Analysis of Fornax-like clusters in numerical simulations and its comparison with Fornax cluster data obtained with S-PLUS

L.J. Zenocratti[1,2], A.V. Smith Castelli[1,2], M.E. De Rossi[3,4] & F.R. Faifer[1,2]

[1] *Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Argentina*
[2] *Instituto de Astrofísica de La Plata, CONICET–UNLP, Argentina*
[3] *Instituto de Astronomía y Física del Espacio, CONICET–UBA, Argentina*
[4] *Facultad de Ciencias Exactas y Naturales, UBA, Argentina*

Contact / ljzenocratti@gmail.com

Resumen / A partir de datos fotométricos en 12 bandas ópticas obtenidos dentro de la colaboración S-PLUS, y con el objetivo de estudiar detalladamente el cúmulo de galaxias de Fornax, en dicha colaboración se definió el proyecto Fornax (S+FP). En el marco de dicho proyecto, y como continuación de un trabajo previo, analizamos candidatos a cúmulos simulados similares a Fornax, extraídos de las simulaciones numéricas cosmológicas EAGLE (modelo RefL0100N1504) e ILLUSTRIS-TNG (modelos TNG100-1 y TNG300-1), seleccionándolos a partir de características observadas en el cúmulo de Fornax. En esta contribución, presentamos la comparación entre las características principales de los cúmulos simulados seleccionados y aquellas observadas en Fornax, con mejoras tanto en nuestros criterios de selección de cúmulos simulados, como así también en la implementación del código usado para generar cantidades simuladas directamente comparables con las observaciones. Entre otras propiedades, se pretende comparar las morfologías de las galaxias simuladas pertenecientes a los cúmulos simulados con aquellas exhibidas por las galaxias en Fornax.

Abstract / Using photometric data in 12 optical bands obtained within the S-PLUS collaboration, and with the goal of studying in detail the Fornax cluster of galaxies, the Fornax project (S+FP) was defined in that collaboration. In the framework of this project, and as a continuation of a previous work, we analyze Fornax-like candidates extracted from the EAGLE (RefL0100N1504 model) and the ILLUSTRIS-TNG (TNG100-1 and TNG300-1 models) cosmological numerical simulations, selecting them according to observed features in the Fornax cluster. In this contribution, we present the comparison between the main characteristics of the selected clusters and those observed in Fornax, with improvements in both our simulated clusters selection criteria, and in the implementation of the code we use to generate simulated quantities that can be directly compared with observations. Among other properties, we plan to compare the morphologies of the simulated galaxies in the selected clusters with those displayed by the galaxies in Fornax.

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) aims at providing detailed spetrophotometric catalogues of the southern hemisphere, mapping $\sim$ 9300 deg^2 of the southern sky. This is achieved by using the 0.8 m T80-South robotic telescope (Cerro Tololo, Chile), equipped with a 1.4×1.4 deg^2 FoV camera, and a system of 12 photometric filters. Complete details about the S-PLUS proyect can be found in Mendes de Oliveira et al. (2019). The S-PLUS Fornax project (S+FP, Smith Castelli et al., 2021; Smith Castelli et al., in prep.) aims at extensively studying the Fornax galaxy cluster, using photometric data in the 12 S-PLUS photometric bands, analysing 98 S-PLUS fields that cover the Fornax cluster and its surroundings (a total sky area of $\approx$ 192 deg^2). As a part of that project, and in order to propose possible formation and evolution paths for the Fornax cluster and its galaxies, we identified Fornax-like clusters in cosmological numerical simulations, based on observed properties of Fornax. In this work, we present our selection criteria to identify simulated Fornax-like clusters, and show preliminary results of our study of such systems and its comparison with S-PLUS observations. This work is a continuation of Zenocratti et al. (2022), but here we have improved our selection criteria of simulated Fornax-like clusters, as well as the implementation of the code we use to generate simulated spectra, colours and magnitudes, as detailed in the following Sections.

