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Exploring the infall region with SCALE:

Galaxy morphologies and star formation rates in the MKW4 cluster

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Abstract. The influence and the transformations undergone by individual galaxies and galaxy groups upon falling into rich galaxy clusters have been extensively studied, primarily focusing on the innermost regions of these large structures. However, to fully comprehend galaxy evolution within clusters, a growing body of evidence has highlighted the need to investigate the distant regions from the cluster centers, known as the infall region, where much of the action occurs. Thus, this project aims to comprehensively study a sample of 58 galaxy clusters, including regions up to $5 \times R_{200}$ and beyond. Extensive information is being obtained about the clusters themselves and their member galaxies, as well as the presence of substructure of the clusters as a whole. To achieve this, spectroscopic and photometric data from the literature and the S-PLUS survey are used. The properties of the member galaxies, as star formation rates and morphological parameters, are correlated with their positions relative to substructures and filaments around the systems, to determine differences attributed to pre- and postprocessing processes, and to conduct a comparative study of various regions within the cluster up to the interface between the cluster and the field. Furthermore, simulations suggest that quenching is most efficient in halos with masses of $10^{13.5}$ to $10^{14.5}$ $M_{\odot}$. With an X-ray mass of $(9.7 \pm 1.5) \times 10^{13}$ $M_{\odot}$ within R_{200} , MKW4 lies within this key regime, making it an ideal system to investigate environmental effects on galaxy evolution. We find that different substructures within MKW4 exhibit distinct evolutionary stages. When compared to the Antlia cluster, a dynamically younger system, the differences in quenched and early-type fractions are minimal.

Resumo. A influência e as transformações sofridas por galáxias individuais e grupos de galáxias ao serem incorporados a aglomerados ricos têm sido amplamente estudadas, com ênfase principalmente nas regiões mais centrais dessas grandes estruturas. No entanto, para compreender de forma completa a evolução das galáxias em aglomerados, um número crescente de evidências tem destacado a necessidade de investigar as regiões mais externas, conhecidas como *regiões de infall*, onde grande parte dos processos físicos relevantes ocorre. Assim, este projeto tem como objetivo realizar um estudo abrangente de uma amostra de 58 aglomerados de galáxias, incluindo regiões que se estendem até $5 \times R_{200}$ e além. Estão sendo obtidas informações detalhadas tanto sobre os aglomerados em si quanto sobre suas galáxias-membro, bem como sobre a presença de subestruturas no conjunto dos sistemas. Para isso, são utilizados dados espectroscópicos e fotométricos provenientes da literatura e do levantamento S-PLUS. As propriedades das galáxias-membro, como taxas de formação estelar e parâmetros morfológicos, são correlacionadas com suas posições relativas a subestruturas e filamentos ao redor dos sistemas, com o objetivo de identificar diferenças associadas a processos de *pre-processing* e *post-processing*. Além disso, é conduzido um estudo comparativo entre diferentes regiões do aglomerado, desde o núcleo até a interface entre o aglomerado e o campo. Simulações indicam que o *quenching* é mais eficiente em halos com massas entre $10^{13.5}$ e $10^{14.5}$ $M_{\odot}$. Com uma massa em raios-X de $(9.7 \pm 1.5) \times 10^{13}$ $M_{\odot}$ dentro de R_{200}, o aglomerado MKW4 situa-se nesse regime crítico, tornando-se um sistema ideal para investigar os efeitos ambientais na evolução das galáxias. Nossos resultados mostram que diferentes subestruturas de MKW4 apresentam estágios evolutivos distintos. Quando comparado ao aglomerado Antlia, um sistema dinamicamente mais jovem, as diferenças entre as frações de galáxias extintas (*quenched*) e de tipos morfológicos *early-type* são mínimas.

Keywords. Galaxies: clusters: general – Galaxies: fundamental parameters – Galaxies: photometry

1. Introduction

Clusters and groups of galaxies evolve and grow over time through hierarchical structure formation (Springel et al. 2001, 2005). As clusters accrete galaxies and groups falling into them (Diaferio & Geller 1997), they become key laboratories for studying galaxy evolution and the combined impact of cluster- and environment-driven processes, including both pre- and post-processing effects (Piraino-Cerda et al. 2024; Haines et al. 2015; Lopes et al. 2024).

Moreover, clusters are the largest virialized structures in the Universe (Walker et al. 2019). These systems are connected within the cosmic web by filaments and nodes that are often characterized by substructures. Nonetheless, many open questions remain regarding the role of filaments and substructures in cluster assembly (Bahe & Jablonka 2025).

In this context, the Southern Photometric Local Universe Survey (S-PLUS; Mendes de Oliveira et al. 2019), with its 12-band optical mapping of the sky, provides an especially powerful means of studying clusters. Its 12-band filter system enables the determination of improved photometric redshifts (photo-z's;

Lima et al. 2022) and the derivation of stellar masses, star formation rates, and other galaxy properties. In this work, we studied the MKW4 cluster, inside the sample of S-PLUS Clusters/Groups And their Large-scale Environments (SCALE) project (Mendes de Oliveira et al., in prep.). Then we are using 330 galaxies with spectroscopy and S-PLUS data.

2. Analysis

2.1. Galaxy properties across substructures and mass ranges

Substructures within and around the MKW4 galaxy cluster were identified using CALSAGOS (Olave-Rojas et al. 2023). Three major substructures were considered for analysis: one in the central region, one around $3R_{200}$, and another near $5R_{200}$.

As low-mass and high-mass galaxies are expected to exhibit different properties, reflecting variations in their responses to environmental and secular internal processes, we divided the MKW4 galaxy sample into two subsamples: those below the median mass and those above it. We then analyzed the differences among the central region, the substructure around $3R_{200}$, and the substructure around $5R_{200}$, as well as galaxies not belonging to any substructure located within $3R_{200}$, between $3R_{200}$ and $5R_{200}$, and beyond $5R_{200}$.

For the substructure at $\sim 3R_{200}$, we find that low-mass galaxies are affected both by the substructure environment and the cluster environment, exhibiting higher specific star formation rates (sSFR) and lower concentration. In contrast, high-mass galaxies exhibit properties similar to those outside substructures at the same distance, suggesting that these substructures have undergone less pre-processing and are currently subject to weaker substructure effects. Their evolution therefore proceeds in a manner comparable to galaxies not embedded in substructures. Alternatively, surrounding galaxies may have already reached the evolutionary stage of those within the substructures, driven by the stronger environmental effects of the cluster.

For the substructure at $\sim 5R_{200}$, which is less affected by the cluster environment, the influence of the substructure environment itself becomes more evident. This suggests that this group has undergone significant pre-processing before infalling into MKW4. For low-mass galaxies, we observe higher concentration (C) and Gini values, along with elevated asymmetry. For high-mass galaxies, sSFR is lower, C and Gini are higher, and M_{20} values are lower.

2.2. Quenched and early-type fractions

Considering quenched galaxies as those with sSFR $< 10^{-11}$ and early-type galaxies following the classification of Lotz et al. (2008), we plotted the quenched galaxy fraction of MKW4 compared to the Antlia cluster. The early-type fraction compared to Antlia values (Lima-Dias et al. in prep). The comparison with Antlia was chosen because it is considered a young, dynamically evolving cluster, while MKW4 is a very relaxed system. Overall, both clusters exhibit similar trends, showing increasing fractions of quenched and early-type galaxies within R_{200}, with comparable values within errors in most bins despite their different dynamical states.

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