The Buildup of the Intracluster Light of A85 as Seen by Subaru’s Hyper Suprime-Cam

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Abstract

The study of low surface brightness light in large, deep imaging surveys is still uncharted territory as automated data reduction pipelines over-subtract or eliminate this light. Using archival data of the A85 cluster of galaxies taken with the Hyper Suprime-Cam on the Subaru Telescope, we show that using careful data processing can unveil the diffuse light within the cluster, the intracluster light. We reach surface brightness limits of $\mu_g^{lim}(3\sigma, 10'' \times 10'') = 30.9$ and $\mu_i^{lim}(3\sigma, 10'' \times 10'') = 29.7$ mag arcsec$^{-2}$. We measured the radial surface brightness profiles of the brightest cluster galaxy out to the intracluster light radius ($\sim$215 kpc) for the $g$ and $i$ bands. We found that both the surface brightness and the color profiles become shallower beyond $\sim$75 kpc suggesting that a distinct component, the intracluster light, starts to dominate at that radius. The color of the profile at $\sim$100 kpc suggests that the buildup of the intracluster light of A85 occurs by the stripping of massive ($\sim 10^{10}M_\odot$) satellites. The measured fraction of this light ranges from 8%–30% in $g$, depending on the definition of intracluster light chosen.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Abell clusters (9); Galactic and extragalactic astronomy (563); Galaxy stellar halos (598); Photometry (1234); Stellar populations (1622)

1. Introduction

Deep observations of galaxy clusters have revealed the existence of a diffuse glow produced by stars not bound to any individual galaxy; the intracluster light (ICL; see Mihos 2016; Montes 2019; for reviews). As the by-product of galaxy interactions, the ICL forms a fossil record of all the dynamical processes the system has undergone and provides a holistic view of the history of interactions within the cluster (e.g., Merritt 1984).

The ICL is key to understanding how brightest cluster galaxies (BCGs) grow with time. Their formation and evolution have been predicted to be rather different from satellite galaxies (e.g., De Lucia & Blaizot 2007). The innermost regions of these massive galaxies appear to have formed the majority of their stars at high redshift and on short timescales (e.g., Thomas et al. 2005), whereas their outer parts are likely assembled as a consequence of multiple minor merging more recently (e.g., Trujillo et al. 2011). As the ICL is often found to be more concentrated around BCGs (e.g., Mihos et al. 2005), it implies that the growth of both components, the BCG and the ICL, are connected. In addition, simulations of the growth rate of BCGs show that both the surface brightness and the color profiles become shallower beyond $\sim$75 kpc suggesting that a distinct component, the intracluster light, starts to dominate at that radius. The color of the profile at $\sim$100 kpc suggests that the buildup of the intracluster light of A85 occurs by the stripping of massive ($\sim 10^{10}M_\odot$) satellites. The measured fraction of this light ranges from 8%–30% in $g$, depending on the definition of intracluster light chosen.

This is changing with the next generation of surveys using state-of-the-art cameras that will be able to reach unprecedented depths over large areas in the sky. An example is the Hyper Suprime-Cam (HSC; Miyazaki et al. 2018) on the 8.2 m Subaru Telescope. This camera is well suited to not only provide the wide field of view necessary to observe nearby clusters but also the time efficiency of a large telescope being able to reach ICL depths in short exposure times. The HSC is currently carrying out the HSC Subaru Strategic Program (HSC-SSP), a survey of 1400 deg$^2$ in five different bands (grizy) plus four narrow filters. The depth and area of this survey will provide the large numbers of galaxy clusters necessary to deepen our knowledge of the formation of the ICL (Aihara et al. 2019).

However, ICL studies need very accurate data processing. The data reduction of HSC data is undertaken with the HSC pipeline (Bosch et al. 2018), a custom version of the LSST$^5$ pipeline. The sky subtraction algorithm in the HSC-SSP DR1

4 Diffuse light has also been detected and studied in groups of galaxies (e.g., Da Rocha & Mendes de Oliveira 2005; DeMaio et al. 2018; Iodice et al. 2020), but the main mechanism of the formation of the intracluster light appears to differ from that for clusters (e.g., Spavone et al. 2020).

5 The Vera C. Rubin Observatory Legacy Survey for Space and Time.
over-subtracts extended halos of bright objects making it almost impossible to study nearby or very extended objects (Aihara et al. 2018). In addition, ICL studies are susceptible to biases due to flat-field inaccuracies and the scattered light from bright stars.

In this work, we use archival HSC images of the cluster A85 (A85) to test a dedicated data processing technique for low surface brightness science and study the diffuse light of this cluster out to ≈215 kpc. The main properties of A85 are listed in Table 1. A85 is a rich cluster of galaxies (~800 spectroscopically confirmed galaxies within 2R200; Owers et al. 2017; Habas et al. 2018) hosting a massive BCG (Mg ∼ 3 × 1014 M⊙; Mehran et al. 2019). Many studies have shown that this cluster is slowly accreting material through several ongoing mergers with at least, two subclusters or groups of galaxies (Bravo-Alfaro et al. 2009; Ichinohe et al. 2015; Owers et al. 2017). In addition, models of the X-ray temperature across the cluster support the picture that A85 has undergone several small mergers in the past few billion years (Durret et al. 2005; Ichinohe et al. 2015).

This cluster provides an ideal target for a pilot study of the ICL using the HSC and dedicated data processing techniques for low surface brightness science. Studying the properties of the ICL in this cluster will inform us of the ongoing processes shaping this cluster and its BCG.

Throughout this work we adopt a standard cosmological model with the following parameters: H0 = 70 km s−1 Mpc−1, Ωm = 0.3, and ΩΛ = 0.7. All magnitudes are in the AB magnitude system.

### Table 1

| Name | R.A. (deg) | Decl. (deg) | z | Distance (Mpc) | Angular Scale (kpc arcsec−1) | Virial M200 (1014 M⊙) | R200 (Mpc) |
|------|------------|-------------|---|----------------|-------------------------------|------------------------|------------|
| A85  | 10.458750  | −9.301944   | 0.0549 | 245           | 1.068                         | 17.0 ± 1.3             | 2.42       |

**Note.** Redshift, mass, and radius are taken from Owers et al. (2017).

inhomogeneities in the images such as gradients and over-subtraction, see Mihos 2019 for a detailed description of the possible biases in low surface brightness imaging), the images must have a flat background and the background subtraction should be performed carefully so as not to eliminate this light. At the time when we started this project, the data reduced with the HSC pipeline (Bosch et al. 2018) for the DR1 of the HSC-SSP survey (Aihara et al. 2018), showed significant oversubtraction around bright sources caused by a background estimation using a relatively small mesh size (128 × 128 pix2 = 21′′ × 21′′). Because the cluster of interest is at low redshift (i.e., extended in the sky, R200 = 2.42 Mpc = 0.63′; Owers et al. 2017), this oversubtraction would likely eliminate the ICL. For this reason, we developed a custom-made process in order to reduce the data, preserving low surface brightness light, i.e., the extended and faint ICL. The code is mainly written in Python and uses Astropy (The Astropy Collaboration et al. 2018) and astronomical software such as SExtractor, SMap, and SCAMP (Bertin & Arnouts 1996; Bertin et al. 2002; Bertin 2006). The steps followed here to reduce the HSC images, after the individual CCD processing, are similar to those performed in Trujillo & Fliri (2016). For this work, as the images were dithered around the BCG of the cluster, we focused only on the innermost 40 CCDs of the camera to reduce inaccuracies due to the nonuniform illumination of the CCDs. This corresponded to a radius of ∼0.42′′ (1.6 Mpc) around the BCG. These are the main steps we conduct to process the data:

1. Derivation of the calibration files (bias and dark).
2. Individual CCD processing and assembly.
3. Flat-field derivation using science images and correction.
4. Camera mosaic with a careful determination of the sky background.
5. Mosaic co-addition and final image calibration.

In the following sections, we describe in detail how these steps are performed.

