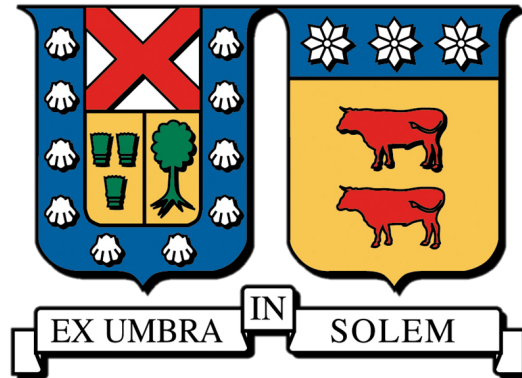


Federico Santa María Technical University

Department of Physics



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Characterization of BreakBRD-type galaxies sample

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Tomás Fuentes Fuentes

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Chapter 1

Abstract

BreakBRD (break bulge in red disk) galaxies are a new sample of spiral galaxies presented in [Tuttle and Tonnesen \(2020\)](#), these galaxies have a red disk, but concentrated star formation, measured by Dn4000. In this thesis work we search for galaxies with morphological characteristics such as breakBRD through a visual classification of high resolution RGB images obtained from the observations of the Hyper Suprime Cam Telescope, from its Public Data Release 3. The galaxies are within groups/clusters with masses $M_{\odot} \geq 10^{13}$ and a cut in the redshift $z \leq 0.2$, the observed host corresponds to the RXGCC survey. We found 154 breakBRD galaxy candidates (approximately 5.55%), corrected their photometry to study their Color magnitude diagram, calculated their stellar masses, compared our sample with the Chang 2015 catalog and found that a large part of our sample is in the star-forming region with a percentage transitioning to the green valley. We used the X-ray survey measurements to study that the mass of the group/cluster does not affect the number of candidates, suggesting that not only environmental effects produce this state. The stellar masses are distributed in a range $10^9 \leq M_{\odot} \leq 10^{11}$, which indicates that the mass-driven mechanisms do not apply to the whole sample.

Acknowledgment

At this moment of culmination and reflection, I wish to express my deepest gratitude to those whose guidance, support and wisdom have been fundamental pillars in the completion of this thesis.

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Chapter 2

Introduction

Understanding galactic evolution is one of the most significant challenges in contemporary astrophysics. It has been observed that the local galaxy population exhibits a bimodal color distribution, where passive galaxies form a well-defined red sequence, while actively star-forming galaxies populate a more sparse blue cloud ([Strateva et al. \(2001\)](#); [Baldry et al. \(2004\)](#)). The transition of galaxies from active star formation to a quiescent state does not appear to be explained by simple evolutionary scenarios, such as gas depletion, without the intervention of additional physical processes.

Galaxies are not uniformly distributed in space, they are housed through different structures, such as groups or clusters. These environments exert a determining influence on the evolution and modification of the characteristics of the galaxies they host. The dynamics of these systems is marked by the interaction of galaxies with the intercluster medium (ICM), which is largely composed of hot gas that we can study through X-ray emission. Understanding the variability of these interactions in different environments, such as galaxy groups and clusters, is essential for the study of galactic evolution and the transformation of galaxies in the specific contexts in which they are found ([Mohr et al. \(1999\)](#)).

The cessation or truncation of star formation is essential for the transition of a galaxy from being blue and star-forming to red and quiescent. Understanding how and when this cessation occurs is crucial for identifying the mechanisms that drive galactic evolution. Galactic quenching is fundamentally segregated by galaxy mass, morphology, and environment ([Peng et al. \(2010\)](#)). The dominant physical processes vary on different scales: massive galaxies are shaped by galaxy-scale processes, such as the disruption of star formation by active galactic nuclei (AGNs) and mergers that alter spiral morphologies ([Somerville and Davé \(2015\)](#)). On the other hand, smaller, star-forming galaxies tend to be more influenced by their environment through processes such as tidal gas stripping and ram pressure. Ram pressure, in particular, is a dynamical phenomenon that occurs when a galaxy moves rapidly through the hot intragalactic medium, resulting in the stripping of its star-forming gas. This process can lead to a significant decrease in the galaxy's star formation rate, as the cold, dense gas essential for new star formation is stripped away and left behind in the form of gas tails as the galaxy advances through the dense intercluster medium ([Boselli and Gavazzi \(2006\)](#); [Gunn and Gott \(1972\)](#)).