2. Simulated Fornax-like clusters

We extracted simulated samples of galaxy clusters from the EAGLE (e.g. Schaye et al., 2015; Crain et al., 2015) and the ILLUSTRIS-TNG (e.g. Springel et al., 2018; Nelson et al., 2018) cosmological hydrodynamical numerical simulations. In both suites, the most relevant physical

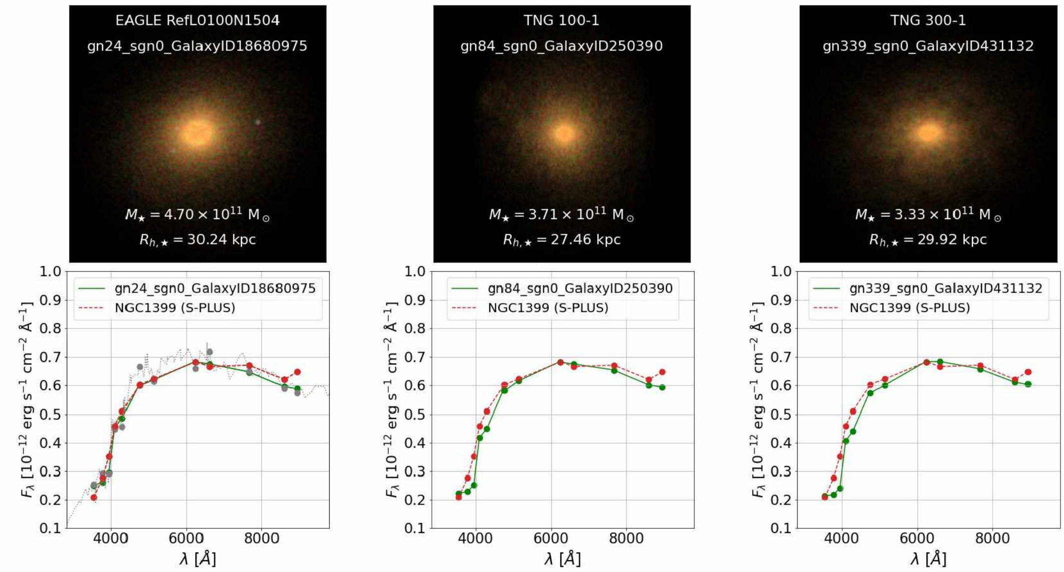

Figure 1: *Top*: mock images of three central galaxies of simulated Fornax-like clusters, extracted from EAGLE RefL0100N1504 (*left*), ILLUSTRIS-TNG TNG100-1 (*middle*), and TNG300-1 simulations (*right*). The galaxy identifier, stellar mass $M_\star$ and stellar half-mass radius $R_{\mathrm{h},\star}$ are listed. Images generated with the composition of gri S-PLUS bands using the scheme of Lupton et al. (2004). *Bottom*: spectral energy distribution of the corresponding galaxies. The solid green line represents the simulated spectrum, while the dashed red line corresponds to the spectrum of NGC 1399 observed with S-PLUS. As a comparison, in the left panel, the dotted grey line shows the simulated SED as estimated by Zenocratti et al. (2022).

processes involved in galaxy formation and evolution are modeled, following the merger histories of dark matter and baryonic structures. The simulations assume a ΛCDM cosmology, with parameters taken from the Planck Collaboration (2015): $h = 0.677$, $\Omega_\Lambda = 0.693$, $\Omega_\mathrm{m} = 0.307$, $\Omega_\mathrm{b} = 0.04825$, and $Y = 0.248$. From EAGLE, we used the reference model RefL0100N1504, while from ILLUSTRIS-TNG, we used the TNG100-1 and TNG300-1 simulations. The EAGLE RefL0100N1504 and ILLUSTRIS-TNG TNG100-1 simulations have box size $L \sim 100$ comoving Mpc and baryonic mass resolution $m_\mathrm{b} \sim 10^6$ M$_\odot$, while the ILLUSTRIS-TNG TNG300-1 has a larger box size ($L \sim 300$ comoving Mpc) but a lower resolution ($m_\mathrm{b} \sim 10^7$ M$_\odot$). Clusters from this simulation were included to extend the simulated sample.

