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Study of the infall region of galaxy clusters using data from the S-PLUS project

A pilot program on the morphology and star formation rates of galaxies 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, where complete spectroscopic information is readily available in the literature. However, 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, to comprehend galaxies' evolution within clusters fully.
This project aims to comprehensively study a sample of 53 galaxy clusters, including regions up to $5 \times R_{200}$. Extensive information is being obtained about the clusters themselves and their member galaxies, as well as the presence of substructure for 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 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. Here, we show a preliminary application for MKW4 cluster.

Resumo. A influência e as transformações sofridas por galáxias individuais e grupos de galáxias ao caírem em aglomerados ricos têm sido extensivamente estudadas, com foco principalmente nas regiões mais internas dessas grandes estruturas, onde informações espectroscópicas completas estão prontamente disponíveis na literatura. No entanto, um crescente corpo de evidências tem destacado a necessidade de investigar as regiões mais distantes dos centros dos aglomerados, conhecidas como a região de *infall*, onde ocorre grande parte da ação, para compreender completamente a evolução das galáxias dentro dos aglomerados.
Este projeto tem como objetivo estudar de forma abrangente uma amostra de 53 aglomerados de galáxias, incluindo regiões até $5 \times R_{200}$. Informações detalhadas estão sendo obtidas sobre os próprios aglomerados e suas galáxias membros, bem como a presença de subestruturas nos aglomerados como um todo. Para isso, são utilizados dados espectroscópicos e fotométricos da literatura e do mapeamento S-PLUS. As propriedades das galáxias membros são correlacionadas com suas posições em relação às subestruturas e filamentos ao redor dos sistemas, com o objetivo de determinar diferenças atribuídas aos processos de pré e pós-processamento, além de realizar um estudo comparativo de várias regiões do aglomerado até a interface entre o aglomerado e o campo.
Aqui, apresentamos uma aplicação preliminar para o aglomerado MKW4.

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

1. Introduction

Pre- and post-processing of galaxies and groups as they enter the cluster, and the consequent transformation they undergo, such as ram pressure stripping, have been well studied in the inner parts of clusters, where complete spectroscopic information is often available in the literature Jaffe et al. 2015; Kelkar et al. 2023. However, the more distant regions of clusters, within the infall region up to $5 \times R_{200}$, have so far received very little attention due to the difficulty of even properly selecting the correct cluster members in these sparse regions (for a recent study on this region, see Lopes et al. 2024). In recent years, it has become increasingly clear, through a growing body of evidence in the literature, that to fully understand the evolution of galaxies in clusters, it is necessary to also investigate the typical environments of their peripheries, the infall region Piraino-Cerda et al. 2024.

In this work, a sample of approximately 50 clusters (which is expected to grow over time as more observations are made) was selected for detailed study using the Southern Photometric Local Universe Survey (S-PLUS, Mendes de Oliveira et al. 2019), which has an optical system consisting of 12 filters, comprising 5 broad and 7 narrow bands. Currently, S-PLUS has observed over 3000 square degrees of the southern hemisphere sky, allowing us to study the extensive regions around galaxy clusters. For some of the analysis, we also use spectra from the Sloan Digital Sky Survey (SDSS) and images from the Legacy Survey.

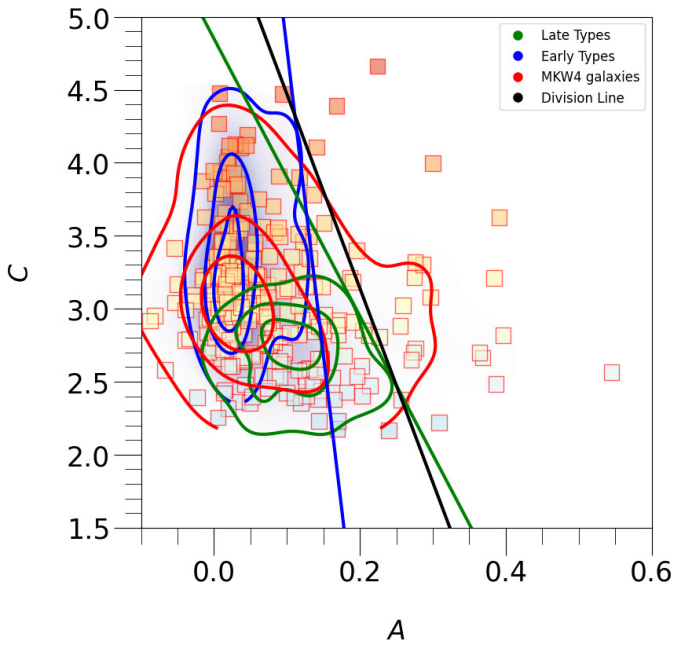

Figure 1. C vs A graph of MKW4 cluster. Density maps were plotted for isolated late-type (green) and early-type galaxies (blue) to compare with the galaxies of MKW4 (red). The adjacent lines were drawn to separate the right region of galaxies with a higher probability of being interacting or asymmetric from those with more regular morphologies.