The HSC CCDs are full-depletion Hamamatsu CCDs (Miyazaki et al. 2012). The individual raw images are 2144 × 2424, divided into four science channels of 512 × 4096 pixels along with the pre-scan, overscan, and non-science regions of each of those channel. Therefore, the next steps to calibrate each CCD have to be performed in each channel separately before the CCD is assembled.

#### 2.1. Custom-made Processing

Exploring the ICL of clusters of galaxies is difficult as it is not only faint, but also extended. This means that in order to avoid biases when measuring the ICL caused by

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6. This issue was improved in DR2 (Aihara et al. 2019), but not completely resolved.
7. https://smoka.nao.ac.jp/

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8. As described in: https://hsc.mtk.nao.ac.jp/pipemodul/pipemodul_4_e/e_hsc/index.html#e-hsc.
frames per CCD. The master bias and dark frames were created as the sigma-clipped (3σ) median for each of the channels of each of the CCDs.

2.1.2. Individual CCD Processing

In this step, we performed the processing and assembly of each CCD for each of the frames to produce a calibrated image. Each of the CCDs was processed independently. For each channel, we computed a median overscan using the corresponding overscan regions, and corrected for overscan, dark, and bias (as derived in Section 2.1.1). We also corrected each channel for nonlinearity as done in the HSC pipeline (Bosch et al. 2018) by applying a polynomial with coefficients determined per amplifier. Before assembling the final CCD image, we applied the gains for each of the channels (provided in the headers). The final size of the assembled CCD was 2048 × 4176 pixels.

2.1.3. Flat-field Correction

An accurate estimation of the flat-field correction is crucial to achieving the goals of this study. Dome flats are not suitable for our goals due to inhomogeneities in the dome illumination that can result in gradients across the image (e.g., Trujillo & Fliri 2016). Consequently, our flat-field correction should be based on science exposures, and ideally, they should be the same science exposures used in this work. However, the images of the cluster are not appropriate for two reasons: (1) there are only nine different exposures, meaning that the resulting flats will be very noisy and (2) the offsets of the dithering pattern are not large enough for this purpose, so the galaxies of the cluster occupy roughly the same physical area of the CCD in all exposures. The latter means that there will not be enough pixels to average in those regions in the resulting flats.

To address this, we downloaded images of random fields from the HSC-SSP wide survey taken on adjacent nights to the A85 observations in order to derive the most reliable flat-field correction possible. Using the SSP wide survey reduces the probability of an extended object in the same physical space of the CCD in all exposures. For the g band, the images were taken on 2014 October 1 (31), 2014 November 18 (9), and 2014 November 25 (9), a total of 49 frames per CCD. The exposure times were 150 s per frame.

For the i band, taking the images from the adjacent nights resulted in substructure remaining after the flat-field correction. This was found to be due to differences in the rotation angle of the instrument in the different set of images (see Appendix A for more details). Therefore, the final images used were taken on 2014 March 27, 2014 September 17, 2015 January 22, 2015 July 11, 2015 July 20, and 2014 September 22, 40 images per CCD in total. The exposure times were 200 s for each frame.

The assembled CCDs showed a steep gradient across the detector that could cause detection algorithms to mistakenly detect and mask regions of the image that do not correspond to any source. To account for this, the construction of the flats was done in two steps.

We first derived a rough flat or preflat. These were derived by stacking the HSC-SSP science images using a median of the normalized images for each CCD, without any masking, to make a CCD flat. Each of the images that went into the flats was visually inspected to eliminate those presenting very bright, saturated stars and extended objects that might introduce errors in the derived flat-field frames. First, we normalized each CCD image to one, using a region of 1000 × 1000 pixels located at the same position in the middle of each CCD. The preflats were created as the sigma-clipped (3σ) median of the normalized images. Once these preflats were derived, we used them to correct the assembled CCD images. We used these preflat-corrected CCD images to build an object mask with SExtractor (Bertin & Arnouts 1996). The settings used for the detection were optimized for faint object detection so to better mask faint sources. Again, for each CCD the masked and normalized images were combined to create the final flats.

Finally, each CCD was divided by the corresponding final flat. In Appendix B, we show a region of our i band images where the improvement of using the flats with the same rotation as the science images can be seen.

2.1.4. Astrometric Calibration and Frame Assembly

Before combining the CCDs into frames, we needed to refine the rough astrometry that the HSC camera provides. To do that, we used SCAMP (Bertin 2006) to put the science images into a common astrometric solution. SCAMP reads SExtractor catalogs and computes astrometric solutions for each individual CCD. The reference used is the stars of the Sloan Digital Sky Survey (SDSS) DR9 catalog (Ahn et al. 2012) in our field of view. The number of stars used in each mosaic frame (40 CCDs) for our astrometric solution is typically around a couple of hundred.

After computing the accurate astrometry for each CCD in each frame, we needed to make sure the CCDs were levelled before building the frame, i.e., all CCDs in the frame had the same sky counts. For each CCD, we ran SExtractor again. We built a mask by using the segmentation map obtained, further expanding the detected objects by 10 pixels. In addition, we masked all bright sources in the CCDs. This included bright stars to minimize the contamination of their extended halos, large galaxies, and ∼700″ in radius around the BCG. This constant correction is computed as the 3σ-clipped median of the remaining pixels and subtracted from the respective CCDs.

After levelling each CCD, we used SWarp (Bertin et al. 2002) to put together the 40 CCDs from each exposure into one single mosaic frame. SWarp resamples the CCDs putting them into a common grid using a LANCZOS3 interpolation function. The result was nine mosaic frames for both g and i bands.

2.1.5. Sky Subtraction

Sky subtraction is one of the most important steps for reducing low surface brightness data, as if done incorrectly, it can introduce unwanted gradients or remove partially or entirely the object we want to study. The sky determination and subtraction were done for each of the mosaic frames individually before the final co-addition step. We first masked all sources in the individual mosaics using the segmentation maps provided by SExtractor and further dilated each object by 20 pixels to minimize contamination of the fainter regions of objects that are not included in SExtractor’s segmentation map. Separately, we generously masked all bright sources (stars and galaxies) as well as the gaps between CCDs and created an additional mask to cover the center of the cluster to avoid contamination of the outer parts of the BCG (as done in Section 2.1.4 but now for the full mosaic). Once the mosaic
was masked, we distributed 50,000 boxes of \(100 \times 100\) pixels randomly throughout the image and computed the 3\(\sigma\) clipped median of the counts. We subtracted this constant sky value from the respective mosaic.

In addition, we also fitted a first degree 2D polynomial to the masked mosaics. As the size of the mosaics is larger than the physical extent of the ICL in the images, this ensures the correction of any remaining gradients in the image while preserving the diffuse light in this cluster. This 2D polynomial was then subtracted from the entire mosaic.

### 2.1.6. Image Co-addition

Once the science mosaics were sky subtracted and in a common astrometric solution, we used SWarp to co-add the mosaics into a final image. SWarp projects the input images into the output frame and co-adds them in an optimum way. The method used for the geometric resampling was LANCZOS3. The final output is created as the median of the nine mosaic frames. Finally, we computed and subtracted a constant sky value from the final co-added images.

The final exposure times of the images were 1800 s (30 minutes) for the \(g\) band and 2160 s (36 minutes) for the \(i\) band. The final \(g\) band mosaic is shown in Figure 1. The field of view is \(52' \times 52'\). In Figure 1, we also show RGB zoom-in images of two regions of the cluster. Region A shows a postage stamp of \(390'' \times 350''\) around the BCG of A85 (framed in purple) and region B shows a \(220'' \times 200''\) region around a massive galaxy belonging to one of the subclusters that was merging into A85 (Ichinohe et al. 2015; Owers et al. 2017; framed in green). The astrometric calibration was not accurate at the corners of our field of view, likely due to the lack of stars available to perform accurate astrometry there.

