Synthetic S-PLUS photometry of simulated galaxies in Fornax-like clusters

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Resumen / El proyecto Fornax de la colaboración S-PLUS (S+FP, por sus siglas en inglés) apunta a estudiar el cúmulo de galaxias de Fornax utilizando datos fotométricos en 12 bandas ópticas. Como parte de dicho proyecto, en este trabajo se presentan los primeros pasos hacia una comparación exhaustiva entre las propiedades de cúmulos de galaxias simulados y las propiedades observadas del cúmulo de Fornax. Nuestro objetivo final es proponer posibles escenarios de formación para dicho cúmulo. Específicamente, presentamos el análisis de candidatos similares a Fornax, extraídos de simulaciones numéricas cosmológicas de vanguardia (e.g. simulaciones ILLUSTRIS-TNG y EAGLE), seleccionándolos a partir de características observadas del cúmulo de Fornax. Calculamos las distribuciones espectrales de energía de las galaxias en nuestros cúmulos simulados, usándolas para estimar parámetros fotométricos que pueden ser comparados directamente con observaciones en las 12 bandas ópticas de S-PLUS. También, generamos cubos de datos con brillos superficiales en esas bandas, junto con imágenes sintéticas de las galaxias simuladas, con el fin de llevar a cabo una comparación inicial con galaxias de Fornax.

Abstract / The S-PLUS Fornax project (S+FP) aims at studying the Fornax galaxy cluster using photometric data in 12 optical bands. As a part of that project, this work presents the first steps towards a comprehensive comparison between the properties of simulated galaxy clusters and the observed characteristics of Fornax. Our final goal is proposing possible formation scenarios for the Fornax cluster. Specifically, we present the analysis of Fornax-like candidates extracted from state-of-the-art cosmological numerical simulations (e.g. ILLUSTRIS-TNG and EAGLE simulations), selecting them according to observed features in the Fornax cluster. The spectral energy distribution of galaxies in our simulated clusters were computed and used to estimate photometric parameters that can be directly compared with observations in the 12 optical bands of S-PLUS. Also, data cubes with surface brightnesses in those bands and synthetic images of the simulated galaxies were generated, in order to carry out an initial comparison with Fornax galaxies.

Keywords / galaxies: elliptical and lenticular, cD — galaxies: evolution — cosmology: theory — surveys — galaxies: clusters: individual (Fornax)

1. Introduction

The Southern Photometric Local Universe Survey (S-PLUS, Mendes de Oliveira et al., 2019) is an imaging survey that maps roughly 9300 deg^2 of the southern sky, using the 0.8 m T80-South robotic telescope, located at Cerro Tololo (Chile). The main goal of S-PLUS is to provide detailed multi-wavelength spectrophotometric catalogues of the southern hemisphere. In order to achieve this, the telescope is equipped with a 1.4×1.4 deg^2 field-of-view camera, and 12 photometric filters (5 broad-band filters corresponding to the SDSS system, and 7 narrow-band filters to trace specific spectral features). Detailed information about the covered area of S-PLUS, its camera and its filter system, can be found in Mendes de Oliveira et al. (2019).

The S-PLUS Fornax Project (hereafter, S+FP) aims at extensively studying the Fornax cluster of galaxies, analysing 23 S-PLUS fields (9 fields in the central region of the Fornax cluster, and 14 additional surrounding fields), covering a total sky area of $\approx 11 \times 7$ deg^2. The objectives of the S+FP include to perform the homogeneous photometry of Fornax galaxies in 12 optical bands, the identification of low surface brightness and dwarf galaxies in the cluster, and the study of bright and compact objects in it, among others. Complete details about this project and its goals are described in Smith Castelli et al. (2021) and will be further amplified in Smith Castelli et al. (in prep.).

