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BLUE early type galaxies in the Fornax cluster

identified and studied using the S-PLUS filter system

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Abstract. In the context of the S-PLUS Fornax Project (S+FP), we recover a population of blue elliptical galaxies in the Fornax cluster, making use of S-PLUS multi-wavelengths data. From the colour magnitude diagram we selected blue objects and visually inspect the correspondent gri images obtained using Legacy data. Studying morphological parameters of these galaxies we find that some of them might be merger remnants. We recover the galaxies star formation histories using Alstar and the S-pectrum. We study the relation between infalling time and the last star formation episode in the blue E.

Resumo. No contexto do Projeto S-PLUS Fornax (S+FP), recuperamos uma população de galáxias elípticas azuis no aglomerado Fornax, fazendo uso de dados de múltiplos comprimentos de onda S-PLUS. A partir do diagrama de magnitude-cores, selecionamos objetos azuis e inspecionamos visualmente as imagens gri correspondentes obtidas usando dados do levantamento Legacy Survey. Estudando os parâmetros morfológicos dessas galáxias, descobrimos que algumas delas podem ser remanescentes de fusões. Recuperamos as histórias de formação estelar das galáxias usando Alstar e o S-espectro. Estudamos a relação entre o tempo de queda no aglomerado e o último episódio de formação estelar no azul E.

Keywords. surveys — methods: observational — galaxies: clusters: individual (Fornax) — galaxies: elliptical and lenticular, cD

1. Introduction

Elliptical galaxies (Es) present a smooth ellipsoidal morphology, reflecting the random and often very elongated orbits of their constituent stars. Generally, Es live in the densest regions of the Universe (Dressler 1980), i.e. in the centre of clusters and groups, and are characterised by an old stellar population, rendering their integrated colour red. With the advent of large scale surveys (SDSS; York et al. 2000), blue Es have been discovered and studied (Strateva et al. 2001; Dhiwar et al. 2022). They are, indeed, a precious piece to compose the puzzle of galaxy formation and evolution, since might be the result of recent star formation, induced either from the environment the galaxy lives in, or accretion. In this context, blue Es act as a tracer of the mass build-up of galaxy clusters and possibly filamentary structures of the cosmic web (Kuchner et al. 2020). The number of blue Es increases with decreasing redshift, while the number density of the red sequence galaxies is also enhancing (Bundy et al. 2005). It implies that blue rest-frame colours can be the result of minor events of star formation (Gebhardt et al. 2003). Blue Es are generally found in low density environments and present stellar masses $\simeq$ 9.6 $M_{\odot}$ (Bamford et al. 2009). Of particular interest is, therefore, studying their location in galaxy clusters. In this work we study a sample of blue Es in the Fornax Cluster, using SPLUS data(Mendes de Oliveira et al. 2019; Smith Castelli et al. 2022).

Figure 1. Examples of selected blue Elliptical galaxies, from the LEGACY survey (top row) and the S-PLUS survey (bottom row), respectively.

2. Data

The S-PLUS Fornax Project (S+FP) aims at studying the Fornax galaxy cluster using the images and catalogs provided by the

Southern Photometric Local Universe Survey (S-PLUS; Mendes de Oliveira et al. (2019)). The S+FP data consist of wide field (1.4×1.4 deg^2) images obtained in 12 photometric (7 narrow- and 5 broad-) bands of 35 pointings covering ∼2.5 Rvir of the cluster (Rvir∼0.7 Mpc∼2 deg) and 63 additional frames covering Fornax outskirts. In addition, we have homogeneous photometry of resolved and unresolved sources located in those 98 S+FP fields from the iDR4 of S-PLUS, as well as additional photometry from two SExtractor runs aimed at recovering bright and faint galaxies not detected in the iDR4 (see Haack et al. in prep.). From the literature, we also compiled a list of ∼900 galaxies reported as spectroscopically confirmed (∼20%) or likely Fornax members (∼80%), all of which are located in the S+FP fields.