A key aspect of galaxy evolution is the distribution of star formation within galaxies. Recent studies have revealed that star formation may be centrally enhanced in galaxies close to the star-forming sequence and suppressed in those below it ([Morselli, L. et al. \(2019\)](#)). This observation

suggests that galaxies not only form from the inside out, but also go extinct following a similar pattern. In this context, a population of galaxies termed "BreakBRDs" (Break Bulge in Red Disk) has been introduced, which exhibit recent star formation in their centers and red disks, challenging the conventional "inside-out" formation model (Tuttle and Tonnesen (2020)).

In this work, we have searched for galaxies that fit the description provided by Tuttle & Tonnesen (2020), i.e., "BreakBRDs" galaxies. We have performed a visual classification of high-resolution images of galaxies, with information from RXGCC X-ray Cluster catalogs (Xu et al. (2022)), and deep observations from the public data release (PDR3) of the Hyper Suprime Cam Telescope (HCS) Aihara et al. (2022). These images were taken from the thesis project "Characterization of a Jellyfish Galaxies Population in X-ray Clusters Surveys" (I. Quiroz 2023). Our goal is to find galaxies with breakBRD morphology to study the possible mechanisms or factors that produce this state, in this work we start that search, presenting a sample of possible candidates, in addition to studying some of its properties and look for ways to define the star formation zone.

These galaxies represent a unique class that falls outside the conventional model of galaxy formation and offer an opportunity to explore new aspects of galactic evolution. By focusing on these galaxies with central star formation and red disks, we seek to shed light on the processes leading to the truncation of star formation in galaxy disks and contribute to a more nuanced understanding of the diversity of evolutionary pathways in the galactic universe.

In this report we assume the following cosmological parameter $H_0 = 70[km\ s^{-1}Mpc^{-1}]$ according to the Lambda cold dark matter model.

Chapter 3

Methods

3.1 RXGCC Sample

In this research work, we classified the RGB images of the galaxies generated in "Characterization of a Jellyfish Galaxies Population in X-ray Clusters Surveys" (Quiroz 2022), important factors to take into consideration in this sample called RXGCC is that they were taken from an X-RAY catalog (Xu et al. (2022)), then for the generation of the images, we made an overlap with the Hyper Suprime Cam telescope observations due to its high resolution for deep distances. The selected galaxies are within 2 virial radii of their host center. The clusters have a mass-cut $M_{\odot} \geq 10^{13}$, and the galaxies found within the clusters were color-corrected ($g - r < 0.8$)¹, which favors the search for blue objects, with a greater presence of gas and possible star formation.

The decision to use the HSC-Public Data Release 3 data is based on its high-resolution capabilities for observations at greater depths, encompassing more than 600 square degrees of multiband data at nominal survey depth. This superior quality in deep observation outperforms other visible data sources, such as SDSS or similar surveys. For this reason, we opted for the HSC data, as it allows us to obtain finer resolution in our images of galaxies, facilitating visual inspection and allowing us to more clearly identify both morphological features of galaxies and details of the surrounding environment.

3.2 Classification Code

One of the crucial steps in the research was the creation of a Python code to classify the galaxies in the RXGCC image set and select potential candidates for BreakBRD galaxies. This process was essential for filtering the large data set and focusing the analysis on galaxies that exhibit particular characteristics of interest.

Classification criteria were established based on the observation of the distinctive features of BreakBRD galaxies. These criteria include the concentration of star formation, the presence of certain morphological features, and the presence of blue color in the RGB images. Galaxies that met these criteria were labeled as possible BreakBRD candidates.

¹The photometry reported by HSC DR3 is poor, as we have concluded below, so this color cutoff is not entirely accurate, but it works.

The code allows us to classify each candidate with a numerical label to give a degree of certainty to the classification, with the label 0 corresponding to a galaxy that we consider to be a good candidate, and 2 for a candidate with a breakBRD characteristic. The criteria are shown in the following table:

Flag	Features
0	The galaxy has a compact star-forming disk surrounded by a larger red disk.
1	The galaxy has spiral arms, or star-forming zones within a longer red disk.
2	The galaxy has zones of star formation, but it does not have a specific or compact disk.

