THE GROWTH OF THE RED-SEQUENCE IN CLUSTERS SINCE z=1

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Support from
Scientific objectives

• Determine the age of the Universe at which cluster galaxies acquired most of their stellar content through bursts of star formation.

• Determine when the red-sequence in clusters was first established and how do cluster galaxies populate the red-sequence.
PART I

Introduction
Galaxy formation

• The central Mpc of clusters is dominated by early-type galaxies (ETGs).

• Two main views for the formation of giant ETGs:
  1) A protogalactic monolithic collapse with dissipational star formation.
  2) A product of mergers in a hierarchical scenario of structure formation.

• Clusters contain a large number of galaxies.
Red-sequence

- ETGs form a well defined sequence in the color-magnitude diagram (CMD), which is known as the Red-Sequence (RS)

- de Lucia et al. (2007) studied the RS for a sample of 18 clusters at 0.4<z<0.8, and they found a deficit of faint RS galaxies (M_v>-20.0)

- Gilbank et al. (2008) went one step beyond and used a sample of 500 clusters at 0.35<z<0.95

\[ L/F \text{ ratio} = \frac{N_{\text{luminous}}}{N_{\text{faint}}} \]
Andreon (2008) studied a sample of 28 clusters. Most of his $z>0.5$ clusters were selected from the MACS survey.

He concluded that the abundance of faint RS galaxies is constant over $0<z<1.3$. 

Increasing trend ?

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![Graph showing trend](image)
PART II

Data
Cluster sample

- 21 cluster candidates with $z_{\text{phot}} \sim 1$ were selected from the Red-sequence Cluster Survey catalogs (RCS-1; Gladders & Yee, 2005)

- We chose only those clusters which showed an overdensity in the redshift space at $z_{\text{spec}} \sim 1$ and had optical richness $B_{g\text{c}R} > 300$.

- The cluster sample used in this thesis work consists of 15 clusters located between redshifts 0.85 and 1.10.
VLT and HST data

• The observations were carried out at the ESO Very Large Telescope (VLT) with ISAAC, and at the Hubble Space Telescope (HST) with ACS.

• We have deep $J_s$ and $K_s$-band imaging of 15 clusters, and $F775W$ ($i_{775}$) and $F850LP$-band ($z_{850}$) imaging for 5 of these clusters.

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PART III

Formation epoch of cluster galaxies
**K$_s$-band LF**

- We built the K$_s$-band LF for the combined cluster sample at $z=1$ through the application of the B+Z method (Muñoz et al 2009).

- It can be described by a Schechter function with $K_s^* = 18.82 \pm 0.25$ and $\alpha = -0.42 \pm 0.28$. By fixing $\alpha = -0.9$ we obtained $K_s^* = 18.39 \pm 0.10$. 

[Graph of K$_s$-band LF]

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Evolution of $K_s^*$

- We adopted the passive evolution models by Kodama & Arimoto (1997) in order to reproduce the observed evolution of $K_s^*$ as function of $z$.

- We concluded that bright cluster galaxies formed most of their stellar content at $z_f=3.5$. 

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PART IV

Growth of the red-sequence in clusters since z=1
CMR of early-type

- The ACS morphological catalogs of 5 RCS-I clusters were kindly provided by Benjamin Koester.
- The classification was performed with MORPHEUS software (Abraham et al., 2007), and we could distinguish between bulge and disk-type galaxies.
• We defined a regular grid in the observed color-magnitude space at $z=1$ of bin size 0.5 mag in $K_{\text{TOTAL}}$ and 0.18 mag in $J-K_{\text{COLOR}}$.

Background subtracted CMD

2-D grid on the CMD used to compute the background-subtracted CMD.

CMD for the combined cluster sample at $z=1$. Best-fit relation was subtracted.
In order to study how cluster galaxies populate the RS, we computed the ratio between the number of bright and faint RS galaxies, hereafter L/F ratio.

\[
L/F \text{ ratio} = \frac{N_{\text{luminous}}}{N_{\text{faint}}}
\]

De Lucia et al. (2007)

- Luminous: \( M_V \leq -20.0 \)
- Faint: \(-20.0 < M_V \leq -18.2\)

Gilbank et al. (2008)

- Luminous: \(-22.7 < M_V \leq -20.7\)
- Faint: \(-20.7 < M_V \leq -19.7\)
Evolution of the L/F ratio of RS galaxies since z=1 for the magnitude limits defined by De Lucia et al. (2007).

Evolution of the L/F ratio of RS galaxies since z=1 for the magnitude limits defined by Gilbank et al. (2008).
REDGROWTH model

• We developed a toy-model for the color evolution of cluster galaxies since $z=1$. This model predicts the change in the number of RS galaxies as function of redshift.

• REDGROWTH consists of a set of model galaxy SEDs computed using the population synthesis code by Bruzual and Charlot (2003) for two SF histories: a single burst SF at $z_f=3$ and an exponentially declining SF of e-folding timescale $\tau=1$, 2, and 7 Gyr.
REDGROWTH results

Predicted evolution of the L/F ratio of RS galaxies since $z=1$, following the magnitude limits defined by De Lucia et al. (2007).

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Conclusions

• That bright cluster galaxies formed most of their stellar content at $z_f=3.5$.

• That progenitors of present-day $M_V>-20$ RS galaxies have undergone a recent burst of star formation at $z=1$.

• That the SF histories of $M_V>-20$ depends strongly on galaxy luminosity: $19.5<K_s<20.2$ have a delay time of 1.5 Gyr, while $20.9<K_s<21.5$ have a delay time of 2.9 Gyr.