidence for inside-out growth of galaxies uncovered through analysis of the stellar population content.

Subject headings: –

1. INTRODUCTION

The Calar Alto Legacy Integral Field Area (CALIFA) survey [Sánchez et al. 2012a] is an ongoing large project of the Centro Astronómico Hispano-Alemán at the Calar Alto observatory to obtain spatially resolved spectra for 600 local (0.005 < z < 0.03) galaxies by means of integral field spectroscopy (IFS). CALIFA observations started in June 2010 with the Potsdam Multi Aperture Spectrograph (PMAS, Roth et al. 2005), mounted to the 3.5m telescope, utilizing the large (74′′ × 64′′) hexagonal field-of-view (FoV) offered by the PPAk fiber bundle [Verheijen et al. 2004, Kelz et al. 2006]. PPAk was created for the DISK Mass Survey (Bershady et al. 2010). Each galaxy is observed using two different setups, an intermediate spectral resolution one (V1200, R ∼ 1650), that covers the blue range of the optical wavelength range (3700-4700Å), and a low-resolution one (V500, R ∼ 850, that covers the first octave of the optical wavelength range (3750-7500Å). A dithering technique was applied to guarantee the full coverage of FoV, providing with 993 independent spectra of each galaxy, and with a final cube of ~2500 spectra of 1′′/spaxel sampling and ~2.5′′ FWHM of spatial resolution (per setup).

A diameter-selected sample of 939 galaxies was drawn from the 7th data release of the Sloan Digital Sky Survey (SDSS), described in [Walcher et al. 2014]. In summary, we selected galaxies within a certain redshift range (0.005 < z < 0.03), and optical extension that fits within the FoV of the instrument (45′′ < D25 < 80′′, where D25 is the isophotal diameter in the SDSS r-band). The CALIFA main observed sample is a sub-selection from this mother sample, based on visibility only. We have currently observed 516 of these objects (December 2014). In addition, several projects have targeted a heterogeneous sample of more than 100 galaxies that comprise the CALIFA extended sample, including (i) objects that are in low numbers in the main sample: dwarf galaxies, faint and compact E/S0, compact blue elliptical galaxies; and (ii) companions in merging/interacting systems when the main galaxy was selected within the CALIFA sample criteria. This extended sample does not fulfill all the selection criteria of the main sample, however, it comprises galaxies that are mostly in the same foot-print in terms of redshift and diameter (the main selection criteria). Both the main and extended samples were observed using the same instrumental configuration, and reduced using the same pipeline, that guarantees the homogeneity of the dataset. Altogether, we have gathered IFU data for more than 600 galaxies.

Compared with other IFS surveys, CALIFA offers a unique combination of (i) a sample covering a wide range of morphological types in a wide range of masses, sampling the Color-Magnitude diagram for M_g > −18 mag; (ii) a large FoV, that guarantees to cover the entire optical extent of the galaxies up to 2.5r_e for an 80% of the sample; and (iii) an accurate spatial sampling, with a typical spatial resolution of ~1 kpc for the entire sample, which allows to obtain spatially resolved spectroscopic properties of most relevant structures in galaxies (spiral arms, bars, bulges, HII regions...). The penalty for a better spatial sampling of the galaxies is the somewhat limited number of galaxies in the survey, compared to more recently started ones, e.g., MaNGA (~10,000 galaxies, Bundy et al. 2014) and SAMI (~3,600 galaxies, Croom et al. 2012), or the foreseen ones, e.g., HECTOR (~100,000 galaxies, [Bland-Hawthorn 2014]. Like in the case of the CALIFA extended sample (~15% of the total objects), not all the MaNGA and SAMI targets have been selected using a single criteria. In MaNGA there are two main selection criteria that comprises galaxies to be covered up to ~1.5r_e (~70% of the sample), and up to ~2.5r_e (~20% of the sample), both of them at a different average redshift, and finally there is a set of so-called ancillary projects that will comprise 5-10% of the total...
observed objects (Bundy et al. 2014). In SAMI the main sample was built-up using a set of volume limited samples at different redshift ranges (∼70% of the sample), with an additional sample built-up by galaxies in clusters (Bryant et al. 2015). In terms of the spectral resolution, while in the red both SAMI and MaNGA surveys have better spectral resolutions than CALIFA (in particular SAMI), in the blue the three have similar resolutions.

As a legacy survey, one of the main goals of the CALIFA collaboration is to grant public access of the fully reduced datacubes. In November 2012 we delivered our 1st Data Release (Husemann et al. 2013), comprising 200 datacubes corresponding to 100 objects. After almost two years, and a major improvement in the data reduction, we present our 2nd Data Release (García-Benito et al., 2014), comprising 400 datacubes corresponding to 200 objects in the 1st of October 2014. The final Data Release, comprising the full dataset is foreseen for spring 2016. This DR will present the data using an updated version of the reduction pipeline, version 2.0, that is currently under development.