Table 3.1: Table showing the different classification labels

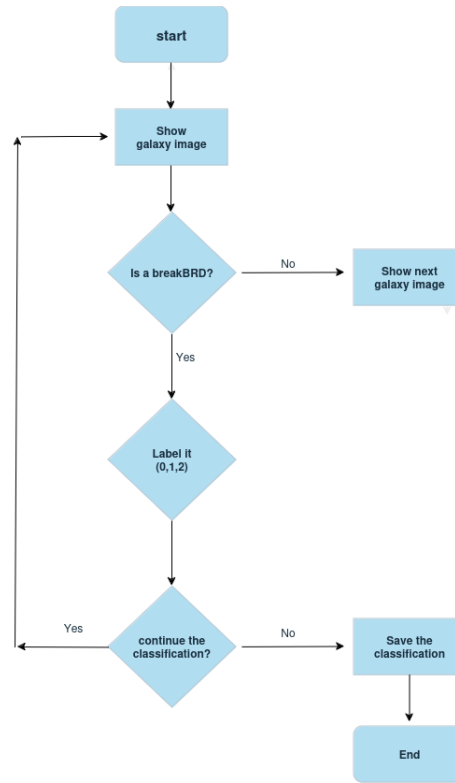


Figure 3.1: Flowchart showing the logical sequence of the visual classification code for galaxy images.

3.2.1 Guide images

Our basis for establishing a selection criterion and thus classify the galaxies were RGB images which were previously separated from the RXGCC sample by my tutor, that have blue zones of formation within a red disk, some have very compact star-forming disks and others have very marked spiral arms, for our classification both cases were considered.



Figure 3.2: The image shows the previously separated galaxies, to establish a visual criterion of breakBRD galaxies, as we can see, all the galaxies present the blue color characteristic of zones with star formation.

Chapter 4

Results

4.1 BreakBRD Candidate Sample

The selection of the BreakBRD galaxy sample was performed by visual classification of RGB images from the RXGCC dataset. A total of 154 candidates were identified as having morphological and visual features. These features include blue regions, which is a signal of star formation, embedded in red disks, which represent areas where star formation was quenched.

After the classification process we have 154 BreakBRD candidate galaxies. That distribute in:

- Flag 0: 46 Candidates
- Flag 1: 42 Candidates
- Flag 2: 66 Candidates



Figure 4.1: Flag 0 - Break BRD Candidates

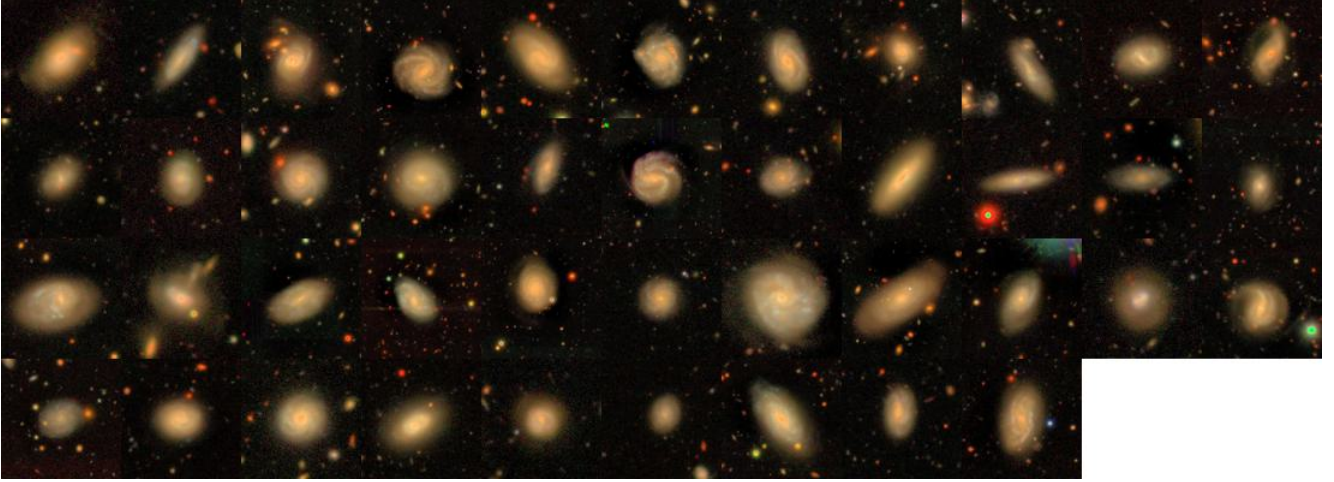


Figure 4.2: Flag 1 - Break BRD Candidates



Figure 4.3: Flag 2 - Break BRD Candidates

In the population study of BreakBRD galaxies, an analysis was performed to investigate the relationship between the group mass and the fraction of BreakBRD galaxies in the group. Through a plot showing the mass of the group on the horizontal axis and the fraction of BreakBRD galaxies on the vertical axis (see figure 4.4), it was observed that there is no obvious correlation between these two variables. This result suggests that environmental processes are not the only factors influencing the state of BreakBRD galaxies, in agreement with what has been reported in the scientific literature [Tuttle and Tonnesen \(2020\)](#).

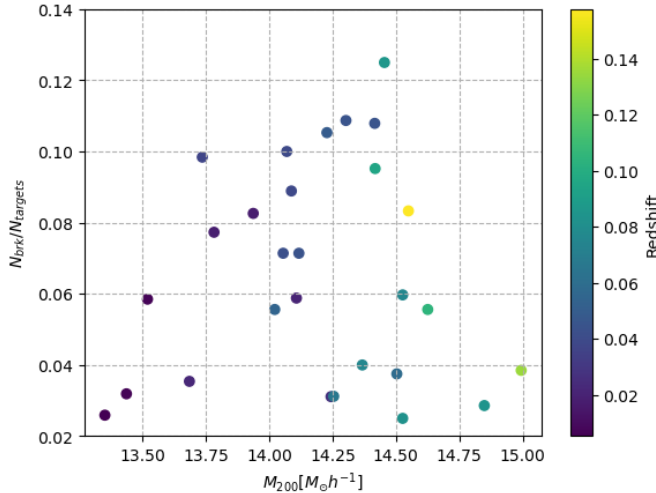


Figure 4.4: The plot illustrates the occurrence of BreakBRD Candidates in different mass ranges of hosts.

Of the 2777 galaxies present in the RXGCC sample, 154 were classified as BreakBRD candidates, representing approximately 5.55% of the total data set. It is worth noticing that the RXGCC sample was selected with a color cutoff ($g - r < 0.8$), which could influence the proportion of BreakBRD galaxies identified. In addition, it was found that, on average, each galaxy group contains approximately 4.72 BreakBRD candidates, results that are similar to those obtained by (Kopenhafer et al. (2020)), who found in IllustrisTNG simulations, analogous candidates to breakBRD, and for $z=0$, 4% of the population were breakBRD.

4.2 Photometry

One of the critical steps in the analysis of our BreakBRD galaxy sample was the evaluation and correction of the photometry. Initially, we relied on the photometry provided by the HSC Survey. However, a significant limitation in the quality of this photometry was identified for extended and low redshift objects, such as the galaxies in our sample.

The accuracy of photometry is essential to determine key properties of galaxies, such as surface brightness, absolute magnitude, and color indices, and can also affect calculations such as stellar mass, as we will see below. Poor photometry can lead to misinterpretations of these properties, affecting subsequent analysis and conclusions derived from the investigation.

To solve this problem we decided to use the Source-Extractor software, with which we realized that indeed our data from the HSC and the photometry done by us differed, then we decided to search for our candidates within SDSS DR18 through query of which we searched with a conesearch. The photometry found for the candidates and that reported by HSC also have differences, so we concluded that indeed the photometry is poor. For this work we decided to stay with the photometry reported by SDSS.

4.2.1 Source Extractor comparison

We applied SExtractor to the .fits images of our candidate galaxies in both the g- and r-filter, we decided to use the MAG_BEST parameter which decides the best fit between MAG_AUTO that provides an estimate of the total galaxy magnitude, based on an adaptive elliptical aperture, and MAG_ISOCOR that provides a corrected isophotal magnitude.