#### 2.1.7. Photometric Calibration

The photometric calibration of our images is based on the photometry of non-saturated stars in our field of view in common with the SDSS DR12 catalog (Alam et al. 2015). For each band, we chose stars within the magnitude range (SDSS “psfMag”) 18–21 mag, to avoid saturated stars in our mosaics, as can be seen in Figure 2, and very faint and noisy sources in the SDSS. For our images, we used “MAG_PETRO,” which provides an estimate of the total flux of the star. We matched the SDSS DR12 photometric catalog to ours, multiplying the frames by a factor to make the photometry in both catalogs equal. The typical number of stars that were used for photometric calibration within each individual mosaic image was \(\sim 700\) stars. The average dispersion in the photometry for each band was \(\sim 0.1\) mag, for both the \(g\) and \(i\) bands.

### 2.2. Modeling and Subtraction of Stars

The careful modeling and removal of stars in deep images is now a common technique in low surface brightness science (e.g., Slater et al. 2009; Trujillo & Fili 2016; Román et al. 2020). This is important in order to minimize the contamination by light scattered by the stars, especially bright stars, in our photometry of the faint ICL.

#### 2.2.1. Point-spread Function (PSF) Derivation

A robust and extended characterization of the PSF of the image is crucial to removing the stars in the field of view, in
particular bright stars close to the object of interest. For example, Uson et al. (1991) showed that the total amount of diffuse light measured around the BCG of A2029 would be in excess without removing nearby stars (their Figure 5).

In order to correct for this, we first constructed the PSF of our images. Generally, to derive PSFs, we needed to use stars with a wide range of brightnesses. The bright, saturated stars were used to characterize the outer parts of the PSF, or wings of the PSF, while fainter stars were used to characterize the core and intermediate parts.

The bright stars in Figure 1 show asymmetries due to internal reflections in the telescope and the nonuniform illumination through it. These asymmetries become more significant further away from the center of the camera. Given the limited amount of very bright stars in our image (N ≈ 10), we could not build a PSF in every position of the camera. Luckily, the object of interest (BCG + ICL) was very close to the center of the camera, therefore deriving a symmetric PSF to subtract nearby stars was a good approximation in this case.

2.2.2. Core and Intermediate Part of the PSF

In order to build the inner parts of the PSF, we followed a similar approach to the one in PSFEx (Bertin 2011). We first obtain a source catalog using SExtractor. The SExtractor catalog provides the half-light radius (“FLUX_RADIUS”) and the magnitude (“MAG_AUTO”) of the detected sources. It also provides the stellarity index “CLASS_STAR” for discerning between stars and galaxies. A CLASS_STAR close to 0 means that the object is very likely a galaxy, and 1 that it is a star. We select the objects of the catalog with CLASS_STAR greater than 0.98. To minimize the asymmetries that can smear the structure of the PSF, we selected stars only in the inner 40′ × 40′ of the image. Their magnitude and half-light radius distribution are shown in Figure 2. We selected non-saturated stars (light green box) to derive the core, while brighter and saturated stars (blue box) were used to derive the intermediate parts of the PSF.

We obtained the core and intermediate parts of the PSF by stacking the corresponding stars following these steps. First, we cut postage stamps around the selected stars of size 100 and 500 pixels² for the core and intermediate parts, respectively. In order to stack the stars, we needed to accurately estimate their center. To do that, we needed to mask all sources other than the selected star in the postage stamp. We used SExtractor’s segmentation map for this. Then, we fitted a 2D Moffat model to the masked postage stamp of the star. Once the center of the Moffat was obtained, we re-centered the postage stamp.

Second, we normalized each star by measuring a 1 pixel width ring at a radial distance of 15 pixels, avoiding the noisier outer parts (for the core stars) and the central saturated parts (for the intermediate stars). We also subtracted the sky around the stars in a 5 pixel width ring at a radius of 13″ for the core stars and 75″ for the intermediate stars.⁹

Finally, we stacked the normalized stars using a 3σ clipped median. The number of stars that were used for the stacking were 51 and 41 for the core, and 29 and 73 for the intermediate parts for the stacking were 51 and 41 for the core, 29 and 73 for the intermediate parts for the g and i bands, respectively.

2.2.3. Outer Parts of the PSF

As discussed above, we wanted a model PSF that is extended enough that we could subtract the wings of stars close to the BCG + ICL system. However, in our field of view there were not enough bright stars to properly derive the outer parts of the PSF. This is also limited by the asymmetries that were more evident as we moved away from the center of the image.

For that reason, we selected a few very bright stars that were in our field of view and derived their radial profiles. The profiles of these stars look very similar despite the asymmetries, therefore, we decided to use the radial profile of the closest bright star (m_i ≈ 11 mag, although saturated) to the center to build the outer part of the PSF. We adopted this methodology as a profile is more resistant to masking residuals or other artifacts that could bias the resulting PSF. It also means that this PSF will be symmetrical (i.e., we lose the spatial information). Note that the center parts of these very bright stars are strongly saturated causing bleeding in the detector, seen as spikes in Figure 1. We do not model these spikes.

We followed the same steps as for the core and intermediate parts. First, we cut a postage stamp of 2000 × 2000 pixels around the star. We masked all sources that were not the selected stars using the segmentation map. In addition, to mask sources that were in the star’s halo, we ran SExtractor on an unsharp-masked image (Sofue 1993) of the postage stamp. The unsharp-masked image was obtained smoothing the stamp by a Gaussian with σ = 30 pixels, which was then subtracted from the original. We combined both segmentation maps, from the original and the unsharp-masked image to create the final mask. We re-centered the postage stamp by fitting a Moffat2D model and shifting it to the new center given by the fit. In this case, the sky is subtracted at a distance of 325″ to avoid contamination from the star flux (S/N ∼ 1). Then, we measured the radial profile of the star.

After deriving the radial profile of the star, we built the 2D outer PSF by assigning the value of each point of the profile to its corresponding radial distance ring around the center. We then convolved the whole stamp with a σ = 1 pixel Gaussian to smooth the abrupt changes at each given radius. This smoothing did not change the shape of the profile of the star.

Finally, we extended this outer part with a power law in a similar way to Montes & Trujillo (2018). This last step is to minimize any sky subtraction issues in the outer parts of the star. We fit a power law to the PSF image between 95″ and

⁹ These radii were defined to reach the background in each of the postage stamps, i.e., to not include flux from the star, at a signal-to-noise ratio (S/N) of ∼1.
141″ for the g band and 221″ and 289″ in the case of the i band. This power-law fit was used to extrapolate the outer regions of the PSF to a radius of 420″.

2.2.4. Connecting the Different Parts of the PSF

Once we derived the four different parts described above, we constructed our final PSF. We followed a similar approach to Infante-Sainz et al. (2020). We used the radial profile of the bright star derived above as a reference for the connection and multiply the other profiles by a factor so that they matched the profile of the bright star at a given radius. The radius at which these connections were made changed depending on the band. Figures 3 and 4 show the final PSF profiles (black thick line) for the g and i bands, respectively. The shaded regions indicate the four different parts used to construct the final PSF derived in Sections 2.2.2 and 2.2.3. The profile of the bright star, which was used for building the outer part of the PSF is labeled as Outer 1 in orange. The power-law extrapolation to the bright star profile is Outer 2 in magenta. The core and intermediate parts are in teal and blue, respectively. We also show the different individual profiles used to construct the final PSF in their respective colors. The radii where the connections were made for each band and each of the different parts are indicated by the vertical lines in the plots in teal (connection between core and intermediate part), orange (between intermediate and the bright star profile) and magenta (between the bright star profile and the power-law extension). The total flux of the final PSFs (g and i) was normalized to 1.

2.2.5. Star Subtraction

To subtract the stars in our images, we followed similar steps to those in Román et al. (2020). We started by building a catalog of the positions of visually selected bright stars. There are two key aspects when fitting these stars: to obtain an accurate center of the star and to perform the flux calibration. We produced postage stamps for each of the stars of 500 × 500 pixels. Then, we masked all sources that were not the central star to avoid contamination that could affect the flux calibration and centering. This masking was done in two steps: (1) a first run to detect all sources with and (2) a second run where the detection image is an unsharp-masked image, with a Gaussian smoothing of σ = 20 pixels. This second step allows us to mask sources that were covered by the halo of the star and not properly detected in the first run. In both cases, the detection was done with SExtractor.

