Dwarf Galaxies: From the Deep Universe to the Present
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Full-spectral fitting techniques to characterise the stellar content of ultra diffuse galaxies

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Abstract. Understanding the peculiar properties of Ultra Diffuse Galaxies (UDGs) via spectroscopic analysis is a challenging task that is now becoming feasible. The advent of 10m-class telescopes and high sensitivity instruments is enabling the gathering of high quality spectra even for the faintest systems. In addition, advances in the modelling of stellar populations, stellar libraries, and full-spectral fitting codes are allowing the recovery of the stellar content shaping those spectra with unprecedented reliability. In this contribution we report on the extensive tests we have carried out using the inversion code STECKMAP. The similarities between the Star Formation Histories (SFH) recovered from STECKMAP (applied to high-quality spectra) and deep Colour-Magnitude diagrams fitting (resolved stars) in two Local Group dwarf galaxies (LMC and LeoA) are remarkable, demonstrating the impressive performance of STECKMAP. We exploit the capabilities of STECKMAP and perform one of the most complete and reliable characterisations of the stellar component of UDGs to date using deep spectroscopic data. We measure radial and rotation velocities, SFHs and mean population parameters, such as ages and metallicities, for a sample of five UDG candidates in the Coma cluster. From the radial velocities, we confirm the Coma membership of these galaxies. We find that their rotation properties, if detected at all, are compatible with dwarf-like galaxies. The SFHs of the UDG are dominated by old ($\sim$ 7 Gyr), metal-poor ([M/H] $\sim$ -1.1) and alpha-enhanced ([Mg/Fe] $\sim$ 0.4) populations followed by a smooth or episodic decline which halted $\sim$ 2 Gyr ago, possibly a sign of cluster-induced quenching. We find no obvious correlation between individual SFH shapes and any UDG morphological properties. The recovered stellar properties for UDGs are similar to those found for DDO 44, a local UDG analogue resolved into stars. We conclude that the UDGs in our sample are extended dwarfs whose properties are likely the outcome of both internal processes, such as bursty SFHs and/or high-spin haloes, as well as environmental effects within the Coma cluster.

Keywords. techniques: spectroscopic, galaxies: formation, galaxies: evolution, galaxies: dwarf, galaxies: stellar content

1. Introduction

The characterisation of the stellar content of any galactic system is of the utmost importance to understand their formation and past evolution. Bursts of star formation and their efficiency, changes triggered by mergers, quenching by ram-pressure stripping or different kinds of feedback, are just a few examples of the large myriad of processes that galaxies might undergo and that are imprinted in their stellar content. It will depend on our ability to extract such information from observations that we could improve our knowledge on galaxy formation and evolution.

Of special interest is the analysis of the stellar content in the low surface brightness (LSB) regime, namely the outer parts of galaxies or the faintest tail of the observed galactic population. The lesser gravity in the former or the low baryonic density in the later, make them striking examples to concentrate our efforts. Radial migration effects, dark matter distribution, or satellite accretion imprint are some of the processes that can be tackled by analysing this faint part of the Universe. In the recent years interest has been renewed in a particular family of LSB galaxies, now known as ultra diffuse galaxies (UDGs, $\mu_g(0) \geq 24$ mag/arcsec^2 and $R_{\rm eff} \geq 1.5$ kpc, van Dokkum *et al.* 2015). As their systematic detection and characterisation become feasible, their importance in providing observational constraints to simulations in the faint part of the luminosity function has increased. In addition, although the consensus is leading towards UDGs being extended dwarf galaxies (Beasley & Trujillo 2016, Beasley *et al.* 2016, Trujillo *et al.* 2017), aspects such as their nature, formation mechanism (SN feedback, high halo spin, environmental-driven quenching) or their true dark matter fraction are still under debate.

However, the study of the stellar content in these systems relies, as for the immense majority of galaxies in the Universe, on integrated information. The derivation of Star Formation Histories (SFHs) based on the distribution of individual stars in a deep Colour-Magnitude Diagrams (CMD), often considered the more reliable approach (Gallart *et al.* 1999), is only applicable to the few dozens of nearby systems for which we can study individual stars. But, how reliable are current characterisations of the stellar composition of external galaxies using integrated light?

