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Project title

Properties and evolution of stellar populations in galaxy clusters.

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1 Theoretical framework

Galaxy clusters are the most massive virialized systems in the universe and play an important role in galaxy evolution. In a compact observable field, they provide large samples of galaxies at the same redshift. In clusters, we can study the direct interaction between galaxies and the intergalactic medium, leading to environmental effects which may cause significant differences between field and cluster galaxy populations (White et al., 2005). Furthermore, we can test models based of galaxy formation and evolution.

Local clusters are dominated by early-type galaxies (ellipticals and lenticulars) and exhibit a lack of late-types (spirals) toward the center, as was shown by Dressler (1980) with the density-morphology relation. This trend is steeper for concentrated clusters, which typically have high X-ray luminosities and central dominant galaxies. Furthermore, while nearby clusters have a few star-forming galaxies, with a lack of luminous spiral galaxies, compared to clusters at higher redshift where such systems were instead found to be quite common, as first noted Butcher and Oemler (1978) by $z \sim 0.3$ for cluster cores showing a remarkable population of blue galaxies. Thus, the identification of the content and properties of clusters at different redshifts should allow us to study the cosmic evolution of galaxies.

For these reasons, galaxy clusters represent astrophysical laboratories for studying the effects of the environment on the evolution of galaxies. In the clusters' outskirts, galaxies are still falling toward the cluster centers, and along the way, galaxies suffer several processes. The most important ones including gravitational interactions among galaxies, whose effects are stronger for low-velocity encounters and high-density environments, and can eventually result in mergers and transform their morphology. Galaxies also interact with the cluster gravitational potential, depending on the distance to the cluster center. Other processes include hydrodynamic interactions between the cold interstellar medium of the galaxy and the hot intracluster medium; the ram pressure is the most efficient process to strip a galaxy of its gas content and is able to cause a sudden quenching of the star formation activity (Cortese et al., 2007; Boselli and Gavazzi, 2006). This gas stripping may favor the transformation of spirals into lenticular (hereinafter S0s) galaxies (Cava et al., 2017).

In addition to the external mechanisms driving galaxy evolution, we have the internal ones, led by star formation and evolution. However, the environment will also influence star formation, for example, when the gas is removed, added, or perturbed. As well, clusters are rich in galaxies hosting very old stellar populations (Fritz et al., 2011). There are other physical processes that influence the internal properties, like supernovae and nuclear activity. The former can heat and drive gas out of galaxies, and it is expected to be more efficient in low-mass galaxies. On the other side, active galactic nuclei (AGNs) are also associated with the quenching of star formation and are expected to be more prominent in galaxies hosting very massive black holes (Kimm et al., 2009).

In order to trace the evolution of galaxies in clusters, a systematic analysis needs a substantial knowledge of the cluster properties, as well as of the galaxies in them. There have been attempts using large amounts of observations with spatial and ground-based telescopes. For instance, Dressler et al. (1997), using HST (Hubble Space Telescope) observations, found that for $0.4 \leq z \leq 0.5$, spiral galaxies are 2-3 times more abundant and S0 galaxies are proportionally less abundant than in nearby clusters, while the elliptical population remains constant or is more abundant. Fasano et al. (2000) completed the study for $0.1 \leq z \leq 0.25$, and noticed that the S0 population lightly grows from $z \sim 0.5$ to $z \sim 0$ at the cost of spirals. This trend was confirmed by Poggianti et al. (2009) for higher redshifts (until $z = 1.2$), and a significant evolution has not been identified for elliptical galaxies in clusters since $z \sim 1$.

In spite of this, the understanding of galaxy properties and their evolution through cosmic time remains surprisingly limited. Observations of galaxies at different epochs may offer a clearer picture of the evolutionary paths taken by galaxies, based on environment, mass, morphology, and star formation rate (SFR). This has been our motivation for the present project. We will take advantage of the recent cluster galaxy surveys (WINGS and OmegaWINGS; see below), which include data available for the community, as well as published data and results that we will access through other collaborations and observational campaigns targeting higher redshift clusters (EDisCS and MORPHS; see below).