To accurately center the star, we calculated the centroids for each star by fitting a 2D Gaussian to the 2D flux distribution of the star using centroid_sources in photutils.

centroid_sources allowed us to define a box for fitting the Gaussian, useful in cases where the center of the star is strongly saturated.

Once the star was masked and centered, we performed the flux calibration. We first derived radial profiles for both the star and the PSF. By using the profiles rather than the stamps we minimized contamination due to masking residuals or other artifacts. To fit each star, we selected a range in radius for the calibration. The radial range is from 0.1 times the saturation level of the image to 4 times the value of the background of each postage stamp. This background was calculated as the standard deviation of the postage stamp with all the sources masked (including the star).

We scaled the PSF profile to match the star profile, using the ratio between the star and PSF values derived from the profiles. Once the PSF was centered and calibrated we subtracted it from the image. We repeated the same process for each of the stars in the catalog for both the g and i bands. Figure 5 shows a region of our image of A85 in the i band. The original image is seen in the left panel, while the middle panel shows the same region with the stars subtracted.

As mentioned above, the stars in the HSC images show asymmetries that become more evident further away from the

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10 The bending in the profile of the i band at 200″ is seen in the bright stars’ postage stamps as well as in their profiles and is not a consequence of the sky subtraction.
center of the image. However, we have built a symmetric PSF. As the object of interest, the BCG is centered in the image, and nearby stars that could affect our photometry will not present significant asymmetries. However, we note that this is a potential source of error for this study.

2.3. Masking

The study of the ICL in clusters of galaxies requires a very careful masking of foreground and background sources to reduce contamination that can affect the determination of the color of this light. In the case of deep images, this masking must be optimized not only for faint and small background objects but also for those that are closer and large.

As a single setup for the detection and masking of both types of sources is unfeasible, we used a two-step approach like that of Montes & Trujillo (2018); a “hot+cold” mode (e.g., Rix et al. 2004). The “cold” mode will detect the extended bright galaxies from the cluster while the “hot” mode is optimized to detect the faint and small sources. We used this approach on a deep combined g + i image, after star subtraction. In the case of the “hot” mode, we unsharp-masked the original image, to enhance the contrast, particularly in the central parts of the BCG. To create the unsharp-masked image, we convolved the image with a box filter with a side of 25 pixels and then subtracted it from the original. The threshold for detection was 1.1σ above the background.

The cold mask was further expanded 10 pixels, while the hot was expanded 5 pixels. Both masks were combined to create the final mask for our images. Before this, we unmasked the BCG on the cold mask. The bleeding spikes were manually masked as well as the residuals from the subtraction of stars and their asymmetries.

We created two masks for the cluster. In the first mask, all the objects of the image were masked except for the members of the cluster contained in our field of view and the diffuse ICL. For that, we used the spectroscopic membership information obtained from Owers et al. (2017). The morphological information obtained from SExtractor’s cold mask run is used to unmask the members of the cluster.

For the second mask, all the objects are masked except for the BCG and ICL. As SExtractor does a poor job detecting low surface brightness outskirts, we manually extended the masks for the remaining objects after visual inspection.

The final mask was again visually inspected to manually mask any remaining light that was missed by the process described above. In the right panel of Figure 5, we show an example of the mask in one region of our image.

2.4. Surface Brightness Limits

Our goal is to study the low surface brightness features in A85 down to the faintest surface brightness possible. For this reason, we needed to know how deep our images were by estimating the surface brightness limits that they reach. To obtain these limits, we calculated the rms of the final masked images by randomly placing 20,000 boxes of 10 × 10 arcsec$^2$ (≈10 × 10 kpc$^2$) across the images. In this case, we also masked the BCG and ICL by adding an ellipse of the semimajor axis (SMA) of 67″ centered in the image.

The 3σ surface brightness limits were $μ_{3σ}^{lim}(3σ, 10″ \times 10″) = 30.9$ mag arcsec$^{-2}$ and $μ_{3σ}^{lim}(3σ, 10′′ \times 10′′) = 29.7$ mag arcsec$^{-2}$. These limits were calculated following Appendix A in Román et al. (2020).

3. The Intracluster Light of A85

3.1. Radial Surface Brightness Profiles

The goal of this paper is to study the diffuse light in HSC images of A85. To that end, we derived the radial profiles for the g and i bands using the software ellipse in IRAF. ellipse fits elliptical isophotes to the 2D images of galaxies using the method described in Jedrzejewski (1987). It provides the mean intensity, ellipticity, position angle (PA), and harmonic amplitudes (deviations from perfect ellipticity) for each fitted isophote. By deriving the 1D profiles this way, we are not assuming any particular model or models to describe the BCG+ICL, as they might be sensitive to the choice of the particular model and prone to degeneracies between the different parameters.

ellipse was run on the star-subtracted, masked images. We first ran the task allowing all parameters to vary freely. In the second run, we fixed the centers to the median centers of the isophotes returned by ellipse in the first iteration. We adopted the median setup in ellipse. The surface brightness profiles reached a signal-to-noise ratio (S/N) of 2.8 (3.0) at 27.1 (25.7) mag arcsec$^{-2}$ in g (i), which corresponds to a radius of 200″ or 213 kpc. Figure 6 shows the output of ellipse for A85. The left panel shows the 700″ × 700″ region around the BCG11 with the fitted ellipses. The 1D radial surface brightness

11 Known as Holm 15A.
profiles as a function of the SMA for the $g$ (green) and $i$ (purple) bands are shown in the middle panel, up to 250$''$. These surface brightness profiles are corrected for the absorption of our galaxy ($E(B-V) = 0.034$; Schlafly & Finkbeiner 2011) and surface brightness dimming. The profiles are also $k$-corrected (Chilingarian et al. 2010; Chilingarian & Zolotukhin 2012). The shaded regions represent the errors of the profiles computed as the rms scatter of each isophote.

The vertical gray lines in all the panels indicate the FWHM of the $g$ (solid; 1.07$''$) and $i$ (dashed; 0.78$''$) bands. The FWHM of each image is given by twice the average “FLUX_RADIUS” (the half-light radius) of stars obtained from SExtractor (see Figure 2). These lines define the regions where the isophotal fits are not reliable. The right panel shows the ellipticity (top) and PA (bottom) with the SMA for both bands.

The surface brightness profiles derived here show a flattening in the central regions of the BCG ($\lesssim 10''$, 11 kpc). This flattening in the inner $\sim 10''$ has already been reported (e.g., López-Cruz et al. 2014; Madrid & Donzelli 2016). In fact, the BCG of A85 is known to host one of the largest cores measured to date (López-Cruz et al. 2014).

Beyond the core, the surface brightness radial profiles roughly follow a Sérsic (1968) profile. However, in the middle panel of Figure 6, there appears to be a break in the profile at a radius of $\sim 70''$ ($\sim 75$ kpc), where the profiles become shallower.

In order to explore whether there is a break in the surface brightness radial profiles, we fit a single Sérsic profile to both bands, excluding the inner $10''$. These fits are performed using a least squares fitting method as suggested in Seigar et al. (2007). The best fits to the profiles are shown in Figure 15 and the parameters are listed in Appendix C. We show the residuals of subtracting the best Sérsic fit from the surface brightness profiles in the top panel of Figure 7. The figure shows that at a radius of $\sim 70''$ ($\sim 75$ kpc) there is an excess of light with respect to the Sérsic fit. This indicates that there is an extra component over the galaxy; the ICL. The position of the break found here is consistent with that in Zibetti et al. (2005), where a similar flattening is found at a radius of $\sim 80$ kpc in their stacked profiles of multiple clusters.

The ellipticity of the diffuse light of A85 increases with radius up to a value of ellipticity $\sim 0.55$ for both bands at a radius of $\sim 200''$ ($\sim 213$ kpc), as shown in the top right panel of Figure 6. Kluge et al. (2020) also observed an increase in ellipticity for A85. However, at a radius of $\sim 250$ kpc, their ellipticity profile drops sharply to a value of 0.1. We do not see any evidence of such a decrease in our profiles. In contrast, the PA does not show any significant change with radius.