To analyse possible formation and evolution paths of Fornax cluster and its galaxies, in the framework of the S+FP, we carried out the identification of Fornax-like clusters in the ILLUSTRIS-TNG and EAGLE cosmological numerical simulations, based on some observed properties of Fornax. In this work, we show some preliminary results regarding our simulated sample, estimating some properties of simulated galaxies that can be comprehensively compared with observed quantities from S-PLUS.

Oral contribution

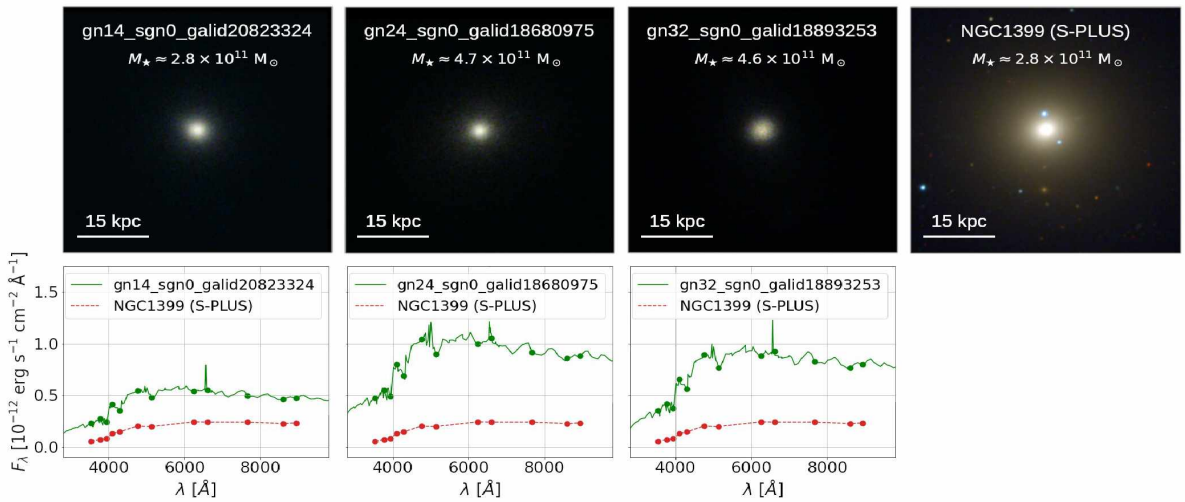

Figure 1: Mock images (*top panels*) and spectral energy distributions (*bottom panels*) of three central galaxies of simulated Fornax-like clusters (green solid lines), extracted from EAGLE RefL0100N1504 simulation. For comparison, the upper right panel shows an image of NGC 1399, generated with the 12 S-PLUS filters. The dashed red line spectrum in the lower panels represents the observed SED of NGC 1399. Circles in the spectra indicate the flux values in the S-PLUS bands.

2. Sample of simulated Fornax-like clusters

We selected simulated samples of galaxy clusters from the ILLUSTRIS-TNG (e.g. Springel et al., 2018; Nelson et al., 2018) and EAGLE (e.g. Schaye et al., 2015; Crain et al., 2015) public cosmological hydrodynamical numerical simulations. In both suites, the main physical processes involved in galaxy formation and evolution (e.g. chemical enrichment, star formation, radiative cooling, and active galactic nuclei and supernovae feedbacks) are taken into account, following the merger histories of dark matter and baryonic structures in a ΛCDM cosmology with parameters taken from the Planck Collaboration (2015), briefly $h = 0.677$, $\Omega_\Lambda = 0.693$, $\Omega_\mathrm{m} = 0.307$, and $\Omega_\mathrm{b} = 0.04825$, and $Y = 0.248$. We remit the reader to the corresponding data releases for full details of each simulation and physics implementation. In this work, we extracted haloes and subhaloes (i.e., clusters and their galaxies) from the ILLUSTRIS-TNG TNG100-1 and the EAGLE RefL0100N1504 models, which have similar box size ($L \approx 100$ comoving Mpc) and mass resolution (gas and dark matter particle masses of $m_\mathrm{gas} \approx 10^6$ M$_\odot$ and $m_\mathrm{DM} \approx 8 \times 10^6$ M$_\odot$, respectively).