2 Objectives and goals

Our general objective is to study the properties and evolution of the galaxy populations in clusters, with a special focus on the characteristics of their stellar populations, and trying to isolate the influences of the cluster properties. This, for both local and intermediate redshifts (from $z \sim 1.0$ to now). More specifically, we aim to answer the following questions:

- What are the main processes transforming galaxies through the cosmic time? What conditions are required? Are any of those dominating over the others and, if so, why and under which circumstances?
- How do galaxy properties change through their evolution that led them to look as we observe them now?
- In which galaxy components do these processes take place?
- How are galaxies affected according to the host cluster properties?
- Are irregular clusters characterized by a younger population of S0s?
- What are the mechanisms mainly contributing to the transformation of spiral galaxies into S0s?
- How do the results obtained at low redshift compare to those derived for clusters at early cosmic epochs?

For this purpose, we have divided the main work into three projects, which we expect to be reflected in published articles, as follows:

1. Formation and evolution of S0 galaxies (with a special focus on their stellar populations). We will analyze how the fraction of S0s changes according to the cluster properties (X-ray luminosity, velocity dispersion), the projected distance to the cluster center, and the local density, and how the S0 population changes with the dynamical relaxation level of the cluster. This study of S0s will provide interesting hints on the physical link between lenticulars and spirals, on the timescale for the transformation from spirals to lenticulars (if it indeed occurs), and on the relation of the S0 population with the projected phase space distribution.
2. Star formation history of galaxies in clusters: How star formation evolves across cosmic time in clusters, and how they relate with cluster properties, environment properties, local density, etc. For this item, we would like to focus on the properties of the stellar populations as a function of the cluster properties, of the galaxies morphology, local density, and stellar mass; in order to disentangle the importance of these factors on the galaxy evolution.

3. A systematic comparison between stellar population features as a function of environment properties. For this study, we can divide the galaxy sample according to their morphological type and stellar mass, and analyze if, how, to which degree, and by which mechanism is the environment responsible for the properties of the stellar population and for quenching effects.

3 Observational data

The full set of observational data available for this study comprises five datasets: WINGS, OmegaWINGS, EDisCS, MORPHS, and PM2GC. Now, we describe each of them.

The Wide-field Imaging Nearby Galaxy-cluster Survey[1] (WINGS; Fasano et al., 2006) was undertaken with the goal of collecting a complete and unbiased sample of cluster galaxies. WINGS is the most homogeneous project targeting galaxies in dense environments to date; it aims to evaluate the physical properties of galaxies in the central parts ($R < 0.6R_{200}$) of local clusters ($0.04 < z < 0.07$), to be used as a reference for evolutionary studies. WINGS consists of 77 galaxy clusters (36 in the northern hemisphere and 41 in the southern hemisphere) with photometric data (WINGS-OPT; Fasano et al., 2006) in the B and V bands (D'Onofrio et al., 2014); and a subsample of 46 clusters with spectroscopic data (WINGS-SPE; Cava et al., 2009).

The WINGS-OPT observations were taken with the Wide Field Camera (WFC) at the 2.5 m Isaac Newton Telescope (INT) in the Roque de los Muchachos Observatory, Canary Islands, for the northern clusters; and with the Wide Field Imager (WFI) mounted at the 2.2 m MPG-ESO telescope in La Silla Observatory, Chile, for the southern clusters. Likewise, the WINGS-SPE observations were obtained with the AF2/WYFFOS multifiber spectrograph at the 4.2 m William Herschel Telescope (WHT) in La Palma, Canary Islands, for the northern clusters, and with the 2dF multifiber spectrograph at the 3.9 m Anglo Australian Telescope (AAT) in the Australian Astronomical Observatory, for the southern clusters.

These datasets represent the largest sample of nearby galaxy clusters, covering a wide range in X-ray luminosities ($\log \mathrm{L_X}[0.1 - 2.4 \text{ keV}] = 43.2 - 44.7$), with a total of 6137 measured redshifts (Cava et al., 2009), 3694 of which are cluster members. This is the project with the highest number of member galaxies to date, with an overlap of $\sim 30\%$ with previously published datasets. Additionally, we count on a very reliable morphological classification, given by Fasano et al. (2012) for the galaxies in the sample.