Departures from perfect elliptical isophotes can be described as Fourier harmonic perturbations (Jedrzejewski 1987). The coefficients of these harmonic series carry physical meaning. For example, B4, the 4th Fourier amplitude, indicates the boxiness/diskiness of the isophotes. In the bottom panel of Figure 7, we show the B4 coefficient as a function of the SMA. The radius where the break of the surface brightness profile is located, 70$''$, also corresponds to where the B4 becomes negative, i.e., the ellipses start showing a boxy shape. This radius is indicated in both panels of Figure 7 by a gray vertical line. This is a confirmation of the boxiness visible in the outer parts of the BCG (inset A in Figure 1). Boxiness has been found to be related to galaxy interactions (e.g., Nieto & Bender 1989).

3.2. Color Profile of the BCG+ICL

Radial color gradients provide valuable constraints in the formation processes of galaxies, and consequently, the BCG and ICL (e.g., Montes & Trujillo 2014, 2018). The radial color profile was measured in 55 logarithmic spaced bins from $0''$ to $200''$. The distance to each pixel in the images is computed as the elliptical distance to the BCG, where the morphological parameters (ellipticity and PA) are the median values from the ellipse isophotes excluding the inner $10''$. 0.37 for the ellipticity and 56$^\circ$ for the PA. For each radial bin, the surface brightness in each band was obtained by averaging the pixel values. The errors were drawn from jackknife resampling, i.e.,

12 Note that the goal of this fit is to locate the break, not to describe the light profile.

13 Our ellipticity profile remains constant at $\sim 0.5$ to a radius of 320 kpc, although the S/N at that radius is $\lesssim 1$. 
repeating the photometry in a subsample of the data for each bin. The number of subsamples per bin was 100. Figure 8 shows the $g - i$ color profile for the BCG+ICL of A85 down to 200″ (213 kpc; light blue line). The color profile is k-corrected and corrected for the extinction of the Galaxy. The error in the color profile, represented as the light blue area, is the sum of the errors in the individual surface brightness radial profiles. We have also plotted the $g - i$ color of the satellite galaxies in the cluster as reported by Owers et al. (2017).

The color profile of the BCG + ICL shows three distinct regions: (i) a flat region out to 10″ indicative of the core of the galaxy, (ii) a negative color gradient from 10 to $\sim$70″ and (iii) a region from $\sim$70″ to $\sim$200″ where the color gradient of the diffuse light becomes shallower. To see if there is a difference, we calculated the gradients of each region as a linear fit to the color profile $g - i$ versus log $R$ ($\Delta g/i$). The fits are shown in Figure 8 as the dark blue lines. The gradients for the different regions are (i) $-0.01 \pm 0.01$ (dashed line), (ii) $-0.24 \pm 0.01$ (dotted line), and (iii) $-0.06 \pm 0.04$ (dashed–dotted line).

The flat color profile at SMA $<10″$ ($<11$ kpc) coincides with the size of the core of the galaxy as seen by López-Cruz et al. (2014). This is consistent with a mixing of the stellar populations in the center of the galaxy.

The region between 10″ and $\sim$75″ (11 and $\sim$80 kpc) presents a negative gradient in the $g - i$ color from 1.45 to $\sim$1.25 ($\Delta g/i = -0.24 \pm 0.01$). It is well known that massive early-type galaxies have negative optical color gradients indicating gradients in their stellar populations, generally metallicity (e.g., Peletier et al. 1990; Davies et al. 1993; La Barbera et al. 2012; Huang et al. 2018; Santucci et al. 2020).

Beyond $\sim$75″ ($\sim$80) kpc, the color profile becomes significantly shallower ($\Delta g/i = -0.06 \pm 0.04$) with a median color of $g - i = 1.25$. The observed behavior of the color profile of A85 is consistent with the color profile in Zibetti et al. (2005) (also, Coccato et al. 2010; Montes et al. 2014; Spavone et al. 2020). Zibetti et al. (2005) explored the $g - r$ color profile of stacked clusters in the SDSS. Their color profile also shows a gradient down to $\sim$80 kpc where it shallows.

There are some nearby bright stars both east and west of the BCG. Inaccuracies in the star subtraction process could bias the colors that we obtain, particularly the colors of the faintest regions of the ICL. In order to assess that potential issue, we derive the color profiles in four different directions of the BCG: north, east, south, and west.

The four different profiles were derived by masking the BCG + ICL except for 90″ wide sections as shown in the left panel of Figure 9, labeled as north (orange, N), east (green, E), south (purple, S), and west (magenta, W). The profiles are derived in the same way as the overall color profile. The right panel in Figure 9 shows the color profiles color coded by their respective sections. The color profiles behave similarly up to $\sim$50″ where the southern profile flattens (purple line, $g - i \approx 1.3$) to a radius of $\sim$100″ (107 kpc). Similarly, the northern (orange) and western
profiles show flattening, and even reddening (north profile), between 80° and 130°.

While for the southern profile there is not a clear origin for the observed flattening, the shape of the northern profile could be affected by the presence of a large satellite (at a projected radius of \(\sim 75''\), zoomed-in in Figure 11). This is also the case for the western profile as there are some galaxies at \(\sim 145''\). We will discuss this in detail in the following section.

Given that the closest bright stars are only located east and west of the BCG, these color profiles confirm that the change in gradient is not caused by the presence of these stars but rather caused by the presence of diffuse light associated with ongoing mergers.

### 3.3. Fraction of Light in the ICL

Studying the amount of light in the ICL can provide information on the efficiency of the interactions that form the ICL. This is given by the ICL fraction, defined as the ratio between the ICL and the total (BCG + galaxies + ICL) flux or luminosity of the cluster. This ICL fraction is an ill-defined quantity in photometric-only studies as separation between BCG and ICL is not obvious. To overcome this problem, astronomers have been using different ways of defining the ICL component in deep photometry. In the following, we describe two of the most widely used definitions. We derived the ICL fraction for A85 using both of them, for ease of comparison with other studies.

#### 3.3.1. ICL Fraction from Surface Brightness Cuts

The most widely used definition is to apply a cut in surface brightness and assume that the light fainter than a certain surface brightness limit is the ICL (typically \(\mu_V > 26.5\) mag arcsec\(^{-2}\), e.g., Feldmeier et al. 2004; Rudick et al. 2011). To derive the ICL fraction for the \(g\) and \(i\) bands, we followed similar steps to those in Montes & Trujillo (2018). First, we applied the mask where all the members of the cluster are unmasked, derived in Section 2.3, to each of the images. In each of the bands, we summed all the pixels that were fainter than a given ICL threshold. The fractions given have a fainter limit of \(\mu < 29.5\) mag arcsec\(^{-2}\) in order to minimize the contamination from inhomogeneities in the background. The ICL fractions are derived applying three different surface brightness cuts: \(\mu > 26\), 26.5, and 27 mag arcsec\(^{-2}\). We provide the ICL fractions for both the \(g\) and \(i\) bands in Table 2.

| Surface Brightness Cuts | 26 < \(\mu\) < 29.5 | 26.5 < \(\mu\) < 29.5 | 27 < \(\mu\) < 29.5 | 27.5 < \(\mu\) < 29.5 |
|-------------------------|----------------------|----------------------|----------------------|----------------------|
| \(f_{\text{ICL}}(g)\)  | 8.8 ± 0.5            | 6.2 ± 0.7            | 4.0 ± 0.9            | 2.4 ± 0.9            |
| \(f_{\text{ICL}}(i)\)  | 3.1 ± 0.7            | 1.9 ± 0.7            | 1.1 ± 0.7            | 0.6 ± 0.7            |
| 2D fit                  | \(g\) 11.0 ± 1.0      | \(g\) 11.5 ± 1.0     | \(i\) 18.0 ± 2.0     | \(i\) 63.7 ± 2.2     |

Table 2

ICL Fraction (%) for A85
The ICL fractions calculated this way account not only for the diffuse light associated with the BCG but also with other galaxies in the cluster. Note that defining the ICL this way means that the measured fractions are a lower limit of the true value; we are missing light in both the brighter (e.g., in projection) and fainter limit.