2. Stellar content from integrated spectra

The analysis of broad-band colours or line-strength indices has been widely used to characterise the stellar component of galaxies. However, degeneracies and limitations to obtain the full extent of SFHs are favouring the use of modern full-spectral fitting techniques to study the stellar content from spectroscopic datasets. In Ruiz-Lara *et al.* 2015, we started a project at testing these techniques by comparing their outcome with that of CMD fitting techniques ("The Storm", Bernard *et al.* 2015) in different systems. While in that work we used different full spectral fitting codes such as `STARLIGHT` (Cid Fernandes *et al.* 2015), `STECKMAP` (Ocvirk *et al.* 2006) or `ULySS` (Koleva *et al.* 2009) to extract the SFH in a region of the LMC bar, in Ruiz-Lara *et al.* 2018a we focused our analysis on the use of `STECKMAP` (the code from which better results are obtained) in the extremely-young, Local Group dwarf galaxy, Leo A. The basis of the full methodology is based on the combination of three different codes. On one hand, determination of the stellar kinematics and gaseous emission line decontamination are achieved using `pPXF` (Cappellari & Emsellem 2004) and `GANDALF` (Sarzi *et al.* 2006 and Falcón-Barroso *et al.*

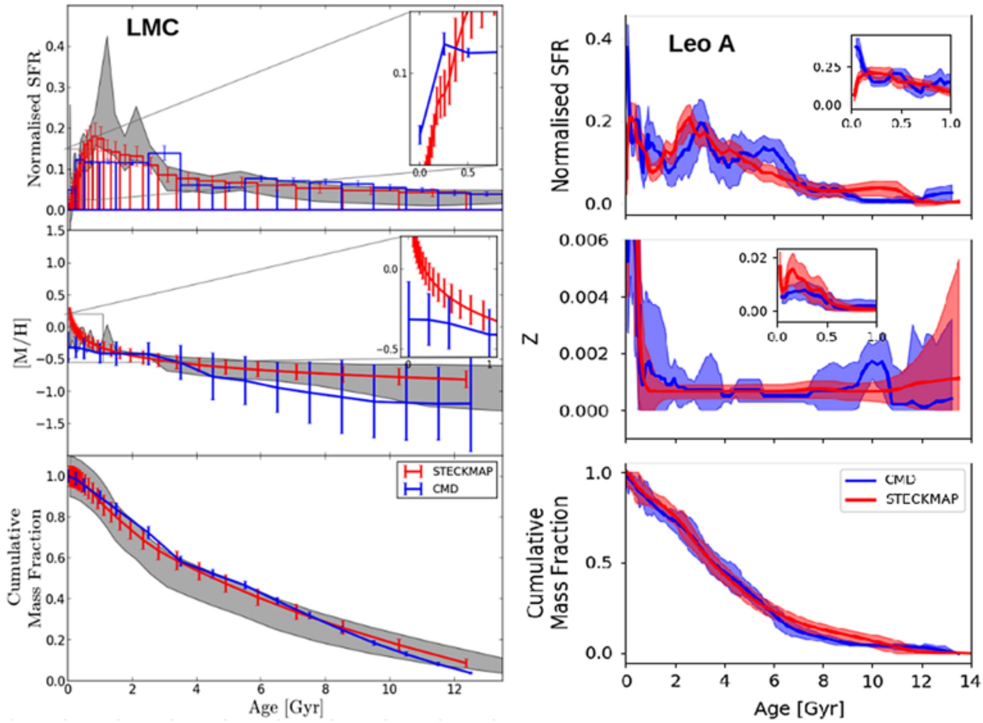

Figure 1. Comparison between the SFH recovered from STECKMAP (red) and a deep CMD fitting (blue) for the LMC (left) and Leo A (right). The grey shaded regions in the LMC case encompass all the different tests carried out during the analysis. For more information we refer the reader to Ruiz-Lara *et al.* 2015 and Ruiz-Lara *et al.* 2018b.

