Boletim da Sociedade Astronômica Brasileira, **35**, no. 1, 110-111

Searching for merging galaxy clusters with S-PLUS

Developing a method to identify clusters with substructures

Giulya Souza[1], Eduardo Cypriano[1], & Lia Doubrawa[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Brasil. e-mail: giulyasouza@usp.br, eduardo.cypriano@iag.usp.br, lia.doubrawa@usp.br

Abstract. The objective of this study is the identification and characterization of galaxy clusters possibly in the process of merging. These merging systems serves as excellent laboratories to study the behavior of their components, especially dark matter, representing the majority of the total mass of these systems. We utilized the PzWav catalog of galaxy clusters, derived from the S-PLUS optical survey, and applied a method developed by our research group. This method employs the density based clustering algorithm HDBSCAN to assign probabilities of galaxy membership to clusters. The goal is to search for subgroups within the identified clusters, with the intention of finding connected pairs of clusters that may represent a system in the process of merging.

Resumo. O objetivo deste trabalho é a identificação e caracterização de aglomerados de galáxias possivelmente em processo de fusão. Esses sistema em colisão servem como excelentes laboratórios para estudar o comportamento de suas componentes, especialmente da matéria escura, que representa a maior parte da massa total desses sistemas. Nós utilizamos o catálogo de aglomerados de galáxias PzWav, feito a partir do levantamento óptico S-PLUS, e aplicamos um método desenvolvido pelo nosso grupo de pesquisa que atribui probabilidades de pertinência de galáxias aos aglomerados utlizando o algoritmo de aglomeramento baseado em densidade, HDBSCAN. A finalidade é buscar por subgrupos nos aglomerados identificados, visando encontrar pares ligados de aglomerados que possam representar um sistema em processo de fusão.

Keywords. Galaxies: clusters: general – Galaxies: groups: general

1. Introduction

Clusters of galaxies are the largest gravitationally bound structures in the known universe, primarily composed of galaxies, intra-cluster gas, and dark matter. When undergoing a merger process, these systems exemplify the hierarchical model of structure formation in the universe and are considered excellent laboratories for studying the interaction between the components of these systems, especially dark matter. The most well-known example of merging clusters is the Bullet Cluster (Markevitch et al. 2004), which is a dissociative collision of clusters (Dawson et al. 2012) where the intra-cluster gas exhibits significant spatial separation from the dark matter component. The discovery of this system provided strong evidence for the existence of dark matter (Clowe et al. 2006), and its study enabled constraints on the self-interaction cross-section of dark matter (Markevitch et al. 2004; Randall et al. 2008).

Detecting merging clusters can be a complex task and, as far as we know, complete catalogs of these systems do not yet exist. This work aims to identify galaxy clusters with substructure richness comparable to the main group, which could represent a connected pair of clusters possibly in a collision process. To achieve this, we used the galaxy cluster catalog generated from S-PLUS survey data through PzWav (Werner et al. 2023; Gonzalez, A. 2014), an optical cluster detection technique. To search for substructures, we applied a method developed by the research group that assigns probability of galaxy membership to clusters for detecting these systems (Doubrawa et al. 2023), using the density based clustering algorithm HDBSCAN to search for subgroups within the identified systems (Campello et al. 2013).

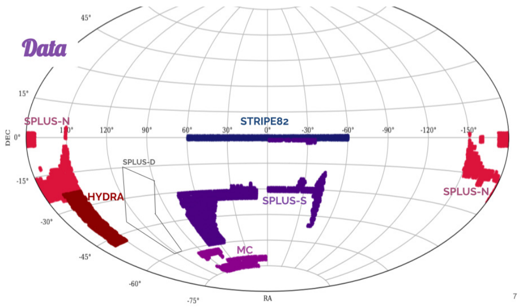

Figure 1. S-PLUS Survey footprint. Image credits: Lia Doubrawa.

2. Data and method

The photometric data from S-PLUS (Mendes de Oliveira et al. 2019) used in this study are from the iDR4. In this analysis, we will utilize the galaxy cluster catalog compiled by PzWav (Werner et al. 2023; Gonzalez, A. 2014) in the Stripe-82 area of the S-PLUS survey footprint, Figure 1, an equatorial region covering approximately 332 deg^2. The catalog includes over 44 thousand clusters within a redshift range of $0.04 \leq z \leq 0.5$, with objects having apparent magnitude in the r-band < 21.