3. Method

In the context of the S+FP, we used a colour-magnitude diagram built from S-PLUS photometry to identify blue Es. The absolute magnitudes, Mr, are obtained using standard cosmological parameters and the luminosity distances (DL), estimated from the spectroscopic redshifts. The colours are corrected for extinction. The best-fit line used to separate objects belonging to the blue cloud is taken from Dhiwar et al. (2022). Then, we visually inspected all the selected objects creating gri colour images from the DESI Legacy Imaging Surveys, which is ≃ 4 magnitudes deeper than S-PLUS. We selected objects having smooth spheroidal shapes. Some examples are shown in Fig. 1.

Moreover, we obtained morfometric parameters of r-band Legacy images for the whole sample, using the Morfometrika (MFMTK) software (Ferrari et al. 2015a). MFMTK is an algorithm designed and developed to perform structural, photometric and morphometric measurements on galaxy images (Ferrari et al. 2015b). The program estimates, among other quantities, single Sérsic 1D and 2D fit parameters and non-parametric morphometric parameters like concentration (C1, C2), asymmetry, M20, entropy (H - a measure of the clumpiness of the light in the image). Detailed explanation of the parameters can be found in Ferrari et al. (2015a).

4. Results and Future Steps

We studied the relation between galaxy morphological visual classification and the morfometric parameters. For example, Fig. 2 shows the location of galaxies in the Concentration versus Entropy diagram, colour coded according to their (u-r) colour. Elliptical galaxies tend to be more concentrated and smooth (low values of H), while spiral galaxies are less concentrated (they have a disk) and present spiral arms and bars (high values of H). Interestingly, the (u-r) colours follow this trend, smoothly degrading from red to green/blue going from objects with high concentration and low entropy to objects with low concentration and high entropy. Blue Es galaxies are shown as blue points. The majority of the blue Es populate the part of the diagram of intermediate early-type galaxies. Some of them are classified as disks and four lie in a region of avoidance of the plot, probably being merger remnants.

Then we calculated the star formation histories of the galaxies using the code Alstar (private communication). The top panel of Fig. 3 shows the 12-band S-PLUS photometric spectrum (hereafter, S-pectrum) of FCC 76 (black crosses) and the AlStar fit (red line). The magenta line shows the the best fit model spectrum in high resolution. A linear combination of stellar populations of 9 ages (0 < t < 14 Gyr) and 5 metalicities (from 1/3 to 3 solar) is used to model the non-parametric star formation history (SFH), including emission lines in the fit. In the

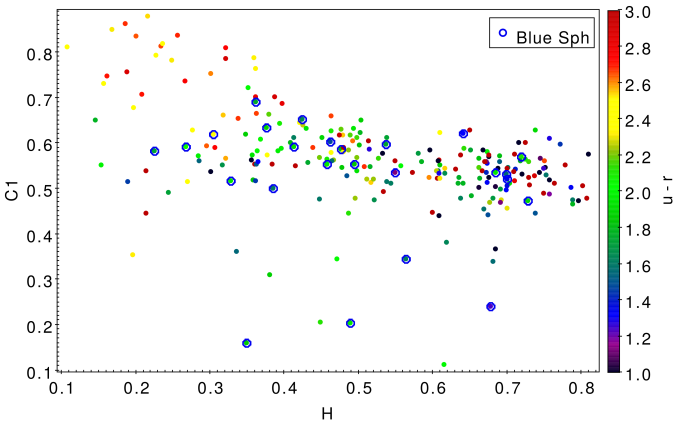

Figure 2. Concentration vs Entropy plot. Galaxies with different morphologies occupy different areas of the plot Ferrari et al. (2015a). Early type galaxies occupy the top-left part of the plot and disk galaxies lie on the bottom right. Objects are colour coded according to their (u-r) colours. Symbol codes are as in the legend. Blue Es seem to be composed by different types of galaxies.

