Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 119-120

Effects of the dynamic stage of clusters on the evolution of infalling galaxies

Felipe C. Ribeiro[1], Henri M. P. Plana[1], André L. B. Ribeiro[1], & Paulo A. A. Lopes[2]

[1] Universidade Estadual de Santa Cruz e-mail: felipeacademico20@gmail.com, plana@uesc.br, albr@uesc.br
[2] Universidade Federal do Rio de Janeiro e-mail: plopes@ov.ufrj.br

Abstract. Galaxy clusters are ideal laboratories for studying environmental effects. We investigate how the dynamical state of clusters influences the evolution of galaxies that undergo environmental effects within the intracluster medium during infall.

Resumo. Aglomerados de galáxias são laboratórios ideais para estudar efeitos ambientais. Investigamos como o estado dinâmico dos aglomerados influencia a evolução de galáxias que sofrem efeitos do meio intra-aglomerado durante o infall.

Keywords. galaxies: clusters: general – galaxies: evolution – galaxies: kinematics and dynamics – galaxies: abundances – galaxies: groups – techniques: spectroscopic

1. Introduction

Galaxy clusters are the largest gravitationally bound structures in the Universe, showing different regimes of density and velocity dispersion that strongly influence galaxy evolution. These effects can be investigated through the projected phase-space (PPS) diagram, where distinct regions reflect the dynamical stage and time since galaxy infall. Environmental factors are known to affect morphology, luminosity, star formation, and gas content (Pérez-Millán et al. 2023). In the outskirts of clusters and groups, the main mechanisms are ram pressure stripping, tidal stripping, and galaxy harassment, while internal processes such as supernova winds and AGN feedback also suppress star formation (Dalla Vecchia & Schaye 2008). Since projected distances alone cannot constrain orbital parameters or infall times, phase-space analyses combining cluster-centric distance and velocity relative to the systemic mean enable discrimination: recent infallers typically have higher velocities, while backsplash galaxies, after crossing pericenter, are found at large radii with low velocities (Rhee et al. 2017).

2. The sample

For this work, we used the catalogs of Lopes et al. (2024), which contain data on galaxies belonging to clusters as well as galaxies in infall. The catalogs include 238 galaxy clusters, from which we selected a subset of 153 clusters containing at least 20 galaxies within R_{200}, ensuring robust statistics. The sample consists of galaxies belonging to clusters and galaxies in infalling groups up to $5R_{200}$, in order to include the infall region and possible preprocessing effects.

Stellar mass cuts of $\log M_\star \geq 9.0$ were applied, ensuring better consistency with previous works and physical relevance of the sample. Cluster classification in the Lopes et al. (2024) catalogs was based on the Gaussianity of the velocity distribution and the separation between optical and X-ray centers. We cross-matched the galaxy cluster data provided in the catalogs with the SDSS MaNGA (Mapping Nearby Galaxies at APO - DR17) spectroscopic sample, adopting a search radius of 30 arcsec for coordinate matching. This resulted in a sample of 603 galaxies. The SDSS MaNGA provides a wealth of data that allows us to correlate the positions of galaxies in phase space with internal physical properties and environmental effects.

3. ROGER

The galaxies were analyzed in the Projected Phase-Space Diagram (PPSD; $\Delta v/\sigma$ vs. R/R_{200}), combining data from Lopes et al. (2024) with MaNGA spectroscopy. For dynamical classification, we used the ROGER code (Reconstructing Orbits of Galaxies in Extreme Regions), which employs machine learning methods (KNN, Random Forest, SVM) trained on cosmological simulations such as YZiCS (Han et al. 2018).

ROGER reconstructs orbital histories from cluster-centric distance and peculiar velocity (de los Rios et al. 2021). The code assigns probabilities for each galaxy to five orbital classes: Core Members (CL, satellites for > 2 Gyr); Recent Infallers (RIN, first infall within 2 Gyr); Backsplash (BS, have crossed R_{200} twice); Intermediate Infallers (IN, now falling in for the first time); and Interlopers (ITL, projection contaminants not bound to the cluster). These classes trace different infall times, orbits, and tidal mass loss, allowing us to identify galaxies that recently underwent environmental processing or are about to interact with the cluster core[1]

4. Results

We performed pairwise proportion tests between the different dynamical classes within each metallicity bin to identify statistically significant differences. To define the metallicity bins, we applied a Gaussian Mixture Model (GMM), which identified three statistically robust components (Low, Medium, and High metallicity). In the high-metallicity bin, BS shows significantly higher fractions than CL, IN, and ITL, while other class pairs are mostly nonsignificant.

For the Medium bin, BS again dominates, and several other pairs, such as CL vs ITL and IN vs RIN, also show significant differences. In the Low bin, no pair exhibits statistically significant differences after correcting for multiple tests. These results indicate that class distributions vary with metallicity, suggesting a link between chemical enrichment and the dynamical state of the galaxy. We performed the stellar mass–metallicity relation for the MaNGA galaxy sample. Considering all galaxies, we found a slope of $+0.0445 \pm 0.0062$. For the different dynamical classes, the slope varies from +0.0774 (IN) to nearly zero (BS and CL).

[1] Code and examples available at https://github.com/Martindelosrios/pyROGER.