4.2.2 Match with SDSS Photometry

After identifying limitations of the photometry provided by the HSC X-ray catalog, we proceeded to perform a match of our BreakBRD galaxy candidates with the Sloan Digital Sky Survey (SDSS) Data Release 18 (DR18). To accomplish this, we used a cone search of the SDSS database, which allowed us to find counterparts in SDSS for each of our HSC candidate galaxies. Importantly, we extracted the cmodel photometry reported by SDSS and also took advantage of extracting the spectroscopic redshift for those candidates that had it, and the photometric for those that did not.

As we can see in Figure 4.5, we noted that the best relationship between the photometries is between SDSS and SourceExtractor, which affirms our position that the photometry reported by HSC is not the best for our downstream analyses.

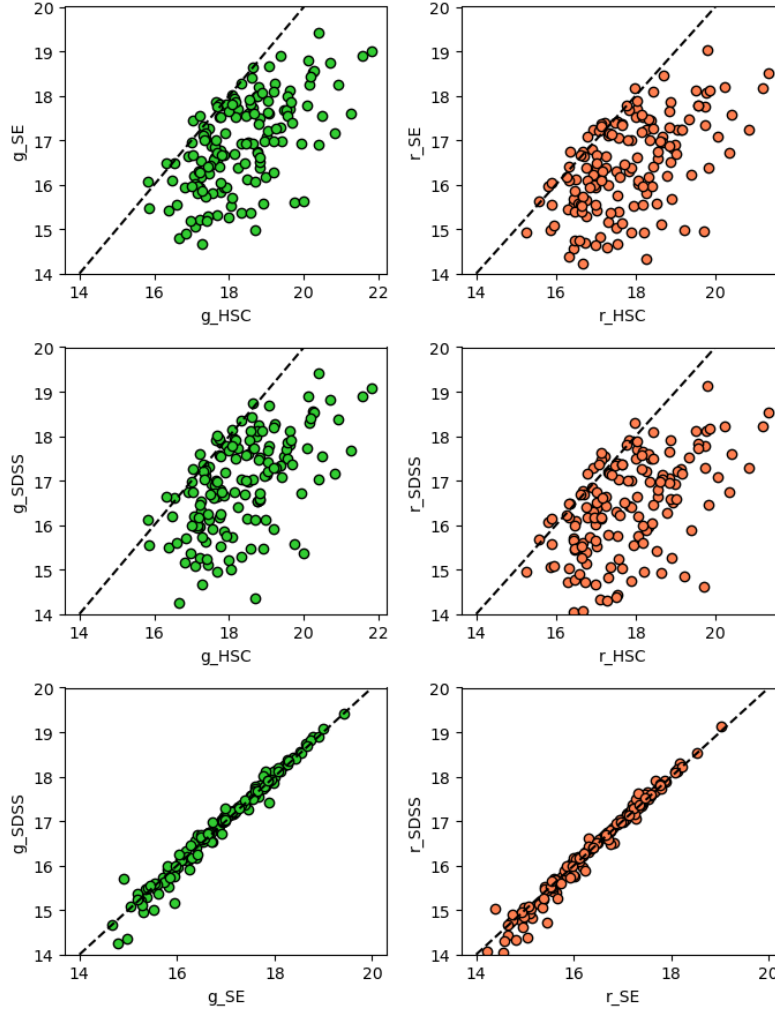


Figure 4.5: The figure shows the different comparisons between the photometries. On the left side we have the green filters and on the left the red filters. In the top panel we compare the HSC vs SourceExtractor photometry. In the middle panel we compare HSC with SDSS. Finally in the bottom panel we compare the photometry of SourceExtractor and SDSS.

4.3 Color Magnitude Diagram

With SDSS photometry we can create a color magnitude diagram more representative of our sample. In order to contrast our breakBRD candidates we plotted them on the [Chang et al. \(2015\)](#) catalog so we could study their position within the CMD.