2006), respectively. Once pure absorption spectra are determined from the targets under analysis, `STECKMAP` is able to determine the chemical enrichment and stellar age distribution that better fits the observed data. Figure 1 shows the remarable agreement between both approaches.

3. Stellar content of ultra diffuse galaxies

Encouraged by the success of this methodology at replicating the galactic SFHs recovered via CMD fitting, we decided to apply it to the elusive systems called UDGs to obtain their first SFHs. We collected high-quality spectroscopic data for a number of UDG candidates in the Coma cluster making use of OSIRIS in its Multi-Object Spectrograph configuration (mounted at the Gran Telescopio Canarias). After a thorough data reduction (details in Ruiz-Lara *et al.* 2018a), we applied the above mentioned methodology to describe the stellar content of 5 UDGs. We found that the analysed UDGs, irrespective of their physical sizes, display similar SFHs characterised by old ($\sim$ 7 Gyr), metal-poor ([M/H] $\sim$ –1.0) and α-enhanced ([Mg/Fe] $\sim$ 0.4) stars (see Fig. 2). In addition, the recovered SFHs as well as the tentative stellar rotation curve measurements presented in this work (see Fig.3) quantitatively agree with those found in dwarf galaxies (although we cannot discard an absence of rotation in them), favoring a formation scenario based on internal processes. Thus, we suggest that the analysed UDGs in Coma are dwarf galaxies formed in low-density environments whose specific properties are shaped by the combined effect of a slow process of immersion in the Coma cluster and internal processes (high spin halo or bursty SFH). The possibility of finding field UDGs remains open, acquiring

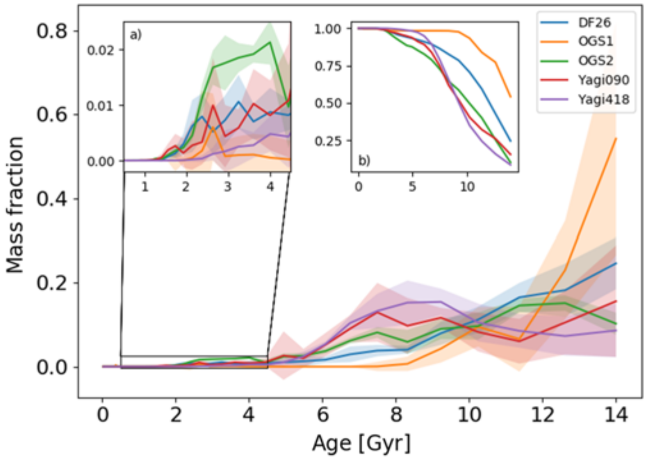

Figure 2. SFHs of the five UDGs under analysis. a) Zoom at young ages. b) Cumulative mass functions. For more information we refer the reader to Ruiz-Lara *et al.* 2018a.

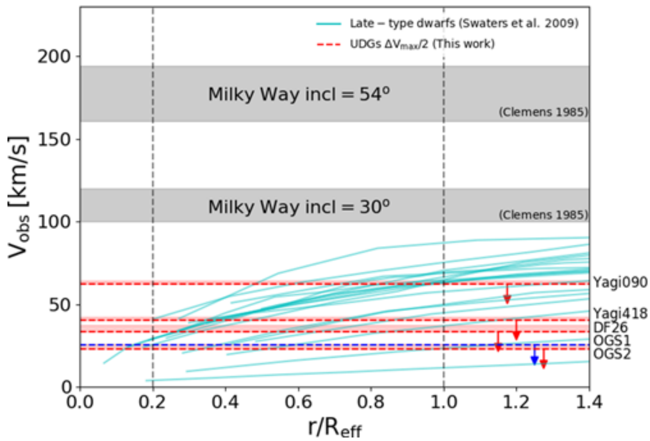

Figure 3. Analysis of the stellar rotation curves compatible with our velocity determinations. For more information we refer the reader to Ruiz-Lara *et al.* 2018a.

in this case the observed properties mainly via internal processes. We provide here new and clear evidence favouring the dwarf-like galaxy scenario. Complete descriptions of the method, analysis, data and results can be found in Ruiz-Lara *et al.* 2018a.

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