As a first sample of simulated clusters, we selected systems at redshift $z = 0$ with a central galaxy of stellar mass 1×10^{11} M$_\odot$ $\leqslant M_\star \leqslant$ 5×10^{11} M$_\odot$, based on the estimated stellar mass of NGC 1399, the central galaxy of Fornax cluster ($M_{\star,\mathrm{NGC1399}} \approx 2.8 \times 10^{11}$ M$_\odot$, Iodice et al., 2019). We also considered a virial mass M_vir and a virial radius R_vir in the ranges 10^{13} M$_\odot \leqslant M_\mathrm{vir} \leqslant 10^{14}$ M$_\odot$ and 0.6 Mpc $\leqslant R_\mathrm{vir} \leqslant$ 0.8 Mpc, respectively, taking into account the estimated values for the Fornax cluster ($M_\mathrm{vir} \approx 6 \times 10^{13}$ M$_\odot$ and $R_\mathrm{vir} \approx$ 0.7 Mpc, Maddox et al., 2019). With our selection criteria, we obtained 43 simulated clusters from EAGLE RefL0100N1504 and 19 from ILLUSTRIS-TNG TNG100-1 simulations, respectively. It is worth noting that, to avoid resolution issues, our simulated clusters consist of galaxies with $M_\star \gtrsim 3 \times 10^8$ M$_\odot$. In this work, only results from EAGLE simulation are shown. Results from ILLUSTRIS-TNG will be presented in a future work.

3. Simulated spectra and mock images

We used the SKIRT radiative transfer code (Camps & Baes, 2020) to generate spectra, data cubes and mock images of the galaxies in our sample of Fornax-like clusters. We followed a similar approach to that implemented by Trayford et al. (2017) and Rodriguez-Gomez et al. (2019) for EAGLE and ILLUSTRIS-TNG galaxies, respectively. In short, we consider stellar sources* in the simulations within a 50 kpc sphere centred in the minimum of potential of a given galaxy. We divided the stellar sources according to their age t in old ($t > 100$ Myr) and young ($t \leqslant 100$ Myr) SSPs. Old SSPs are assigned GALAXEV (Bruzual & Charlot, 2003) spectral energy distributions with a Chabrier (2003) initial mass function, while young SSPs are assigned MAPPINGS-III (Groves et al., 2008) spectral models**.

The simulated spectra were constructed with a grid of 333 wavelengths between 0.1 and 2.5 μm (see Trayford et al., 2017 for details), which includes the effective wavelengths of S-PLUS filters. In order to obtain data cubes and mock images with the same image scale as S-PLUS (0.55 arcsec pixel^{-1}), we assume that our simulated galaxies are located at 20.9 Mpc from the observer (the estimated distance to the Fornax cluster, Iodice et al., 2019), and adjust the field of view and number of pixels of the instruments simulated by SKIRT

*In both EAGLE and ILLUSTRIS-TNG simulations, a stellar source or, equivalently, a star particle, represents a simple stellar population (SSP), not an individual star.

**We use GALAXEV models for old SSPs because these are widely used, and fit the local galaxy population in the optical bands with reasonable star formation and enrichment histories. On the other hand, the MAPPINGS-III models track young stars and include dust absorption within the star-forming cloud that hosts these young populations.