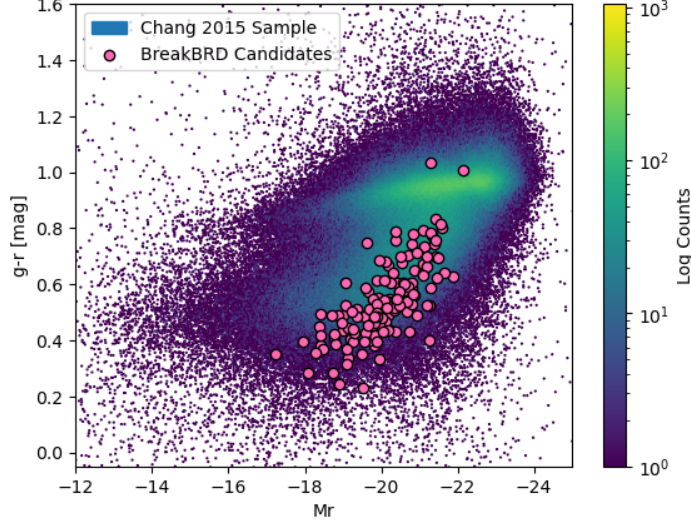


Figure 4.6: Color-magnitude diagram showing the distribution of BreakBRD galaxy candidates (pink dots) compared to the sample of galaxies in the catalog of Chang et al. (2015).

BreakBRD galaxy candidates, marked in the diagram (see figure 4.6), are predominantly observed in the blue cloud region, with some transitioning into the red sequence. This pattern suggests that the selected BreakBRD galaxies may be undergoing stages of active star formation, although with possible signs of progressive evolution to more mature states. In future researches we will study that for galaxies in the breakBRD state, as their star-forming disk becomes more truncated, galaxies should be closer to the green valley, since they would possess a more extended red disk.

4.4 Stellar Masses

Recent research suggests that the star formation quenching process is significantly influenced by stellar mass, with higher mass galaxies more likely to experience cessation of star formation activity Peng et al. (2010). For our sample we have calculated the stellar masses using the Mass/Luminosity relation which is a function of color, described by Bell et al. (2003), the formula we used was the following:

$$\log_{10} \left(\frac{M}{L_r} \right) = -0.306 + 1.097(g - r) \quad (4.1)$$

Where M is the stellar mass of the galaxy.

By combining stellar masses and galaxy color, we could construct a CMR plot, which will allow us to distinguish between blue, green and red galaxies. We know that this relationship presents a bimodality between galaxies with active star formation that are associated with bluer colors, and galaxies that have had a quenching, which are grouped towards redder colors, and there is a transition zone between both populations called green valley.

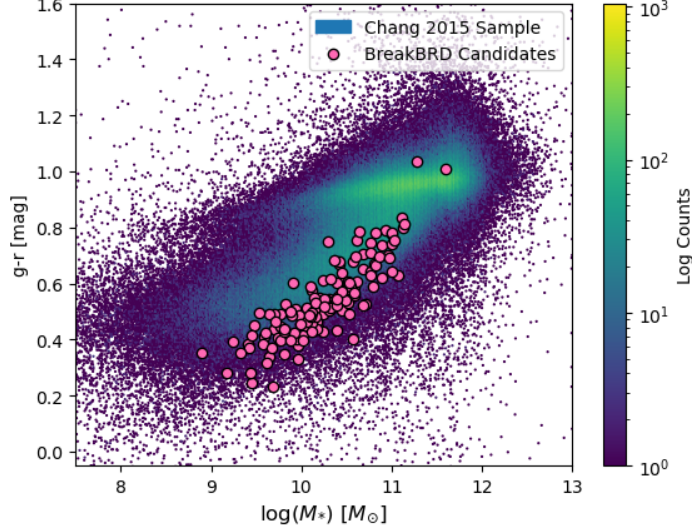


Figure 4.7: Stellar mass vs color plot for both samples, in pink-dots our breakBRD candidates sample.

From our sample of candidates we can notice that most of them are within the category of blue galaxies, and we have candidates within the green valley. These results are comparable with those obtained in [Tuttle and Tonnesen \(2020\)](#) where they found that their breakBRD sample was within the green valley with a strong tail in the blue of star formation region. In addition to the conclusion that breakBRD galaxies are distributed along a mass range, implying that mass-driven quenching mechanisms are not the only factor that drifts toward this state

4.5 Delimiting star formation zones

The purpose of this section is to preview some of the future work with breakBRD galaxy candidates, our challenge is to be able to limit the star formation zones, since so far we have only made a visual classification, we do not have the spectrum of all the candidates, so for now we discard using spectral ratios such as the Dn4000. In this section we present color maps, which can be very useful to limit the bluest areas of the galaxy, then we show a color gradient, which with the help of a color map, we can study the variation between the truncated disk and the end of the red disk.