For the selected clusters, all available information regarding both the clusters and their member galaxies is being gathered, within the region up to $5 \times R_{200}$.

2. Methods

The methodology involves the use of several different programs to extract various information and properties, such as:

- **Shifting Gapper Technique**: This method is applied to select member galaxies of a galaxy cluster.
- **Astromorphlib** Krabbe et al. 2024: A package designed for analyzing the morphology of galaxies and determining non-parametric parameters such as Concentration and Asymmetry.
- **Pygalfitm**: A package that interfaces with GALFITM, a tool for extracting galaxy information from multi-band data by modeling objects in images and fitting their surface brightness distributions.
- **Alstar** Thaina-Batista et al. 2023: A tool that performs Spectral Energy Distribution (SED) fitting to derive star formation rates (SFR) by decomposing the information into components representing stellar population bursts with varying ages and metallicities.

3. Results

The MKW4 cluster (RA: 180.988, DEC: 1.888) is a galaxy cluster located at a redshift of $z \approx 0.02$. By analyzing the member galaxies of this cluster with `Astromorphlib`, a plot of Concentration (C) versus Asymmetry (A) can be generated, as shown in Figure 1, to distinguish the most probable interacting galaxies within the cluster. The Spectral Energy Distribution (SED) fitting and the Star Formation Rate (SFR) of a galaxy in MKW4, as modeled by the `Alstar` program, are presented in Figure 2.

4. Conclusions

Here is presented an application of the tools previously discussed for MKW4, which enabled the identification of potential interacting galaxies and properties such as SFR, facilitating the study and inference of their evolution and current state. The plan is to extend this approach to all clusters in our sample, with the following objectives:

- Establish relationships between galaxy morphologies and their positions within the cluster's substructures;
- Analyze SFR and other properties by correlating them with the positions of the galaxies in the substructures;
- Investigate intracluster light in groups around the infall region and compare it with the main halo;
- Utilize photometric redshifts data from S-PLUS to enhance the search for member objects within the clusters;
- Employ X-ray data from eROSITA to broaden the search for clusters to be studied.

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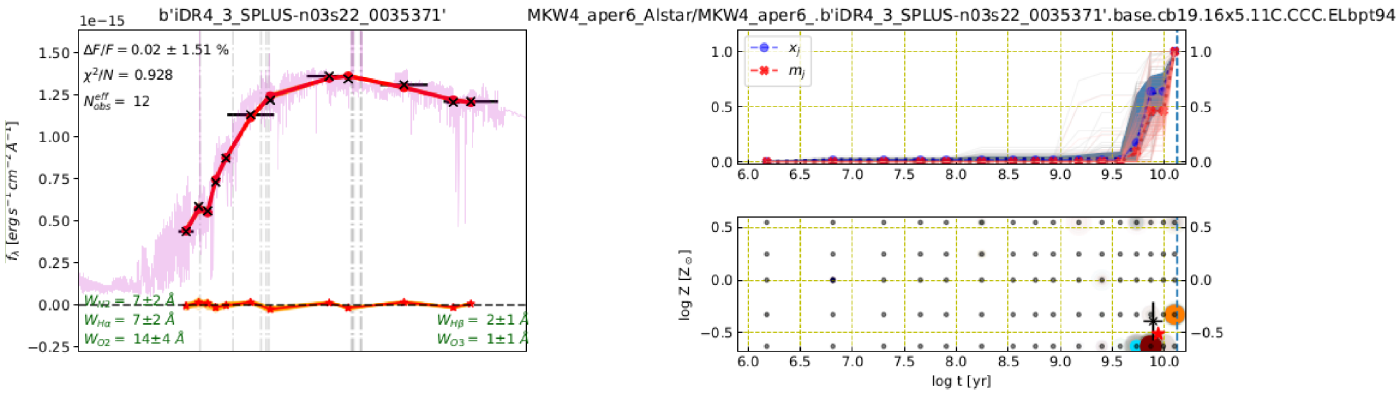

Figure 2. SED fitting in fluxes and the modeled SFR over time for UGC 6958, a red spiral galaxy considered a member of the MKW4 cluster, along with the estimated metallicities.