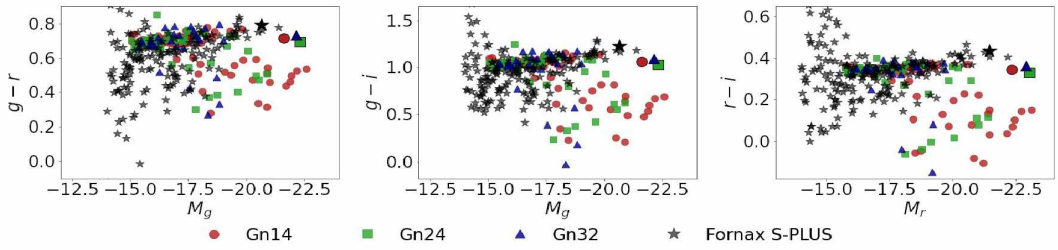

Figure 2: Colour-magnitude diagrams of three simulated Fornax-like clusters, extracted from EAGLE RefL0100N1504 simulation. Each symbol corresponds to a given simulated cluster. For comparison, star symbols correspond to galaxies reported in the literature as spectroscopically confirmed or likely members of the Fornax cluster, observed with S-PLUS (Smith Castelli et al. in prep.). Only those observed galaxies with magnitudes $M_r < -15$ and $M_g < -15$ are plotted, to compare magnitudes in the range of simulated quantities. Larger symbols represent the central galaxy of the corresponding cluster.

accordingly, using a cubic box of 100 Mpc to enclose the simulated stellar sources. We used the 12 S-PLUS bands as the wavelength grid to generate our data cubes.

As examples of mock images and simulated spectra, in Fig. 1, we show RGB images of the central galaxies of three simulated Fornax-like clusters (top panels), with their corresponding spectral energy distributions (SEDs, bottom panels), extracted from the EAGLE RefL0100N1504 simulation. These central galaxies exhibit similar morphologies to NGC 1399: they have spheroidal shapes, without evidence of spiral arms or other kind of structure. With respect to the SEDs of these galaxies, the fluxes are quite higher than those observed in NGC 1399, but the shape of the simulated spectra are consistent with observations from S-PLUS.

4. Simulated magnitudes and colours

Using the simulated spectra and the transmission curves of the S-PLUS filters, we calculated the magnitudes of all the galaxies in our simulated Fornax-like clusters, in the 12 S-PLUS bands. In Fig. 2 we show some colour-magnitude diagrams for three of our selected Fornax-like candidates, extracted from EAGLE RefL0100N1504 simulation. As can be seen, our simulated magnitudes and colours are consistent with the S-PLUS observations of the Fornax cluster. Also, the so-called red sequence of galaxies, a typical feature in colour-magnitude diagrams of galaxy clusters, is clearly defined in the simulations.

5. Summary and work in progress

As a part of the S+FP, we selected Fornax-like galaxy clusters from state-of-the-art cosmological hydrodynamical simulations, based on observed properties of the Fornax cluster. We computed the SEDs of galaxies in our simulated clusters with the SKIRT code, using them to estimate magnitudes in the 12 S-PLUS photometric bands. Our preliminary estimates of spectra, magnitudes and colours are consistent with those from S-PLUS, and broadly consistent with what is expected from observations of galaxies in clusters. Data cubes of our simulated galaxies were also generated with SKIRT, using the 12 S-PLUS bands, aiming at a comprehensive comparison with S-PLUS observations.

We are currently revising our selection criteria of simulated Fornax-like candidates, to retrieve the most similar systems to the Fornax cluster. Also, variations of our first implementations of SKIRT runs are being tested, in order to achieve a better comparison with S-PLUS observations. This will be followed by a robust statistical analysis of simulated spectra/magnitudes and physical properties of simulated cluster galaxies (such as masses, stellar ages and metallicities), and the post-processing of simulated images (e.g. their convolution with a point spread function and the addition of instrumental and background noises, consistent with those in S-PLUS images) to estimate their structural parameters (ellipticities, orientations, radii, etc), which will be thoroughly compared with results derived from S-PLUS. The last step of this contribution to the S+FP is the study of formation histories of simulated Fornax-like clusters, aiming at proposing possible formation and evolution scenarios for the Fornax cluster.

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