2. CALIFA: MAIN SCIENCE RESULTS

The data products that can be derived from the IFU datasets obtained by the CALIFA survey comprise information on the stellar populations, ionized gas, mass distribution and stellar and gas kinematics. Figure 1 shows an example of two of the indicated dataproducts for the 516 galaxies of the CALIFA main sample observed up to December 2014: (i) the equivalent width of Hα, that traces the areas of star-formation across the galaxies, being proportional to the specific star-formation rate and (ii) the stellar velocity maps obtained using the low-resolution V500 setup (better quality ones are derived using the high-resolution V1200). These dataproducts are presented along the Color-Magnitude diagram. The red-sequence of early-type/dry galaxies is clearly identified as a pink-sequence in the left-hand panel, illustrating the location of those galaxies with little or none star-formation. In some cases there are clear blue-spots in the center of those galaxies, indicating, most likely, the presence of an AGN. The blue cloud is dominated by galaxies with evident star-formation all over its optical extension, with the spiral arms clearly identified as areas of dark-blue color, corresponding to H β regions or aggregations.

The bimodal distribution clearly visible in the distribution of EW(Hα) along the color-magnitude diagram is less evident in the distribution of stellar velocity maps. While most of the slow-rotating systems are located along the red-sequence, there is a considerable number of fast-rotating objects at a similar location. Only the combination of this information with the distribution of stellar velocity dispersion clarifies if those galaxies are pressure or rotationally supported. In summary, both panels illustrate how CALIFA conveys a panoramic view of the spatial resolved spectroscopic properties of galaxies in the Local Universe.

Different science goals have been already addressed using this information: (i) New techniques have been developed to understand the spatially resolved star formation histories (SFH) of galaxies (Cid Fernandes et al., 2013, 2014). We found the solid evidence that mass-assembly in the typical galaxies happens from inside-out (Pérez et al., 2013). The SFH and chemical enrichment of bulges and early-type galaxies are fundamentally related to the total stellar mass, while for disk galaxies it is more related to the local stellar mass density (González Delgado et al. 2014a). González Delgado et al. (2014a): negative age gradients indicate that quenching progresses outward in massive galaxies (González Delgado et al. 2014a), and age and metallicity gradients of spirals are not altered significantly by the presence of a bar.

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Fig. 2. — *Left panel:* Distribution of the oxygen abundances at the effective radii as a function of the integrated stellar masses for the CALIFA galaxies (236, circles), together with those from the CALIFA feasibility studies (31, squares). *Right Panel:* Distribution of the differential oxygen abundances with respect to the solid-line shown in the left-panel (i.e., the dependence on the stellar mass), as a function of the integrated SFR for the CALIFA galaxies.

...et al. [2014]; (ii) we explore the origin of the low intensity, LINER-like, ionized gas in galaxies. These regions are clearly not related to star-formation activity, or to AGN activity. They are most probably related to post-AGB ionization in many cases (Papaderos et al. [2013]); (iii) we study the effects of the aperture and resolution on IFS data. CALIFA provides a unique tool to understand the aperture and resolution effects in larger single-fiber (like SDSS) and IFS surveys (like MaNGA, SAMI). We explored the effects of the dilution of the signal in different gas and stellar population properties (Mast et al., 2014), and proposed a new empirical aperture correction for the SDSS data [Iglesias-Páramo et al. 2013]; (iv) CALIFA is the first IFU survey that allows gas and stellar kinematic studies for all morphologies with enough spectroscopic resolution to study (a) the kinematics of the ionized gas (García-Lorenzo et al. [2014]), (b) the effects of bars in the kinematics of galaxies (Barrera-Ballesteros et al. [2014]); (c) the effects of the interaction stage on the kinematic signatures (Barrera-Ballesteros et al., submitted); (d) measure the Bar Pattern Speeds in late-type galaxies (Aguerri et al., accepted); (v) extend the measurements of the angular momentum of galaxies to previously unexplored ranges of morphology and ellipticity (Falcón-Barroso et al., in prep.); (vi) using CALIFA data we probed for the first time spectroscopically the different association of different SN types to the star-formation of their environment (Galbany et al. [2014]); and (vii) finally we analyze in detail the effects of galaxy interaction in the enhancement of star-formation rate and the ignition of galactic outflows (Wild et al. [2014]).