To search for substructures within the clusters in the catalog and identify potential merging systems, we will employ the method developed by the research group that estimates the probability of galaxy membership in a given cluster, called AME (Adaptive Membership Estimator, Doubrawa et al. 2023). The HDBSCAN algorithm (Campello et al. 2013) is capable of detecting multiple subgroups in generic data sets, given the desired number of subgroups and the minimum number of members in each group, as exemplified in Figure 2. Thus, AME can be used

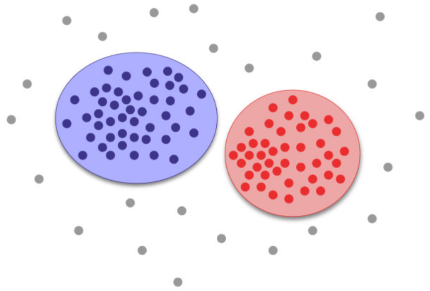

Figure 2. HDBSCAN example diagram.

to search for a main cluster and a substructure, probabilistically assigning galaxies to each group. The method also determines the richness (λ) of the groups as the sum of the probabilities of individual galaxies, and the main cluster is defined as the one with the highest richness among the two groups.

To select our sample of clusters with substructures, we first ran AME for clusters in the PzWav catalog with a signal-to-noise ratio (S/N) ratio greater than 4. This run is executed with an absolute magnitude cutoff of $M < -20.25$ to ensure a volume-limited sample, extending up to redshift $z < 0.45$ (Doubrawa et al. 2023). Among the approximately 12 thousand clusters, the algorithm finds that 673 have a substructure. To select only systems with a significant substructure, we applied a cutoff requiring that the secondary structure has at least 4% of the richness of the main cluster, i.e., $\lambda_{\rm sub}/\lambda_{\rm main} \geq 4\%$. This results in a sample of 191 galaxy clusters with a substructure in the Stripe-82 area.

3. Analysis and preliminary results

Our hypothesis is that if the clusters selected by our method indeed have a substructure, the distribution of galaxies in these systems should be bimodal, with one peak at the center of the main cluster and another at the center of the substructure. Based on this, we produced maps of the projected distribution of galaxies in the clusters, considering the probabilities of belonging to each group. However, since most clusters in our sample have few galaxies (≤ 10), we performed this analysis using a stacking technique. To conduct the stacking, we used the positions of the main cluster center, determined by PzWav, and the substructure center, determined by AME, for each system as references.

Before stacking, we performed a rotation and normalization of all 191 clusters so that the center of the main structure is at the origin, and the center of the substructure is on the horizontal axis at $x = 1$. After this alignment, we summed the galaxies from all clusters and plotted two distributions of the stacked galaxies: one considering the probability of belonging to the main cluster and the other considering the probability of belonging to the substructure. The sum of these two is the final distribution, shown in Figure 3.

Observing the density map in Figure 3, it can be stated that the galaxy distribution is clearly bimodal, and the stacking result suggests that statistically, AME is an efficient method for detecting substructures in galaxy clusters. Additionally, we observed that despite the translation of the main structure center to the origin, the peak of the main structure distribution is not shifted to the left. This occurs because, when assigning probabilities to galaxies, AME assigns a non-zero probability to most galaxies in the substructure region of also belonging to the main structure. This "leakage," combined with the fact that the center of the main structure is determined by PzWav without considering

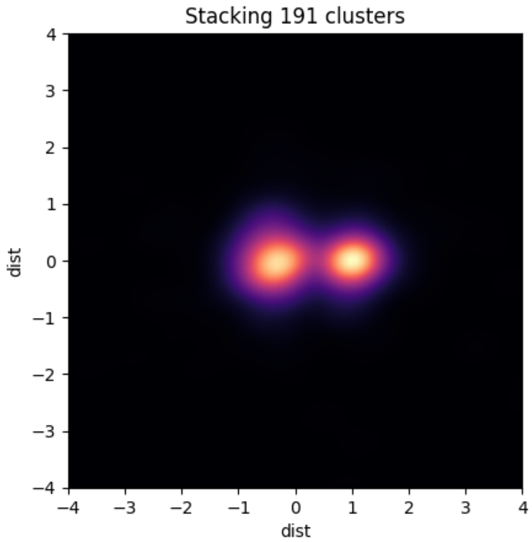

Figure 3. Stacked map of the 191 clusters with substructure.

the presence of a substructure, causes the shift in the distribution peak.

4. Conclusion

The preliminary results of this study strongly indicate that our method is effective in identifying galaxy clusters with substructure, which, in the context of this study, may represent connected pairs of clusters possibly in a collision process. In the next steps, we intend to conduct tests to assess the detection sensitivity of AME using simulations of clusters with substructure. Additionally, we will complement our analysis with mass maps of the clusters in our sample, utilizing weak gravitational lensing effects. It is expected that the mass distribution will also exhibit the bimodality identified in this photometric analysis.

Acknowledgements. The authors of this work would like to express their gratitude for the funding provided by the CAPES funding agency, which enabled the development of this study as part of a master's research.

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