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Unveiling the stellar population properties of the intracluster light

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Abstract. Intracluster light (ICL) is a diffuse stellar component of clusters and groups of galaxies that is not gravitationally bound to any individual galaxy. Its stellar population properties can provide insights into the dynamical history of galaxy clusters and groups. Furthermore, it is expected to follow the overall dark matter distribution, offering a means to deduce the properties of dark matter halos. However, due to its low surface brightness nature (μ_V > 26.5 mag arcsec^{-2}), studying this component is challenging and requires special care. The data acquisition strategies must be well-planned to obtain deep imaging, and we must perform a data reduction process appropriate to preserve low surface brightness structures. In this work, we present the observational strategy and procedures that we employ to enhance the detection of the ICL in MegaCam/CFHT deep optical data (*g* and *r*-bands). Analyzing the radial profile of the central galaxies using PHOTUTILS/`ellipse`, we present our preliminary results of the BCG+ICL radial profiles of four targets.

Resumo. A luz difusa intra-aglomerado (ICL) é uma componente estelar difusa de aglomerados e grupos de galáxias que não está gravitacionalmente ligada a nenhuma galáxia individual. As propriedades de suas populações estelares podem fornecer uma melhor compreensão sobre a história dinâmica de aglomerados e grupos de galáxias. Além disso, espera-se que o ICL siga a distribuição de matéria escura, oferecendo um meio de inferir propriedades dos halos de matéria escura. No entanto, devido ao seu baixo brilho superficial (μ_V > 26.5 mag arcsec^{-2}), estudar esta componente é um desafio e requer cuidados especiais. As estratégias para a aquisição de dados devem ser bem planejadas para obter imageamento profundo e é preciso de uma redução de dados apropriada para preservar estruturas de baixo brilho superficial. Neste trabalho, nós apresentamos a estratégia observacional e os procedimentos que empregamos para aprimorar a detecção do ICL em dados profundos no óptico (bandas *g* e *r*) da MegaCam/CFHT. Analisando o perfil radial das galáxias centrais usando PHOTUTILS/`ellipse`, nós mostramos os nossos resultados preliminares dos perfis radiais da BCG+ICL de quatro alvos.

Keywords. Galaxies: photometry – Galaxies: groups: general – Galaxies: clusters: general – Techniques: image processing

1. Introduction

Over the past 25 years, the number of studies on the low surface brightness (LSB) field, such as ultra-diffuse galaxies (e.g., van Dokkum et al. 2015), galactic cirri (e.g., Román et al. 2020), intracluster light (e.g., DeMaio et al. 2015), and tidal features (e.g., Román et al. 2023), has increased significantly, mainly due to the technological advancement in astronomical instrumentation that allowed us to obtain deeper images. However, the difficulty in studying them remains, even nowadays. There are many aspects that must be considered. Otherwise, a considerable amount of light information can be lost if the observational strategies and data reduction techniques are not appropriate. For this reason, the weather conditions, observation strategies (e.g., dithering), desired image depth, data reduction techniques (e.g., sky subtraction and flat-fielding), point spread function (PSF), contamination from galactic cirri or bright stars, and the correction of artifacts (e.g., ghosts) are critical aspects that must not be ignored in LSB studies. For example, night sky gradients and over-subtraction of the sky background are common issues that need to be addressed.

In this work, we aimed to study the intracluster light (ICL), which is an extended diffuse stellar component of clusters and groups of galaxies that is not gravitationally bound to any individual galaxy. The properties of its stellar population (such as color, metallicity, and spatial distribution) and fraction can provide insights into the dynamical history of galaxy clusters and the evolution of the brightest cluster galaxy (BCG). Furthermore, it is expected to follow the overall dark matter distribution, offering a means to deduce the properties of dark matter halos and validate the predictions of the ΛCDM cosmological model. Due to its low surface brightness nature (μ_V > 26.5 mag arcsec^{-2}, Rudick et al. 2006), we first developed an image processing strategy to preserve the ICL emission in our images, then we described here some of our preliminary results.

2. Sample and Data Reduction

We used deep optical observations from the MegaCam (*g* and *r*-bands) at the Canada-France-Hawaii Telescope (CFHT) to analyze the 1D and 2D surface brightness profile of the BCG+ICL of three galaxy groups and one cluster (Table 1). The data was reduced by the Elixir-LSB pipeline (Duc et al. 2015), which was specially designed to detect low surface brightness features.

Table 1. Sample of galaxy clusters and groups observed with MegaCam/CFHT.