4.5.1 Color Maps

In order to study the star formation zones in our breakBRD candidates, and thus strengthen the visual analysis of the classification, we have created color maps for 5 candidates that appear to have a compact star formation disk.

The purpose of color maps is to be able to distinguish the color difference ($g-r$) of each pixel of the image. In order to create them we have corrected the fits through convolutions with the point spread functions, to be able to correct atmospheric effects in images, such as reddening, which were the following:

$$G_{filter} * R_{psf}$$

$$R_{filter} * G_{psf}$$

Then we rest both results pixel by pixel and obtain the color map.

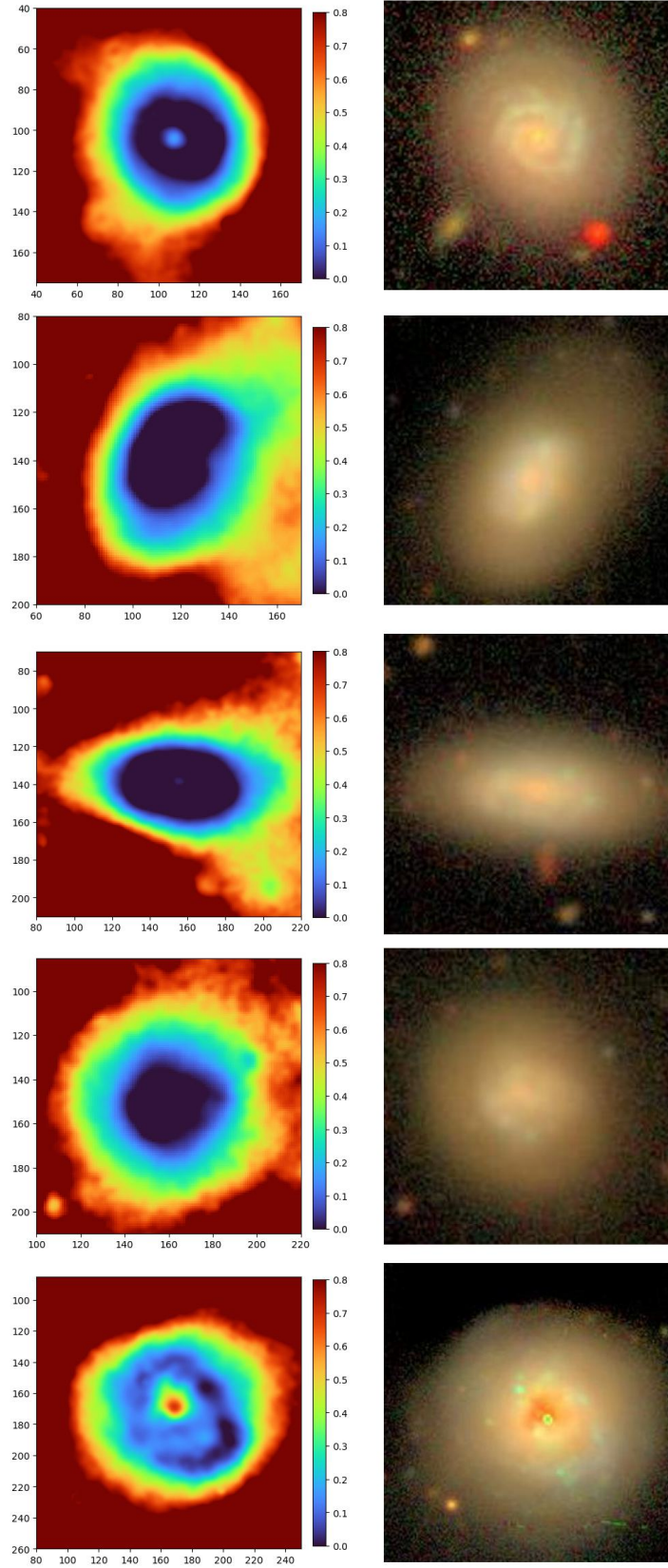


Figure 4.8: The images on the left show the colormaps generated for the chosen candidates, while the images on the right show the RGB images.

We still do not have a consensus on what color value determines to limit the truncated star formation area, but as we can see in the image (see figure 4.8), the galaxies present centrally very blue areas, maybe a good limiter can be the dark blue area marked by $(g - r < 0.1)$ since it contrasts well with the areas we see in the RGB images.