We selected clusters at redshift $z = 0$, with a virial mass 10^{13} M$_\odot \leqslant M_\mathrm{vir} \leqslant 10^{14}$ M$_\odot$ (given that $M_\mathrm{vir,\ Fornax} \approx 6 \times 10^{13}$ M$_\odot$, Maddox et al., 2019). NGC 1399, the central galaxy of the Fornax cluster, has stellar mass $M_{\star,\,\mathrm{NGC\,1399}} \approx 2.8 \times 10^{11}$ M$_\odot$, so we selected clusters in which the stellar mass of the central galaxy is 1×10^{11} M$_\odot \leqslant M_\star \leqslant 5 \times 10^{11}$ M$_\odot$. Moreover, given that NGC 1399 has spherical morphology and half-light radius $R_\mathrm{NGC\,1399} \approx 30$ kpc (see e.g. Iodice et al., 2019), to refine the sample of simulated Fornax-like clusters presented in Zenocratti et al. (2022), we restrict our sample of clusters to those with stellar half-mass radius 20 kpc $\leqslant R_{\mathrm{h},\star} \leqslant$ 40 kpc, and a visually spherical morphology. In this work, we do not impose restrictions to the virial radius of simulated clusters, in contrast with Zenocratti et al. (2022). We obtained 10 simulated Fornax-like clusters from EAGLE RefL0100N1504, 6 clusters from ILLUSTRIS-TNG TNG100-1, and 29 clusters from TNG300-1. Each simulated cluster is identified with an unique number within the simulation ('gn' or 'GroupNumber'), and each galaxy is completely identified with the 'GroupNumber' of the cluster it belongs to, and two additional numbers ('sgn' or 'SubGroupNumber', and 'GalaxyID'). The 'GalaxyID' identifier is unique for each galaxy within the simulation, while 'sgn' can be used to identify central (sgn=0) and satellite (sgn>0) galaxies. To avoid resolution issues, we only consider simulated galaxies with $M_\star \geqslant 10^8$ M$_\odot$.

3. Mock images and simulated spectra

We used the SKIRT code (Camps & Baes, 2020) to generate mock images, spectra, and data cubes of all the galaxies in our sample of Fornax-like clusters. Our implementation of SKIRT is based on that described in Zenocratti et al. (2022), but here, the wavelength grid we use (for both the spectra and the datacubes) includes only the 12 S-PLUS photometric bands with their corresponding transmission curves (an important improvement with respect to the previous work). The obtained spectra and the derived magnitudes and colours (see Sec. 4), can be directly compared with S-PLUS observed data. Mock images were generated with the S-PLUS image scale (0.55 arcsec px^{-1}), using a square FoV of (100 kpc)^2 at the distance of Fornax, and assuming the same distance modulus of Fornax, ($m - M = 31.51$, Iodice et al., 2019). Top panels of Fig. 1 show mock images of the central galaxy for three simulated Fornax-like clusters (one per each simulation used in this work), generated using the gri S-PLUS bands and the scheme of Lupton et al. (2004) with the same stretch and softening parameters in all galaxies. Bottom panels of Fig. 1 show the spectral energy distribution (SED) of the corresponding galaxy, compared to the SED of NGC 1399. The simulated spectra are normalized at $\lambda = 6258$ Å with the corresponding to NGC 1399, and it can be seen that they are consistent with S-PLUS observations.