3.3.2. ICL Fraction Assuming a Functional Form

Despite its simplicity, one of the limitations of the above definition is that it does not account for the amount of ICL in projection on top of the BCG. Another common approach is using functional forms to describe both the BCG and ICL (e.g., Gonzalez et al. 2005; Seigar et al. 2007; Spavone et al. 2018, to name a few). In our case, we use GALFIT (Peng et al. 2002) to simultaneously fit two two-dimensional Sérsic profiles: one to describe the BCG and one for the ICL. The parameters for the two fitted Sérsic components are given in Table 4 in Appendix C. Although the fits seem to describe well the overall profile, they are not able to reproduce the inner core of the galaxy (as in the case of the single Sérsic fit, Figure 15). Contrary to the single Sérsic fit performed in Section 3.1, we now find that the inner component is an exponential, similar to the outer component ($n_1 \sim 1$ and $n_2 \sim 2.15$). This difference between the single and double Sérsic fits is probably caused by the single component trying to fit the outer parts of the BCG+ICL profile.

As expected from the ellipse 1D profiles in Section 3.1, the more extended component (the ICL) has a higher ellipticity than the inner component (the BCG, see also Kluge et al. 2021). However, the PAs in both models are not significantly different ($\Delta PA \sim 4^\circ$).

The 1D surface brightness profiles obtained with ellipse for the double Sérsic fits are shown in Figure 10. As in Figure 6, the observed surface brightness profiles of the $g$ and $i$ bands are shown in mint green and purple, respectively. The two different Sérsic models (inner and outer) are shown by the dashed gray lines, while the sum of both models is represented by the solid black line. As in Figure 7, it can be seen that the outer component, the ICL, dominates at around $\sim 60^\prime$–$70^\prime$.

The ICL fraction obtained using the outer Sérsic model is given in Table 2. We have also derived the fraction of BCG+ICL with respect to the total and the ratio between the ICL and BCG+ICL.

The ICL fractions derived from assuming a double Sérsic to describe BCG+ICL are higher than those from surface brightness cuts. This is expected because we extrapolated the contribution of the diffuse light in the line of sight of the BCG, which results in adding more ICL that surface brightness cuts cannot account for. Figure 10 shows that while the extended Sérsic component begins to dominate at $r = 70$ kpc, a surface brightness limit of $m_g > 26$ mag arcsec$^{-2}$ will measure all the light beyond 110 kpc as ICL. Note that a surface brightness cut also accounts for diffuse light that is associated with the other galaxies in the cluster and might give a more complete picture of the formation of ICL in clusters.

The fractions calculated in this section include all member galaxies of the cluster. That is, $r = 0.42^\circ = 0.67 \times R_{200}$ (where $R_{200} = 0.63^\circ = 2.42$ Mpc; Owers et al. 2017). Other studies measure the ICL fraction in smaller radius, typically $R_{500}$ (e.g., Gonzalez et al. 2007). This means that, in comparison, we are including more galaxies and therefore deriving a higher total luminosity for the cluster. That yields to lower ICL fractions than in other studies with more limited field of views (e.g., Burke et al. 2015; DeMaio et al. 2020). For this reason, we have also calculated the fractions within $R_{500} = 1.2$ Mpc = $18.7^\prime$ (Ichinohe et al. 2015). The fractions within $R_{500}$ can be found in Table 5 in Appendix F.

4. Discussion

In this work, we have used archival HSC data to explore the radial surface brightness and color profile of the BCG of A85 to a radius of $200^\prime$ (213 kpc). We found that both the surface brightness and color profile become shallower beyond $70^\prime$ (75 kpc), indicating that an extra component, the ICL, starts to dominate. In the following, we will discuss the implications of our results.

4.1. The Fraction of Light in the ICL

The ICL is a product of the interactions between galaxies within the cluster (Rudick et al. 2009), therefore, its fraction can provide information on the efficiency of those interactions, while the evolution of this component with time gives an estimation of their timescales. However, measuring the ICL...
fraction is difficult as the transition between BCG and ICL happens smoothly, making it hard to separate both components. In addition, studies use different bands and definitions for the ICL complicating direct comparison.

In general, the ICL fractions derived here using surface brightness cuts are in agreement with those in the literature for clusters at similar redshifts (although in different, adjacent, bands and surface brightness limits, e.g., Krick & Bernstein 2007). Our ICL fraction at $\mu > 26$ mag arcsec$^{-2}$ is $\sim 9.8\% \pm 0.5\%$ (Table 5). This is in agreement with the median ICL fraction (using the same band and surface brightness cut) in Kluge et al. (2021): 13% ± 13%. It is also in agreement with the ∼11% at $\mu_V > 26.5$ mag arcsec$^{-2}$ derived in the simulations of Rudick et al. (2011).

Simulations show that 70% of the stellar mass of the BCG is accreted (Qu et al. 2017; Pillepich et al. 2018). This means that most of the BCG is formed in a similar way to the ICL, and therefore they should be studied in order to understand the growth of BCGs. For this reason, we also measured the fraction of BCG+ICL over the total luminosity of the cluster, $f_{\text{BCG+ICL}}$. This fraction is ∼46% at $r < R_{500}$, in agreement with Gonzalez et al. (2007, 2013) for clusters at similar redshifts.

The fraction of ICL over the BCG+ICL component, $f_{\text{ICL/BCG+ICL}}$ (∼64%) indicates that most of the total light in the BCG+ICL system in A85 is in the ICL. This result agrees with the fractions from previous observations and simulations (e.g., Gonzalez et al. 2005; Zibetti et al. 2005; Seigar et al. 2007; Cañas et al. 2020; Kluge et al. 2021). In the simulations of Conroy et al. (2007), similar fractions are achieved if all the stars from disrupted satellites end up in the ICL (their Figure 4). These results from simulations, coupled with the observed mild evolution in mass of BCGs (e.g., White et al. 2008; Collins et al. 2009; Lidman et al. 2012; Oliva-Altamirano et al. 2014; Bellstedt et al. 2016), suggests that a significant fraction of the mass of infalling satellites goes to the stellar halo + ICL instead of adding a significant fraction of mass to the BCG (e.g., Laporte et al. 2013; Contini et al. 2018).

### 4.2. Stellar Populations of the BCG

Studying the colors of the ICL in clusters allows us to infer the properties of the progenitor galaxies from which the ICL accreted its stars, and consequently, the mechanisms at play in the formation of this component.

In Section 3.1, we presented the surface brightness radial profiles of the BCG + ICL for the $g$ and $i$ bands. Both surface brightness profiles show a flat region in the inner 10″ (11 kpc), denoting the presence of a core (e.g., López-Cruz et al. 2014; Madrid & Donzelli 2016). In the same way, the measured color profile is flat in the inner 10″, indicating that the stellar populations in this region are well mixed. Mehrgani et al. (2019) used the Multi Unit Spectroscopic Explorer (MUSE) data to infer the stellar kinematics of this BCG, finding that this central region hosts a supermassive black hole with a mass of $4.0 \pm 0.8 \times 10^{10} M_\odot$. They concluded that the BCG of A85 is a result of the merger of two cored early-type galaxies.

Beyond 10″, the surface brightness profiles follow a Sérsic (1968) profile down to ∼70″ (∼75 kpc). At the same time, the color profile shows a negative gradient from $g - i = 1.25$ to $g - i \approx 1.25$. The central flattening and subsequent gradient in color is also observed in the integral field spectroscopy observations of A85 in Edwards et al. (2020). They find that out to 30 kpc the metallicity of the galaxy shows the same behavior as our color profile: a flattening in the inner ∼10 kpc (∼10″, followed by a decrease to ∼30 kpc (28″).