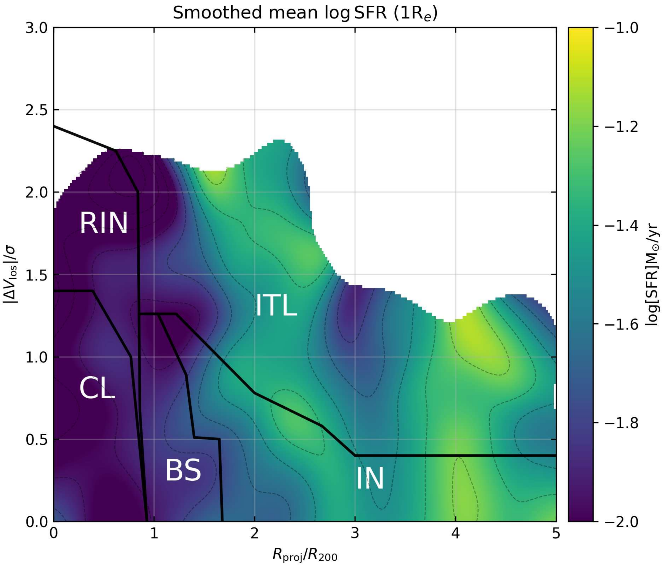

Figure 1. Estimated SFR at $1R_e$ for MaNGA galaxies in PPSD phase space. CL, BS, and RIN regions show lower star formation than IN and ITL regions.

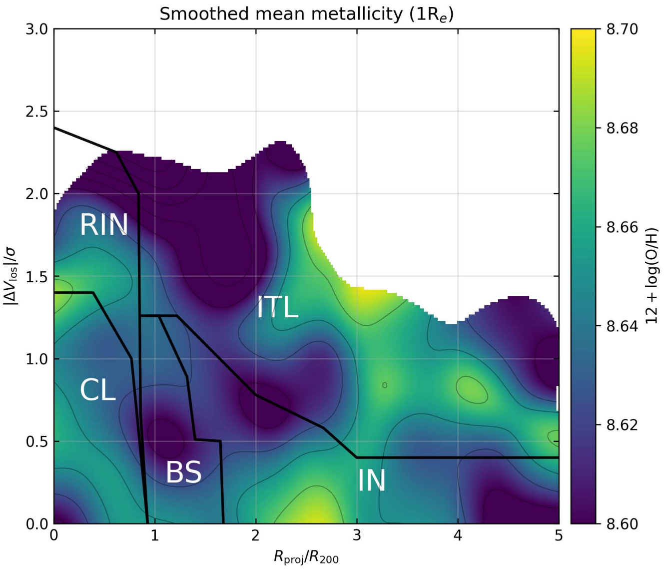

Figure 2. Estimated metallicity at $1R_e$ for MaNGA galaxies in PPSD phase space. Lower metallicity is observed in BS regions and some parts of IN and ITL.

This variation is significant within the observed dispersion, although the slope for BS and CL has low statistical significance. Overall, Fig.1 shows that star formation tends to increase with projected radius, from log(SFR) = −2 to −1 $M_\odot$/yr. Fig. 2 indicates that metallicity variations correlate with the dynamical class, highlighting regions with lower chemical enrichment. We then tested these bins using a Generalized Linear Model (GLM), confirming that they reflect significant differences in the distribution of dynamical classes. This approach ensures that the subsequent analysis of class fractions across metallicity bins is statistically consistent and does not depend on arbitrary binning choices.

Our study shows that the dynamic stage of galaxies within clusters critically influences their evolution, with galaxies undergoing prolonged or intense interaction with the core (CL, BS,

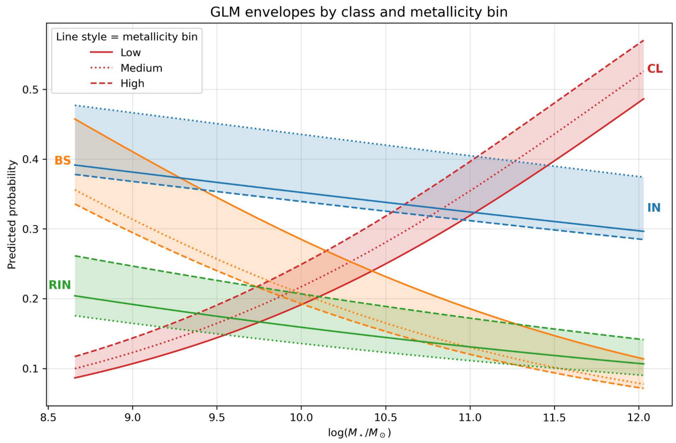

Figure 3. Three metallicity bins reveal significant differences in dynamical classes, linking orbital stage to galaxy evolution.

RIN) exhibiting star formation suppression and a flattening of the stellar mass-metallicity relation.

Although backsplash (BS) galaxies can present higher metallicities Fig. 3, indicating a preserved prior chemical enrichment, their star formation is severely inhibited, suggesting that environmental processes act differently on the interruption of galactic growth and the modification of their chemical properties.

Thus, dynamic classification within the PPSD proves essential for unraveling the complex and multifaceted impact of the cluster environment on the evolutionary history of galaxies. Future studies will further dissect the precise environmental mechanisms driving these observed trends, especially exploring the intricate interplay between orbital dynamics and the evolving metallicity of backsplash populations.

5. Conclusions

Our results demonstrate that the orbital history of galaxies in clusters critically affects their evolution. Galaxies with prolonged or intense interaction with the core (CL, BS, RIN) exhibit quenched star formation and a flatter stellar mass–metallicity relation. In contrast, infalling (IN) and interloper (ITL) galaxies retain higher star formation rates and lower metallicities. These findings reinforce phase–space classification as a powerful tool for tracing environmental effects in high-density regions.

Acknowledgements. We thank the PROFÍSICA and the UESC for academic support, and CAPES for the master's scholarship that made this work possible. Finally, we thank the SAB for the opportunity to present this work.

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