There are other surveys like GAMA (Galaxy And Mass Assembly), which offers a sampling down to low-mass halos but lacks a large number of massive clusters at similar redshifts to those in WINGS; or SDSS, which provides large cluster catalogs, but has a much lower imaging quality (as measured by seeing, depth, and pixel scale)[2]. However, in spite of the superiority of the WINGS dataset in comparison with these other surveys, its lack of observations in the external parts of the clusters is a limiting factor when trying

[1] `https://sites.google.com/site/wingsomegawings/`

[2] WINGS reaches galaxy magnitudes 1.5 deeper than the SDSS.

to perform a complete study of the many phenomena occurring at distances of one virial radius (R_{200}), where it is expected that still gas-rich spiral galaxies are falling onto the clusters. For this purpose, the WINGS observations were extended to cover clusters at least to their virial radius.

This new campaign, known as OmegaWINGS[3] (Gullieuszik et al., 2015), collected both photometric (B and V bands) and spectroscopic data (Moretti et al., 2017) for a subsample of 45 galaxy clusters selected from the original WINGS sample, using OmegaCAM at the 2.6 m VLT Survey Telescope (VST), placed at Cerro Paranal, Chile. With a field of 1 deg^2, the camera covered up to at least $1R_{200}$; it confirmed cluster membership for 7497 galaxies, thus doubling the number of cluster members in WINGS. Therefore, OmegaWINGS is the first one of its kind, reaching a higher dynamic range of galaxy magnitudes and masses at the WINGS redshifts.

In order to compare our results for local clusters with higher redshift clusters, addressing in this way the issue of evolution in the cluster environment, we will use the ESO Distant Cluster Survey[4] (EDisCS; White et al., 2005). This survey shares many of the WINGS and OmegaWINGS features but for higher redshifts, from 0.4 to almost 1.0 (more than half of the universe age). The sample is composed of the most luminous objects in the Las Campanas Cluster Survey. The program was carried out using FORS2 at the Very Large Telescope (VLT) for 20 galaxy clusters, with the B, V, and I filters. Redshifts and memberships have been determined for the galaxies of the 20 clusters (Halliday et al., 2004; Milvang-Jensen et al., 2008), although, for the time being, galaxy morphology is only known for 10 clusters (Desai et al., 2007).

In addition, we will use the MORPHS[5] dataset. The spectroscopic sample of MORPHS (Dressler et al., 1999) consists of 10 clusters spanning a redshift range $z = 0.37 - 0.56$, with 424 cluster members and other 233 field galaxies. For all of them several properties have been published: redshifts and spectral line strengths (Dressler et al., 1999), and photometry and morphology for 204 of the cluster galaxies and 71 in the field (Smail et al., 1997), from imaging with the WFPC2 (Wide Field and Planetary Camera 2) on the HST. The MORPHS spectroscopic campaign combines data taken with the 5.1 m P200/COSMIC (Hale Telescope) at the Palomar Observatory, the 4.2 m WHT/LDSS-2 (William Herschel Telescope) at La Palma, and the 3.5 m NTT/EMMI (New Technology Telescope) at La Silla Observatory.

To complete our study of galaxy evolution in clusters, we plan to use the Padova-Millennium Galaxy and Group Catalogue (PM2GC; Calvi et al., 2011). This is representative of a general population of field galaxies in the local universe ($0.04 \leq z \leq 0.1$). The complete sample of PM2GC consists of 3210 galaxies brighter than $M_B = -18.7$, selected from the Millennium Galaxy Catalogue (MGC; Liske et al., 2003). Calvi et al. (2011) used a Friends-of-Friends (FoF) algorithm to identify galaxy groups, from single, pairs, triplets, and larger groups. This provides a valuable database to study the environmental influence on galaxy properties. The authors have also determined the stellar

[3] `https://sites.google.com/site/wingsomegawings/omega-wings`

[4] `https://wwwmpa.mpa-garching.mpg.de/galform/ediscs/`

[5] `http://star-www.dur.ac.uk/~irs/morphs.html`

mass, morphology, surface brightness parameters, star formation history, and local density for all the galaxy sample.