At ∼70″, the surface brightness profiles depart from the Sérsic profile (top panel in Figure 7). This corresponds to where the isophotes show a boxy shape (indicated by the gray vertical line in Figure 7). Simulations suggest that boxiness is the result of a past dry merger event (e.g., Naab et al. 2006). In addition, at this radius, the color profile becomes shallower. These pieces of evidence point to an extra component originating from accreted stars: the ICL. It is not possible to break the degeneracy between stellar age and metallicity using only one color. Previous deep observations of clusters of galaxies show clear radial gradients in colors (e.g., Williams et al. 2007; Montes & Trujillo 2014, 2018; DeMaio et al. 2015, 2018; Iodice et al. 2017; Mihos et al. 2017), indicating radial gradients in metallicity, while the ages of the ICL in nearby systems are old ($>10$ Gyr, e.g., Williams et al. 2007; Coccato et al. 2010). This is consistent with the results in Edwards et al. (2020), who only found a very mild decrease in age to 30 kpc for A85, from ∼15–10 Gyr. Therefore, at <30 kpc, the color profiles likely mostly trace changes in metallicity. However, we cannot test here whether the decrease in age becomes significant beyond 30 kpc.

The shape of the color profile is reminiscent of the three different regions found in the metallicity profile of M87 in Montes et al. (2014) (see also Coccato et al. 2010). In M87, the metallicity gradient becomes shallower in the outer parts of the galaxy. This is a consequence of the mixing of the stellar populations of the accreted galaxies. This also appears to be the case for A85 and is supported by the change in the slope of the surface brightness profiles, where the outer parts of the galaxy (the ICL) are built via the accretion of satellite galaxies.

In Section 3.2, we derived color profiles of the BCG+ICL in four different 90° wide sections, finding that the southern color profile between 50″ and 100″ (53–106 kpc) is redder than the other profiles (∼1.3; Figure 9). Similarly, the north and west profiles become flat between 80″ and 130″.

To explore whether there is any evidence of infalling material that might be causing the flattening of the profiles, we subtracted the ellipse models from the image for both bands to enhance any signs of interactions or asymmetries. In Figure 11, we show the inner 700″ × 700″ region of A85 with the model generated from the ellipse fits subtracted. We drew arcs to demarcate the areas in the image corresponding to the flattening of the color profiles, color coded according to the direction of the corresponding profile in Figure 9. Toward the north, we found a faint tail associated with a large satellite galaxy (zoomed-in in Figure 11 and marked with a purple arrow). The presence of this faint tail might explain the sudden reddening of the northern color profile at ∼130″ shown in Figure 9. As there are no other signs of disturbance, this galaxy is probably just starting to interact with the BCG. To the west, there is some diffuse light associated with two galaxies that are likely interacting with the BCG. Even with our careful and conservative masking, the diffuse light associated with these interactions might be contaminating our profiles.

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15 More specifically, it is the stellar halo or envelope (bound to the BCG) + ICL (bound to the cluster) as we cannot distinguish between both components using imaging alone.

16 ICL + stellar halo.
quickly destroyed by the strong, evolving tidal field of the cluster with timescales of $\lesssim 1$ Gyr. Therefore, for a star not to have orbited the galaxy but any stream to be smeared, we suggest that this interaction likely happened a few gigayears ago.

4.2.1. The Ellipticity Profile and the ICL as a Tracer of Dark Matter

A significant anisotropy in the orientation of the orbits of the progenitors of the ICL will produce an elongation in the ICL distribution. This elongation, i.e., ellipticity, is expected to increase with increasing radius up to the value of the original distribution, i.e., the cluster distribution. The ellipticity of the diffuse light of A85 increases with radius up to a value of $\sim 0.55$ at $\sim 200''$ ($\sim 213$ kpc), for $g$ and $i$ (Figure 6). However, the PA does not change significantly with radius, i.e., the inner and outer components are aligned.

This increase in ellipticity with radius was also observed in this cluster by Kluge et al. (2020). The same trend in radius has been measured in other massive galaxies and clusters (e.g., Gonzalez et al. 2005; Tal & van Dokkum 2011; Huang et al. 2018; Kluge et al. 2020, 2021). The ellipticities of the diffuse light in these systems tend to the typical values for the distribution of galaxies within clusters (Shin et al. 2018). When fitting a double Sérsic model to the 2D distribution of light of the BCG+ICL, we also found that the ellipticity of the outer component, the ICL, has a higher ellipticity ($\sim 0.5$) than the inner component, the BCG ($\sim 0.2$).

The value of the ellipticity at large radii derived here is consistent with the axis ratio measured for A85 using weak-lensing modeling by Cypriano et al. (2004). That is, the ICL has the ellipticity of the dark matter halo of the cluster. These results agree with the picture proposed in Montes & Trujillo (2019) that the ICL is a good luminous tracer of the dark matter distribution in clusters of galaxies.

4.3. The Buildup of the ICL of A85

The change in the slope of the surface brightness profile of the BCG, the boxiness of the isophotes, and the change in the slope of the color gradient at a radius of $\sim 70''$ ($\sim 75$ kpc) suggests strongly that the BCG and ICL can be considered as distinct stellar components with different assembly histories, and that the accreted component (ICL) starts to dominate at that radius. Integrated light spectroscopy (e.g., Dressler 1979) and planetary nebulae kinematics (e.g., Arnaboldi et al. 1996) of nearby clusters show that the radial velocity dispersion increases with radius to reach the value of the velocity dispersion of the galaxies in the cluster (Longobardi et al. 2018). That means that the stars forming the ICL are following the potential of the cluster rather than the potential of the BCG. We can conclude that the radius where the potential of the A85 cluster begins to dominate is $\sim 70''$ ($\sim 75$ kpc, see Figure 10). Previous works have also shown that, in massive clusters $(10^{14}$–$15 M_\odot)$, BCGs tend to show this break radius at around 60–80 kpc (e.g., Gonzalez et al. 2005; Zibetti et al. 2005; Seigar et al. 2007; Iodice et al. 2016).

We can calculate an approximate mass of the progenitor of the merger using the color of the southern profile. If the average color of the reddening in the southern profile is around $g - i = 1.3$ (Figure 9), and assuming an age of 10 Gyr, the metallicity of the progenitor would be $[Z/H] = -0.013$ (using the models of Vazdekis et al. 2016), i.e., slightly subsolar metallicity. Using the mass–metallicity relation from Gallazzi
et al. (2005), this corresponds to a galaxy of \( \sim 3 \times 10^{10} M_\odot \). The galaxies toward the north and west that interact with the BCG have masses of the order of \( \sim 7 \times 10^{10} M_\odot \) (Owers et al. 2017). This is in agreement with observations in other clusters (Montes & Trujillo 2014, 2018; Morishita et al. 2017; DeMaio et al. 2018) and with simulations (Purcell et al. 2007; Contini et al. 2014, 2019; Cui et al. 2014). These studies conclude that galaxies of \( \sim 10^{10} M_\odot \) are the main contributors to the ICL in massive clusters of galaxies.

5. Conclusions

In this work, we have presented deep observations in the g and i bands of the central 52′ × 52′ of the cluster A85, obtained with Hyper Suprime-Cam on the Subaru Telescope. The surface brightness limits reached are 30.1 and 29.7 mag arcsec\(^{-2} \) (3\( \sigma \), 10 × 10 arcsec\(^2 \)), for the g and i bands, respectively. Taking advantage of the depth of these images, we were able to study the diffuse light of this cluster down to 200′′ (213 kpc) from the BCG. At \( \sim 70′′ \) (\( \sim 75 \) kpc), the surface brightness profiles become shallower and the isophotes show a boxy shape, strongly indicating the presence of an accreted component: the ICL. In addition, at the same radius the color profile becomes shallower, a consequence of the mixing of the stellar populations of the accreted galaxies.

Furthermore, the color profile toward the north, west, and south of the BCG show a redder color compared to the other profiles as if there is remaining material in that direction from a merger that happened a few gigayears ago. This work shows that even short exposure times (\( \sim 30 \) minutes) on large telescopes can unveil the assembly history of clusters of galaxies.

The results presented in this work show the extraordinary power of ground-based observatories to address the origin and evolution of the ICL. In the future, the Legacy Survey of Space and Time will be able to provide deep multiband observations of the southern sky, allowing the study of the ICL in a range of cluster masses and redshifts (Montes 2019; Brough et al. 2020). However, as demonstrated in this work, careful data processing techniques are crucial in order to obtain the maximum benefit from the upcoming data.

