Asociación Argentina de Astronomía
BAAA, Vol. 52, 2009
J.J. Clariá, E. Brandi, A.E. Piatti & F.A. Bareilles, eds.

PRESENTACIÓN ORAL

The bright end of the color-magnitude relation

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Abstract. We investigate the origin of the color-magnitude relation (CMR) followed by early-type cluster galaxies by using a combination of cosmological *N*-body simulations of cluster of galaxies and a semi-analytic model of galaxy formation (Lagos, Cora & Padilla 2008). Results show good agreement between the general trend of the simulated and observed CMR. However, in many clusters, the most luminous galaxies depart from the linear fit to observed data displaying almost constant colors. With the aim of understanding this behaviour, we analyze the dependence with redshift of the stellar mass contributed to each galaxy by different processes, i.e., quiescent star formation, and starbursts during major/minor and wet/dry merger, and disc instability events. The evolution of the metallicity of the stellar component, contributed by each of these processes, is also investigated. We find that the major contribution of stellar mass at low redshift is due to minor dry merger events, being the metallicity of the stellar mass accreted during this process quite low. Thus, minor dry merger events seem to increase the mass of the more luminous galaxies without changing their colors.

Resumen. Investigamos el origen de la relación color magnitud (RCM) observada en galaxias de tipo temprano residentes en cúmulos, combinando una simulación cosmológica de *N*-cuerpos y un modelo semianalítico de formación de galaxias (Lagos, Cora & Padilla 2008). Obtenemos un buen acuerdo entre la tendencia de la RCM simulada y observada. Sin embargo, en mucho cúmulos, las galaxias más luminosas de la relación se separan del ajuste lineal realizado a los datos observados, mostrando colores casi constantes. Con el objetivo de entender este comportamiento, analizamos la dependencia con el corrimiento al rojo de la masa estelar aportada a cada galaxia por diferentes procesos: formación de estrellas debido al gas frío disponible, y brotes estelares durante fusiones menores/mayores y secas/húmedas, y durante eventos de inestabilidad de disco. Se investigó también la evolución de la metalicidad de la componente de masa estelar contribuida por cada uno de estos procesos. Encontramos que la mayor contribución a la masa estelar de las galaxias es debida a las fusiones secas menores, siendo bastante baja la metalicidad de la masa estelar acretada por la galaxia. De este modo, las fusiones secas menores parecen agregar masa estelar a las galaxias más masivas sin alterar los colores de las mismas.

1. Introduction

It has long been known that there exists a bimodal distribution of galaxies in the color-magnitude plane, separated into a tight color-magnitude relation (CMR) and a "blue cloud". The first one, also known as the "red sequence", is populated prototypically by early-type galaxies which are gas-poor and have low levels of star formation, while late-type galaxies are typical objects of the blue cloud. The color-magitude relation can be understood as a mass-metallicity relation; the more luminous, and consequently, the more massive galaxies in this relation have deep potencial wells capable of retaining the metal content released by supernovae events and stellar winds. The CMR seems to be quite universal since it is followed by galaxies in the field as well as in groups and clusters (Bower et al. 1992), being the fraction of red galaxies larger in denser environments. Generally, a linear relation has been used to fit the correlation between luminosity and color of cluster galaxies lying in the red sequence; however, different fits have been suggested (e.g., Janz & Lisker 2009). The CMR constitutes one of the major tools for testing galaxy formation models. Dry mergers are considered as the prime candidates to account for the strong mass and size evolution of the stellar spheroids at $z < 2$ (van der Wel et al. 2009). As noted by Bernardi et al. (2007), the galaxy color is not expected to change during dry mergers, since there is no associated star formation, thus galaxies move in the CMR as the mass of the system increases, but the color remains fixed. Skelton et al. (2009) presented a simplified model in which dry mergers of galaxies already on the red sequence midly change the CMR slope at higher luminosities, reproducing the change of slope observed in the bright end of the CMR for the galaxies of the Sloan Digital Sky Survey. Their model and results relies on a strong assumption on the gas fraction threshold chosen to distinguish between dry and wet mergers. In this article, we use a semi-analytic model of galaxy formation (Lagos, Cora & Padilla 2008, (LCP08)), to investigate the change of slope in the bright end of the CMR of early-type cluster galaxies, taking into account the mass of stars and metals contributed to each galaxy by quiescent star formation and starbursts during merger and disc instability events.

2. The Red Sequence

Our model reproduces very well the general trend of the CMR of cluster galaxies, as becomes evident from the comparison of the results obtained from a simulated cluster with virial mass $\approx 1.3 \times 10^{15}\, h^{-1}\, \mathrm{M}_{\odot}$, and early-type galaxies observed in the central region of the Antlia cluster (Jiménez et al. 2008). We find that the more massive and luminous galaxies ($-23 \leq M_{\mathrm{T}_1} \leq -19$, in the Washington photometric system) do not follow the linear fit to observational data, but show bluer colors ($C - T_1 \approx 1.7$) instead, as detected in other clusters (see Figure 1). We divided the simulated CMR in bins of one magnitude from $M_{\mathrm{T}_1} = -16$ to $M_{\mathrm{T}_1} = -23$, in order to investigate the different processes that explain the bluer