4.5.2 Color gradient

In the effort to understand color gradients in BreakBRD galaxy candidates, we applied an Elliptical Isotope Analysis approach using the Python package `photutils.isophote`.

The overall colors of galaxies are influenced by multiple factors, including dust content, the average age of their stellar populations, and metallicity. These attributes are not uniform and often vary radially within a galaxy.

In future reaserches, we will measure the color gradient of our BreakBRD candidates to compare it with the evolution of single stellar population and thus determine the time it took for the galaxy to reach that state of breakBRD.

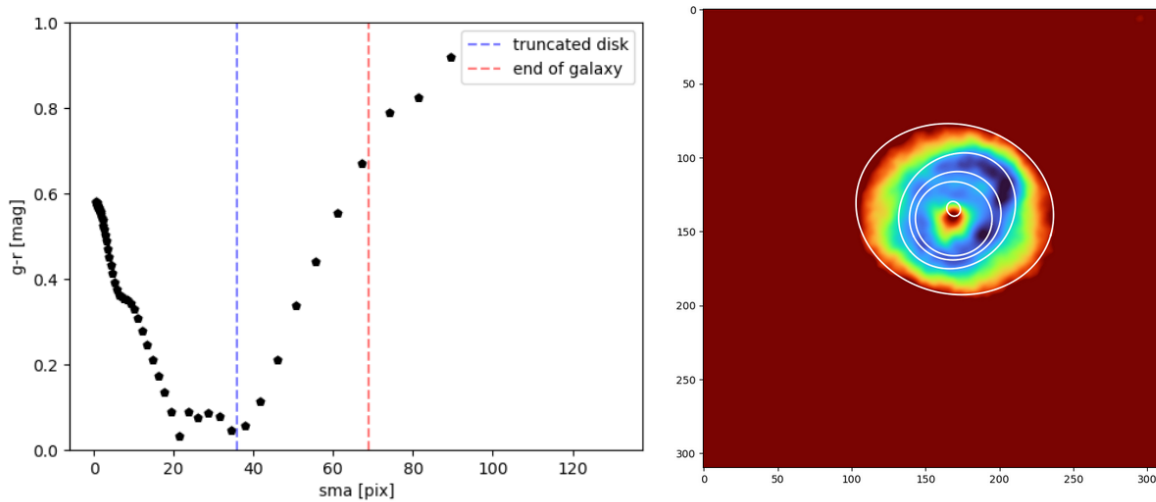


Figure 4.9: The left panel shows the color difference as a function of galaxy radius (in pixels). The right panel shows the color map of the galaxy with the isophotes on top. The blue line and the red line correspond to the last two isophotes marked on the color map.

For the galaxy studied in Figure 4.9 the color gradient between the end of the star-forming disk is approximately 0.65, which might suggest that the galaxy may be older, so that its disk allows for that difference.

Chapter 5

Conclusion

In this work we have visually classified 154 breakBRD galaxy candidates, taking advantage of the high resolution provided by HSC observations, and we also studied their main characteristics, and the conclusions we reached are the following:

1. There are galaxies with morphology of BreakBRD-type galaxies (presented in TT20) in the RXGCC sample within two virial radii with respect to the group/cluster center.
2. The mass of the host group/cluster does not seem to affect the fraction of BreakBRD candidates (figure 4.4).
3. Our candidates are distributed over a range of stellar masses, which may suggest that mass-driven mechanisms are not the only ones affecting this type of galaxies (figure 4.7).
4. Candidates are in the blue-star forming zone of the CMD, and a few candidates are transitioning through green valley (figure 4.6 and 4.7).
5. After classification, we obtained that 5.5% of the sample are BreakBRD candidates. Moreover, the average breakbrd within the groups is close to 4.72 [candidates/group].

For future research we will use MAGPHYS to create SEDs of our candidates to obtain parameters such as the star formation rate. We will make a second classification for a sample that is 5 virial radii away from the cluster center in order to study BreakBRD in other environments, away from groups/clusters. We will use the color gradients that we will generate to simulate the evolution of a single stellar population to determine the age of that gradient. Finally we would like to compare our candidates with breakBRD analogues found in the IllustrisTNG simulation.

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