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Facility: Subaru Telescope

Software: Astropy (The Astropy Collaboration et al. 2018), SExtractor v2.19.5 (Bertin & Arnouts 1996), SWarp v2.38.0 (Bertin et al. 2002), SCAMP v2.0.4 (Bertin 2006), photutils v0.7.2 (Bradley et al. 2019), pillow (van Kemenade et al. 2020), ellipse (Jedrzejewski 1987), GALFIT (Peng et al. 2002).

Appendix A

Effect of Instrument Rotation on the Flat Fields

In Section 2.1.3, we discussed that we used HSC-SSP images of adjacent nights to the observations of A85 in order to derive a sky flat. However, in the case of the i band, using the images of adjacent nights resulted in significant background substructure in the individual CCDs, and consequently, a global structure in the individual frames. The source of this structure seems to be related to the rotation angle of the instrument (“INR-STR” in the header) being considerably different from that of the observed images \( \langle \text{INR-STR} \rangle \approx -5 \) in the HSC-SSP Wide images compared to \( \langle \text{INR-STR} \rangle \approx 124 \) for A85.

To test this hypothesis, we downloaded images from the SMOKA archive where INR-STR was close to the angle of the A85 i band images. As it was difficult to find the same rotation angles as the A85 images, we downloaded images with angles between 100 and 140. The average rotation angle of these images are \( \langle \text{INR-STR} \rangle \approx 114 \). The dates when those images were taken are listed in Section 2.1.3. In Figure 12, we show a comparison of the two different flats derived for CCD number 80.\(^{17} \) The flat derived from the images from adjacent nights is shown in the left panel, labeled as Flat. The middle panel shows the flat derived from the images with a median instrument rotation close to the A85 images, labeled as Flat. The right panel of Figure 12 is the ratio of the two flats; Flat divided by Flat,. The presence of a significant gradient across the CCD can be seen. This gradient is of the order of \( \sim 1\% \).

In Figure 13, we show the comparison of the final co-added images for the i band using the flats derived using science images of adjacent nights (labeled Flat, left panel) and using the flats obtained with the science images with the same rotation as the A85 image (the final image used in this work labeled Flat, right panel). In the left image, we can see inhomogeneities caused by the poor flat-field correction to the individual CCDs.

\(^{17} \) Map of the CCD arrangement here: https://hsc.mtk.nao.ac.jp/pipdoc/pipdoc_4_e_/images/CCDPosition_20140811-1.png.
An accurate flat-field correction is crucial to minimize errors in low surface brightness science, especially in extended and diffuse objects such as the ICL. For this reason, we derived the flats from science observations instead of using the HSC master flats as inhomogeneities in the illumination can introduce gradients in our images. During this work, we found that the HSC master flat from CCD 75 does not contain a feature that is present in the data (indicated by purple lines in Figure 14). We do not know the reason for this discrepancy. However, the master flat does seem to reproduce all other features seen in the CCD image.
Appendix C
Sérsic Fits 1D and 2D

In Figure 15, we show the single Sérsic fits to the radial surface brightness profiles of A85, for the $g$ (green) and $i$ (purple) bands. The best-fit effective radius ($r_{\text{eff}}$) and Sérsic index ($n$) parameters are listed in Table 3, for both bands. Table 4 lists the parameters from the double Sérsic fit obtained using GALFIT in Section 3.3.2.

Figure 15. 1D single Sérsic fits to the BCG+ICL profile of A85.

| Band | $r_{\text{eff}}$ (arcsec) | $n$   |
|------|-----------------|------|
| $g$  | 39 ± 6          | 4.0 ± 0.7 |
| $i$  | 36 ± 4          | 4.9 ± 0.8   |
Table 4
Parameters from the Double Sérsic fit from GALFIT

| Band | $m_1$ (mag) | $r_{\text{eff},1}$ (arcsec) | $n_1$ | $\epsilon_1$ | PA$_1$ | $m_2$ (mag) | $r_{\text{eff},2}$ (arcsec) | $n_2$ | $\epsilon_2$ | PA$_2$ |
|------|-------------|-----------------------------|------|-------------|--------|-------------|-----------------------------|------|-------------|--------|
| g    | 14.37 ± 0.01 | 15.02 ± 0.01 | 1.08 ± 0.01 | 0.20 ± 0.01 | 54.40 ± 0.02 | 13.49 ± 0.01 | 173.0 ± 0.2 | 2.14 ± 0.01 | 0.49 ± 0.01 | 58.63 ± 0.02 |
| i    | 12.96 ± 0.01 | 14.29 ± 0.01 | 1.04 ± 0.01 | 0.19 ± 0.01 | 54.16 ± 0.02 | 12.20 ± 0.01 | 172.6 ± 0.2 | 2.18 ± 0.01 | 0.53 ± 0.01 | 58.82 ± 0.02 |
Appendix D

Color Profiles of A85 after Masking Diffuse Structures

In Section 4.2, we discussed the existence of diffuse structures north, south, and west of the BCG with associated diffuse light that might be causing the flattening of the color profile. In Figure 16, we show the $g-i$ color profile (top panel) and the B4 coefficient (bottom panel) with these structures masked. We did not find any significant change within errors.

Figure 16. Color profile and B4 coefficients as a function of the SMA after masking the collection of galaxies to the south of the BCG. We did not find any significant difference within errors with respect to the results from Section 3.2 (in dark blue).
Appendix E
Calculation of the Orbital Period around A85

To estimate the orbital period ($T$) of a star at a given radius ($R$) around A85 we used Kepler's third law:

$$T = 2\pi \sqrt{\frac{R^3}{GM_R}},$$

(E1)

where $M_R$ is the mass of the BCG of A85 inside a radius $R$ and $G$ is the gravitational constant (Binney & Tremaine 1987).

In order to calculate $M_R$ for A85, we followed the prescription in Bell et al. (2003) to calculate the mass-to-light ratio ($M/L$) as a function of the $g-i$ color, assuming a Salpeter (1955) IMF. The radius is computed as the elliptical distance to the BCG, where the morphological parameters (ellipticity and PA) are the median values from the ellipse isophotes excluding the inner 10″: 0.37 for the ellipticity and 56° for the PA. The expression we have used to estimate the $M/L$ in the g band is

$$\log(M/L_g) = -0.379 + 0.914 \times (g - i)$$

(E2)

from Table 7 in Bell et al. (2003). The color used is the median $g-i$ color inside a radius $R$, $k$-corrected and corrected by the extinction of the Milky Way.

Appendix F
ICL Fraction at $r < R_{500}$

In Table 5, we list the ICL fractions inside $R_{500}$ ($=1.2$ Mpc = 18.7″). We also list the BCG+ICL fraction with respect to the total luminosity of the cluster and the ICL fraction with respect to the BCG+ICL.

| Surface Brightness Cuts | 26 < $\mu$ < 29.5 | 26.5 < $\mu$ < 29.5 | 27 < $\mu$ < 29.5 | 27.5 < $\mu$ < 29.5 |
|-------------------------|-------------------|-------------------|-------------------|-------------------|
| $f_{\text{ICL}}(g)$    | 9.8 ± 0.5         | 7.0 ± 0.8         | 4.6 ± 1.0         | 2.7 ± 1.0         |
| $f_{\text{ICL}}(i)$    | 3.6 ± 0.8         | 2.2 ± 0.8         | 1.4 ± 0.8         | 0.7 ± 0.8         |
| 2D fit                 |                   |                   |                   |                   |
| $k$                    | 29.9 ± 1.0        | 30.3 ± 1.0        |                   |                   |
| $i$                    |                   |                   | 45.4 ± 2.0        | 47.7 ± 2.0        |
| $f_{\text{BCG+ICL}}$   |                   |                   | 66.1 ± 2.2        | 63.7 ± 2.2        |

| $f_{\text{ICL}}$       | 29.9 ± 1.0        | 30.3 ± 1.0        |                   |                   |
| $f_{\text{BCG+ICL}}$   | 45.4 ± 2.0        | 47.7 ± 2.0        |                   |                   |
| $f_{\text{ICL/BCG+ICL}}$ | 66.1 ± 2.2        | 63.7 ± 2.2        |                   |                   |