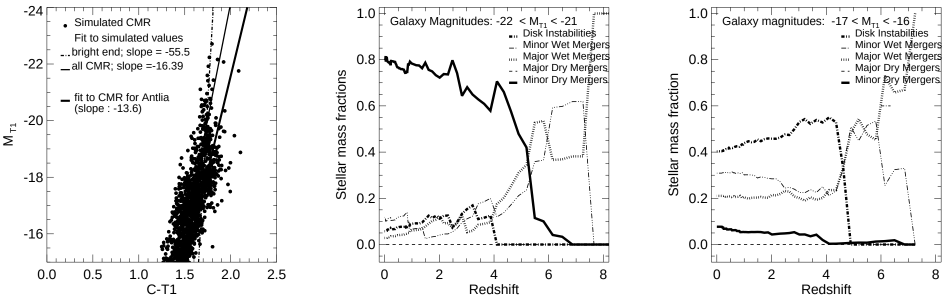

Figure 1. *Left panel*: Simulated CMR (filled circles) with linear fit to the three brightest magnitude bins (dashed-dotted line), and fit to the observed CMR for Antlia cluster (solid line). *Middle panel*: Stellar mass fractions due to the different processes that lead to galaxy formation for the brightest magnitude bin in the CMR ($-22 \leq \mathrm{M}_{\mathrm{T}_1} \leq -21$). *Right panel* : Idem as middle panel but for the faintest magnitude bin ($-17 \leq M_{\mathrm{T}_1} \leq -16$).

colors of the brigther galaxies in our simulation. We analyse the evolution of mass and metallicity of the stellar component contributed by different processes: quiescent star formation and starbursts during major wet, major dry, minor wet and minor dry merger, and disc instability events. Mergers are classified as minor or major according to the ratio between the baryonic mass of the galaxies involved; if this ratio is less than 0.3, the merger is classified as a minor one. These mergers are then distinguished between dry or wet depending on the amount of cold gas available in the remanent galaxy; if it is less than 60 % of the baryonic mass, the merger is considered dry. During dry mergers there is no star formation. This choice allows us to reconcile observational data with the synthetic galactic populations given by the model of LCP08.

We compute the stellar mass fraction contributed by the different processes at all magnitude bins, without taking into account quiescent star formation, which is the process that provides the major contribution at all magnitude bins at all redshifts. The evolution with redshift of these fractions is shown in Figure 1. We can see that, for a set of very luminous galaxies ($-22 \leq M_{\mathrm{T}_1} \leq -21$), the most important process that contribute to the stellar mass at low redshifts is dry merger. Minor wet merger events and disc instabilities are also important but in lower degree. As we move in the CMR to lower magnitude bins, the relative importance of these processes changes. For the least luminous galaxies ($-17 \leq M_{\mathrm{T}_1} \leq -16$), we find that the most relevant process for $z \lesssim 4$ is disc instability, followed by minor wet mergers, minor dry mergers and major dry mergers. This last process is the least relevant one for all magnitude bins.

We also explore the metallicity of the stars accreted during different events and estimate the average at each magnitude bin (Figure 2.) The average is estimated for two different sets of processes, quiescent star formation and disc instability, on the one hand, and merger event processes, on the other. Processes in the former set can be considered as internal ones giving rise to galaxy evolution in isolation, while those in the latter, are responsible for the external contributions to the metal content of the galaxies.

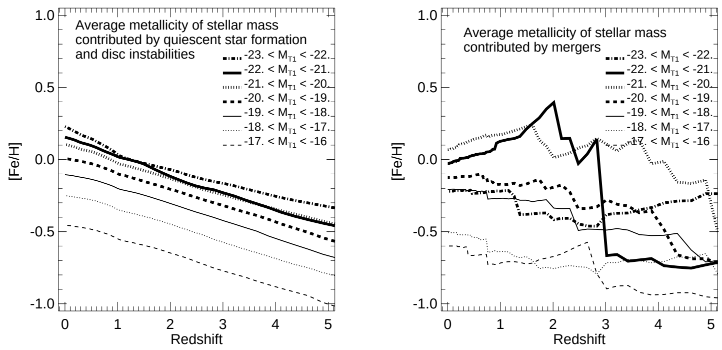

Figure 2. *Left panel*: Average metallicity for each magnitude bin as a result of star formation for quiescent star formation and disc instability events. *Right panel*: Idem as left panel, but for all types of merger events.

For galaxies departing from the linear fit to observed data ($-19 \leq M_{\mathrm{T}_1} \leq -23$), the average metallicities due to internal processes increase monotonically with decreasing redshift reaching values comprised in the range $0 \leq$ [Fe/H] ≤ 0.25 at $z = 0$. We note that in this case, the more luminous the galaxy, the higher the achieved metallicity. Conversely, the stellar mass contributed by external processes have mainly subsolar metallicities ($-0.22 \leq$ [Fe/H] ≤ 0.1), being the most massive galaxies the one receiving the least amount of metals (cf. Figure 2). Hence, as a consequence of mergers, the final metallicity of the more luminous galaxies along the CMR ($0 \leq$ [Fe/H] ≤ 0.15 at $z = 0$), is lower than the one that would have if only internal processes were acting.

3. Conclusions

We find that the major contribution of stellar mass to the more luminous galaxies of the CMR at low redshift is due to minor dry mergers (see Figure 1), being the metallicity of the accreted stellar mass quite low. It this way, assuming that colors are mainly driven by metallicity, it seems that the departure of the bright end of the CMR from a linear fit can be explained by the effect of minor dry mergers; they would increase the mass of the galaxies without changing their colors.

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