4 Methodology

In this project, we propose to study the properties of galaxies in clusters and the processes playing a role in galaxy evolution through the cosmic time. In this regard, we will use several physical properties of the galaxies and clusters which we count on, such as:

- Morphology
- Local density
- Projected radial distance
- Phase space diagram
- Absolute magnitude
- Spectral class
- Cluster mass

In order to determine the stellar population properties, we will use the SINOPSIS code with which we can calculate other essential physical properties for all the galaxies in the databases:

- Stellar mass
- Star formation rates

Thus, we will study the stellar populations as a function of galaxy morphology, environment (local and global), and other properties.

SINOPSIS[6] (SImulatiNg OPtical Spectra wIth Stellar population models) is a spectrophotometric fitting code described by Fritz et al. (2007, 2011). SINOPSIS reproduces the main spectral features of observed spectra of galaxies in the optical, assuming the theoretical spectra of simple stellar populations of different ages. To run the code, we only need the spectrum of the galaxy, the redshift, and the magnitude. The outputs are several physical parameters, including the stellar mass, star formation rate in given age bins, metallicity, dust extinction, and the average age of the galaxy stellar populations, with the corresponding errors.

It is important to mention that we have access to the full databases. The WINGS and EDisCS datasets have been made public, while the OmegaWINGS dataset is in the process to be published. In addition, the MORPHS and PM2GC databases are also public. As an example, in Figure 1 we display the absolute B magnitude and redshift ranges of the S0 galaxies present in the WINGS and OmegaWINGS datasets, which is the galaxy sample to be used in the first project of this work. We also show, in Figure 2, the fraction of S0s with respect to the total number of galaxies per cluster as a function of global properties of the clusters, such as the X-ray luminosity and velocity dispersion. It is worth mentioning that we already ran the code on the S0 member galaxies in the samples of WINGS, OmegaWINGS, and EDisCS.

[6] `http://www.irya.unam.mx/gente/j.fritz/JFhp/SINOPSIS.html`

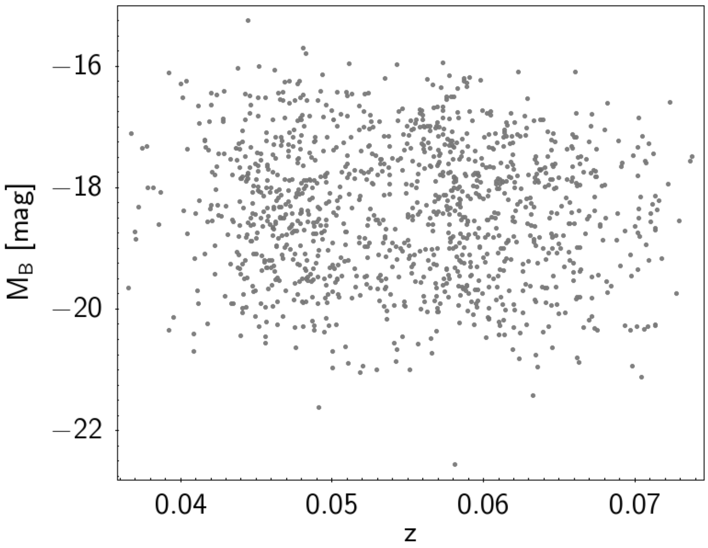

Figure 1: Distribution of absolute magnitude in the B band as a function of redshift for the S0 member galaxies in the WINGS and OmegaWINGS cluster sample.