Name	RA	DEC	Redshift
NGC 1132	02h52m51.8s	-01d16m29.1s	0.02
NGC 7556	23h15m44.5s	-02d22m53.5s	0.03
A1991	14h54m31.5s	+18d38m32.4s	0.06
UGC 842	01h18m53.6s	-01d00m07.2s	0.05

As the study of low surface brightness structures requires special attention, we also applied careful post-processing that includes sky subtraction, masking sources, point spread function (PSF) modeling, and removal of the scattered light field produced by stars. The photometric calibration was performed using non-saturated stars from the 16th data release of the

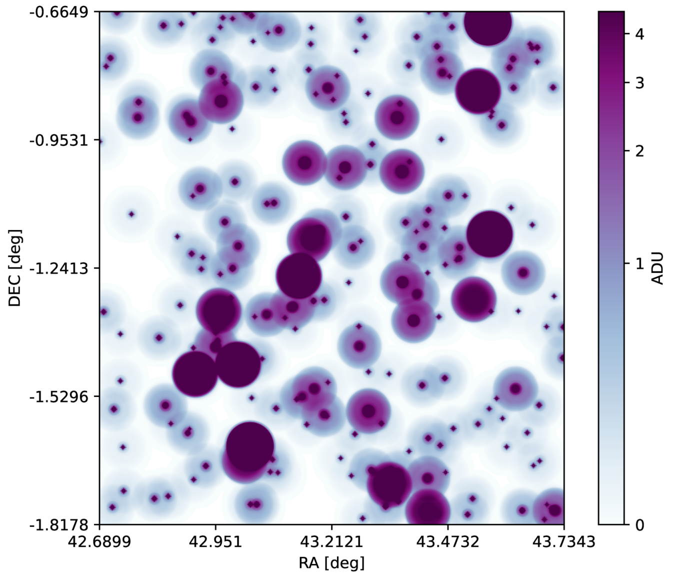

Figure 1. Example of the scattered light field model in NGC 1132 image (g-band). The color map is in the *asinh* scale.

Sloan Digital Sky Survey (Ahumada et al. 2020). We applied k-correction (Chilingarian et al. 2010; Chilingarian & Zolotukhin 2012), dust reddening (Schlafly & Finkbeiner 2011), and surface brightness dimming correction. The surface brightness limits achieved were $\mu_g^{lim}(3\sigma, 10'' \times 10'') = 29.4$ - 30.7 mag arcsec^{-2} and $\mu_r^{lim}(3\sigma, 10'' \times 10'') = 28.8$ - 29.3 mag arcsec^{-2} in our images.

3. Post Processing

There are some key aspects to consider when preserving low surface brightness structures during image processing. The first is flat fielding, which is already performed by the Elixir-LSB pipeline. The second is the sky background subtraction, which must be done carefully to avoid over-subtraction. Finally, a good understanding of the point spread function is crucial for correctly distinguishing the diffuse light of true ICL from the scattered light of stars in the observed field.

We adopted a more sophisticated method to estimate the sky background value, replacing traditional techniques such as sigma clipping or image median. We followed the method presented by Borlaff et al. (2019), which involves using the `NoiseChisel` program (GNU Astro, Akhlaghi & Ichikawa 2015), specifically developed to detect low surface brightness sources and structures, to create masks, and computing the median of the probability density function of the background medians, generated via resampling (bootstrapping). According to Borlaff et al. (2019), the estimated value using this method is the closest to the true sky background value (see Figure 9 from this paper). Here, we used `NoiseChisel` in default mode, with a small modification to make it more aggressive (`-snminarea=5`), and filtered the outliers ($3\sigma_{\mathrm{MAD}}$ from the median) from the masked image. After that, a constant value was subtracted from the original image.

It is well known that MegaCam creates many artifacts in its images, mainly the extensive envelope around the brightest stars. These halos result from multiple internal reflections within the instrument, contaminating the light from nearby galaxies and causing an artificial reddening (Duc et al. 2015; Karabal et al. 2017). For this reason, we carefully model the PSF using the brightest stars for the outer parts and the faintest stars for the central part. We created a catalog of stars using the software SExtractor Bertin & Arnouts (1996) and, to mask sources close to the stars, we used the software `NoiseChisel` and `Segment` (Akhlaghi & Ichikawa 2015). Figure 1 shows an example of the scattered light field model used to subtract the stars and their halos in one of our targets.

4. Preliminary Results

We found a flattened color profile in most of our targets ($\nabla_{g-r} \approx 0$ kpc^{-1}), except for UGC 842, which shows a weak negative gradient ($\nabla_{g-r} \approx -0.005$ kpc^{-1}). The absence of gradients (positive or negative) in the color profiles suggests that past mergers could have mixed the stellar populations, flattening the profile in the process. It also indicates the possibility of mergers being the main formation mechanism of ICL in these cases. On the other hand, the negative gradient on the BCG+ICL color profile of UGC 842 indicates that the main formation mechanisms of ICL can be the stellar stripping or dwarf disruption (DeMaio et al. 2015). All details of our findings will be described in Parra Ramos et al. (in prep.).

5. Conclusions

In this work, we aimed to study the internal structure of BCGs and detect the ICL in order to get information about the dynamical activity history of galaxy clusters and groups. To achieve these goals, we carefully processed the images to preserve low surface brightness features and the intracluster light, employing more sophisticated methods for sky subtraction and PSF modeling. By analyzing the radial color profiles, we found clues that mergers were possibly the main formation mechanism of ICL in most of our targets. In the future, we expect to increase our sample with deep optical observations from DECam/Blanco to find clues about the main formation process of the ICL in groups and clusters in different ranges of mass and redshift.

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