3. RESULTS OF OUR STUDIES OF THE H II REGIONS

The program to derive the properties of the H II regions was initiated based on the data from the PINGS survey of Rosales-Ortega et al. [2010]. This survey acquired IFS mosaic data for a dozen of medium size nearby galaxies. In (Sánchez et al. [2011]) and Rosales-Ortega et al. [2011] we studied in detail the ionized gas and H II regions of the largest galaxy in the sample (NGC 628). The main results of these studies are included in the contribution by Rosales-Ortega in the current edition. We then continued the acquisition of IFS data for a larger sample of visually classified face-on spiral galaxies (Márquez et al. [2011]), as part of the feasibility studies for the CALIFA survey (Sánchez et al. [2012]). The spatially resolved properties of a typical galaxy in this sample, UGC 9837, were presented by viironen et al. (2012).

In (Sánchez et al. [2012b]) we presented a new method to detect, segregate and extract the main spectroscopic properties of H II regions from IFS data (HIIEXPLORER). A preliminar catalog of ~2600 H II regions and aggregations extracted from 38 face-on spiral galaxies compiled from the PINGS and CALIFA feasibility studies was presented. We found a new local scaling relation between the stellar mass density and oxygen abundance, the so-called Σ-Z relation (Rosales-Ortega et al. [2012]).

The same catalog allows us to explore the galactocentric radial gradient of the oxygen abundance (Sánchez et al. [2012b]). We confirmed that up to ~2 disk effective radius there is a negative gradient of the oxygen abundance in all the analyzed spiral galaxies. The gradient presents a very similar slope for all the galaxies (∼0.12 dex/r_e), when the radial distances are measured in units of the disk effective radii. Beyond ~2 disk effective radii our data show evidence of a flattening in the abundance, consistent with several other spectroscopic explorations, based mostly on a few objects (e.g. Bresolin et al. [2009]).

In (Sánchez et al. [2013]) we presented the first results based on the catalog of H II regions extracted from a enlarged sample of galaxies (∼100). We studied the dependence of the Σ-Z relation with the star formation rate. We found no secondary relation different from the one induced by the well known relation between the star formation and the mass, contrary to what was claimed other authors (Lara-López et al. [2010], Mannucci et al. [2010]), based on single aperture spectroscopic data (SDSS). Although the reason for the discrepancy is still not clear, we postulate that simple aperture bias, like the one present...
in previous datasets, may induce the reported secondary relation. Figure 2 presents an updated version of these results, including the last list of analyzed galaxies, until July 2014 (236 galaxies from the CALIFA sample together with 31 galaxies from the CALIFA-pilot studies). The left panel shows the $M$-$Z$ relation found for these galaxies, with color code indicating the integrated SFR for each galaxy. It is appreciated that the stronger gradient in SFR is along the stellar mass, as expected for star-forming galaxies. Once subtracted the best fitted function to the $M$-$Z$ relation, the residuals of the abundance do not present any evident secondary relation with the SFR (as it is seen in the right panel). Thus, the results presented in Sánchez et al. (2013) are confirmed with a sample of galaxies enlarged by almost a factor two.

We also confirmed the local $\Sigma$-$Z$ relation unveiled by Rosales-Ortega et al. (2011), with a larger statistical sample of H II regions (~5000). This nebular gas $\Sigma$-$Z$ relation is flatter than the one derived for the average stellar populations (González Delgado et al. 2014), but both of them agree for the younger stars, as expected if the most recent stars are born from the chemically enriched ISM. In Sánchez et al. (2014), we confirmed that the abundance gradients present a common slope up to ~2 effective radii, with a distribution compatible with being produced by random fluctuations, for all galaxies when normalized to the disk effective radius of $\alpha_{O/H} = -0.1$ dex$/r_e$. Similar results are found when the gradient is normalized to other scale-lengths of the galaxy, like $r_{25}$, with a sharper slope, $\alpha_{O/H} = -0.16$ dex$/r_{25}$ (Sánchez et al. 2014). When using the physical galactocentric distance the gradient is shallower ($\alpha_{O/H} = -0.03$ dex/kpc) and presents a tail towards large slopes, up to ~0.15 dex/kpc, with a clear morphological dependence. The use of different abundance calibrators does not affect the main conclusion, although it changes the numerical value of the gradient, as recently published by Ho et al. (2015), using CALIFA-DR1 and CALIFA-feasibility survey data.

Finally, in Sánchez et al. (2014b), we found evidence that H II regions keep a memory of their past, by analysing the correspondence between the properties of these ionized regions with that of their underlying stellar populations.

4. CONCLUSIONS

In summary the results from the CALIFA survey present a coherent picture of the mass-growth and chemical enrichment of galaxies. All the results indicate, so far, that the bulk of the galaxy population presents an inside-out growth (at the mass range covered by the survey), with a chemical enrichment dominated by local processes, and limited effects by processes like outflows or radial mixing.

We are still analysing the data, and in particular we are trying to uncover the chemical enrichment processes at different ages using inverse methods to derive them form the stellar populations (González Delgado et al., in prep.), and the current picture could be modified on the basis of the new results.

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