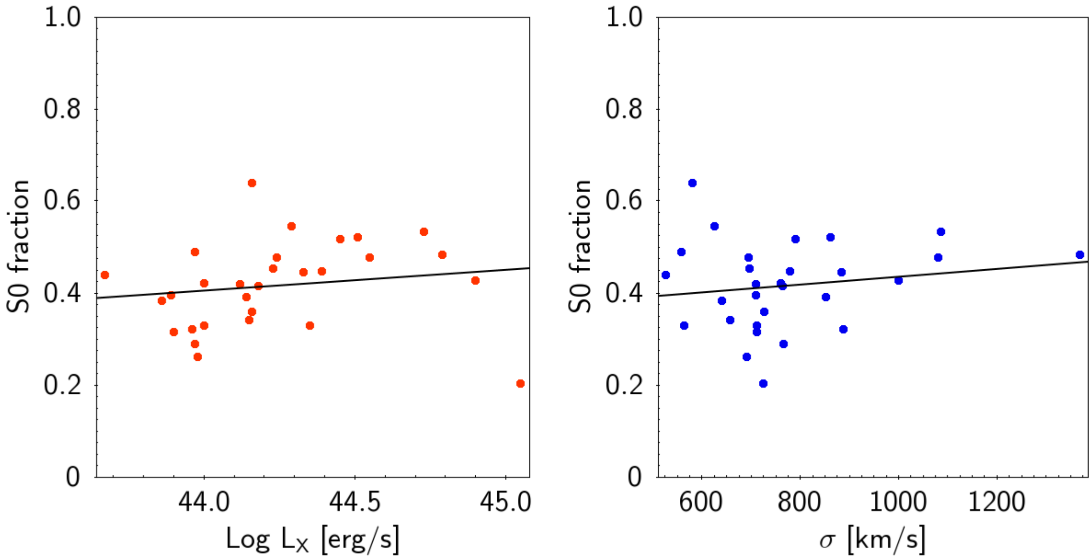

Figure 2: Fraction of S0 galaxies within $0.6R_{200}$ for 29 clusters in the WINGS dataset, as a function of X-ray luminosity (left panel) and dispersion velocity (right panel) of the cluster. The black lines show the least-square fit.

5 Tentative table of contents

The thesis is planned to have the following chapters:

1. Introduction

   1.1 What are S0 galaxies, formation and evolution processes

   1.2 Simulations to understand formation of S0s

   1.3 Star formation history in galaxies

   1.4 Stellar population properties: the global and local environment

2. Observational data

   2.1 Description of WINGS and OmegaWINGS datasets (aim, data, survey, instruments)

   2.2 Spectra and general information (list of clusters and properties)

   2.3 High redshift: EDisCS and MORPHS (aim, data, survey, instruments)

   2.4 Magnitude and radial completeness

   2.5 The low-density environment data: the PM2GC catalog

3. Physical properties description

   3.1 SINOPSIS code (physical parameters, setup, outcomes)

   3.2 Morphologies

   3.3 Local densities

   3.4 Projected distances

   3.5 Definition of substructures

4. Formation and evolution of S0 galaxies in clusters

5. Star formation histories of cluster galaxies: the role of the global and local environments

6. Galaxy evolution as a function of the environment: clues from the stellar population analysis

7. Summary and conclusions: the big picture of galaxy evolution in the low vs high-density environment frame

   Appendix: Catalogs of physical properties for galaxies used in this thesis

   Bibliography

6 Timetable

The principal activities planned to be realized during these eight semesters are listed below:

Semester	Academic activities	Practical activities
1	☑ Reading of bibliography ☑ Selection of the sample (morphology, membership, spectrum)	☑ Installation and test of the SINOPSIS code ☑ Running the code for S0s of WINGS, OmegaWINGS, and EDisCS
2	☐ Study and analysis of the physical features obtained with SINOPSIS for WINGS, OmegaWINGS, and EDisCS. ☐ Reading of bibliography ☐ First article writing	☐ Presentation of my Master's degree thesis in LARIM 2019, Antofagasta, Chile ☐ Workshop: Extragalactic Spectroscopic Surveys (GALSPEC 2019), Santiago, Chile
3	☐ Retrieving of physical properties in the datasets ☐ Revision and sending of the first article	☐ Application exam presentation
4	☐ Second article writing ☐ Reading of bibliography	☐ Running SINOPSIS for all the galaxies in the datasets
5	☐ Second article writing ☐	☐ Participating in an international school
6	☐ Revision and sending of the second article ☐ Third article writing	☐
7	☐ Third article writing ☐ Thesis writing	☐ Participating in an international congress
8	☐ Revision of the thesis ☐ Defense of thesis	☐ Postdoc application

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