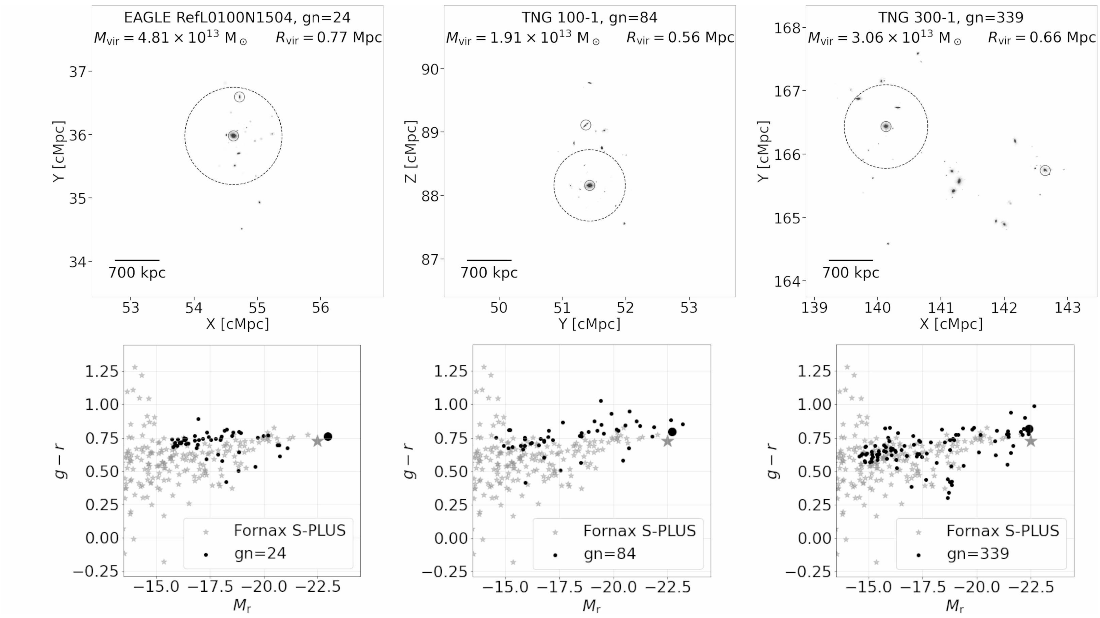

Figure 2: *Top*: schematic view of three simulated Fornax-like clusters, extracted from EAGLE RefL0100N1504 (left), ILLUSTRIS-TNG TNG100-1 (middle) and TNG300-1 (right). Dashed black circles enclose the cluster virial radius, centred in the central galaxy. Solid red circles enclose the central galaxy and the second most massive galaxy in the cluster. The cluster 'GroupNumber', virial mass and virial radius are listed in each panel. *Bottom*: $M_{\rm r}$ vs. $(g-r)$ colour-magnitude diagrams of each simulated cluster. For comparison, grey stars correspond to Fornax galaxies observed with S-PLUS.

4. Spatial distribution and colour-magnitude diagram of simulated galaxies

Using mock images and SEDs generated with SKIRT, we can, respectively, visualize the distribution of galaxies in each Fornax-like cluster, and estimate their magnitudes and colours with the 12 S-PLUS bands. Three of our Fornax-like candidates (one extracted from each simulation used here) and their corresponding $M_{\rm r}$ vs. $(g-r)$ colour-magnitude diagrams (CMDs) are shown in the top and bottom panels of Fig. 2, respectively. The Fornax-like cluster extracted from TNG300-1 (top right panel) looks more similar to the Fornax Cluster, in the sense that there are two main sub-structures: the central region (analogue to the central region of Fornax), and a second region outside the virial radius of the cluster, resembling the surroundings of NGC 1316 (Fornax A; see e.g. Smith Castelli et al., 2021, Fig. 1). With respect to CMDs, the simulated diagrams shown here are consistent with the CMD of Fornax obtained from S-PLUS. Observed colours and magnitudes were extinction- and reddening-corrected, and they were extracted from S-PLUS DR3 catalogues. S-PLUS magnitudes were measured using several apertures, optimised for different applications. Here, we used apertures labelled as 'AUTO', defined in terms of the Kron elliptical aperture to integrate the total flux of extended soruces, being these magnitudes the most appropriate for bright objects (see Almeida-Fernandes et al. 2022 for details).

5. Further work

We are still improving our implementation of the SKIRT code, to obtain simulated magnitudes, colours and mock images as similar as possible to those observed with S-PLUS. With refined simulated images, a morphological analysis (both visual and quantitative) will be carried out, aiming at comparing statistically the population of galaxies in our simulated clusters with those in the Fornax cluster. Physical properties of simulated galaxies in our Fornax-like clusters will be studied and compared exhaustively with those derived from S-PLUS observations. Our final goal is to analyse the assemble history of our simulated clusters, to propose possible formation and evolution scenarios for the Fornax galaxy cluster.

Acknowledgements: We thank Asociación Argentina de Astronomía for allowing us to communicate our results. We acknowledge support from PICT-2015-3125 and PICT 2019-03299 of ANPCyT, PIP 112-201501-00447 of CONICET and G151 of UNLP. We acknowledge the Virgo Consortium for making their EAGLE simulation data available, and the Max Planck Computing and Data Facility for undertaking and making public the ILLUSTRIS-TNG simulations. S-PLUS is an international collaboration founded by Universidade de Sao Paulo, Observatório Nacional, Universidade Federal de Sergipe, Universidad de La Serena and Universidade Federal de Santa Catarina.

References

Almeida-Fernandes F., et al., 2022, MNRAS, 511, 4590
Camps P., Baes M., 2020, Astron. Comput., 31
Crain R.A., et al., 2015, MNRAS, 450, 1937
Iodice E., et al., 2019, A&A, 627, A136
Lupton R., et al., 2004, PASP, 116, 133
Maddox N., et al., 2019, MNRAS, 490, 1666
Mendes de Oliveira C., et al., 2019, MNRAS, 489, 241
Nelson D., et al., 2018, MNRAS, 475, 624
Planck Collaboration, 2015, A&A, 594, A13
Schaye J., et al., 2015, MNRAS, 446, 521
Smith Castelli A.V., et al., 2021, BAAA, 62, 180
Springel V., et al., 2018, MNRAS, 475, 676
Zenocratti L.J., et al., 2022, BAAA, 63, 205