bottom panel of Fig. 3 is shown the non-parametric SFH of FCC 76 as cumulative flux (blue) and mass (red) curves, ranging from 0 at t = 0 to 1 at t = 14 Gyr ago. The blue and red shaded areas represent ranges of possible solutions, as obtained from Monte Carlo runs. The dashed lines indicate the best fit to the observed data, while the dotted ones trace the mean solution of the simulated spectra. A last episode of star formation happened $10^{7.5}$ yrs ago. Most of the stellar mass in FCC 76 is older than $10^{9.5}$ yrs, yet a fraction of stellar mass reside in younger populations contributing to 25% in light. Emission lines are evident, in particular the H_α line. FCC 76 lies outside the cluster virial radius ($R_{vir} \simeq 0.7$ Mpc), within the in-falling region (Rhee et al. 2017), suggesting that the star formation could have been triggered by the interaction with the hot intracluster medium, at the moment of the galaxy infall. For other six blue E we obtained reliable fit with Alstar. The low rate of success is due to the large error bars on the narrow-band integrated magnitudes. In total, four of the blue E galaxies present clear H_α emission both in the S-pectrum as well as in the H_α colour images, see Fig. 4 as an example. All these galaxies are in the in-falling region of the cluster and some present spiral like features in the H_α map, suggesting they might be faded spiral galaxies. We are now improving the photometry for the objects with large errorbars, in order to extend the analysis to the whole sample of blue E.

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The authors made use and acknowledge TOPCAT[1] (**?**) tool to analyse the data.

[1] `http://www.starlink.ac.uk/topcat/(TOPCAT)`

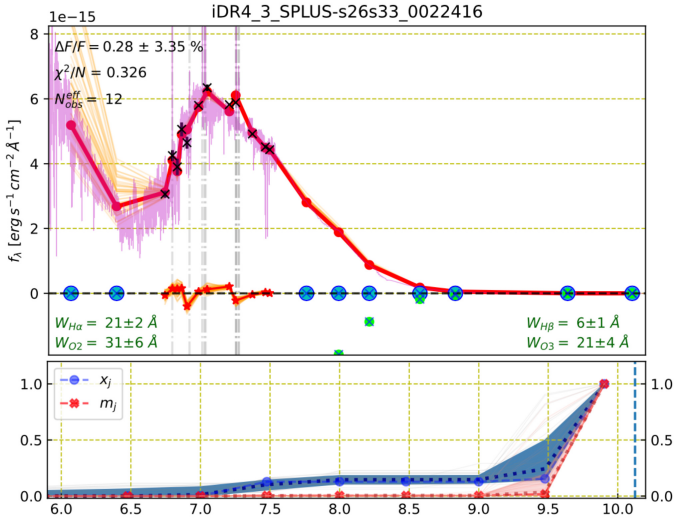

Figure 3. Top panel: Example of spectral fitting with AlStar. The fit was performed on the S-pectrum of FCC 76. Bottom panel: The non-parametric SFH of FCC 76 is shown.

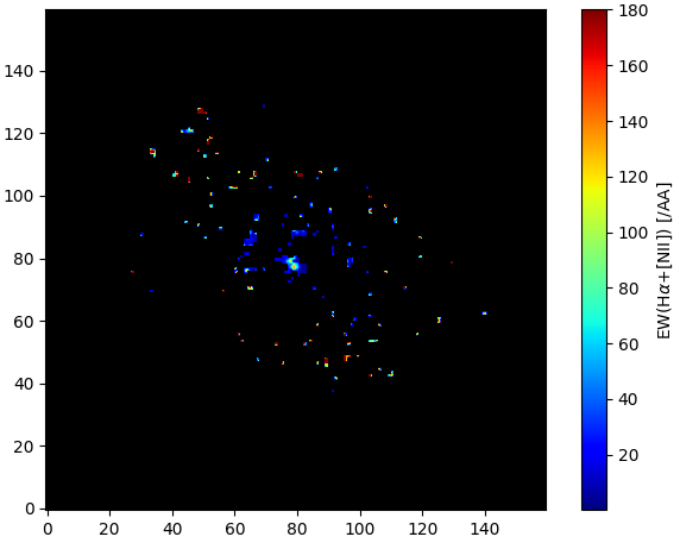

Figure 4. H_α map of FCC 76, see Lopes et al. in prep.

The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; Proposal ID #2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Prop. ID #2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall z-band Legacy Survey (MzLS; Prop. ID #2016A-0453; PI: Arjun Dey).

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