Chemical effects on the development of the colour–magnitude relation of cluster galaxies

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Abstract. We investigate the development of the colour-magnitude relation (CMR) of cluster galaxies. This study is carried out using a semi-analytic model of galaxy formation and evolution coupled to a sample of simulated galaxy clusters of different masses, reinforcing the conclusions reached by Jiménez et al. (2009). We compare both simulated and observed CMRs in different colour-magnitude planes, finding a very good agreement in all cases. This indicates that model parameters are correctly tuned, giving accurate values of the main properties of galaxies for further use in our study. In the present work, we perform a statistical analysis of the relative contribution to the stellar mass and metallicity of galaxies along the CMR by the different processes involved in their formation and evolution (i.e. quiescent star formation, disc instability events and galaxy mergers). Our results show that a mix of minor and major dry mergers at low redshifts is relevant in the evolution of the most luminous galaxies in the CMR. These processes contribute with low metallicity stars to the remnant galaxies, thus increasing the galaxy masses without significantly altering their colours. These results are found for all simulated clusters, supporting the idea of the universality of the CMR in agreement with observational results.

Resumen. Investigamos el desarrollo de la relación color–magnitud (RCM) de las galaxias residentes en cúmulos. El estudio se realiza combinando un modelo semianalítico de formación de galaxias con simulaciones cosmológicas de N-cuerpos de cúmulos de galaxias de distintas masas. Los resultados obtenidos refuerzan las conclusiones dadas en Jiménez et al. (2009). Comparamos las RCM simuladas con las observadas en tres planos color–magnitud, obteniendo muy buen acuerdo en los tres casos, lo que indica que los parámetros del modelo están bien calibrados y los valores obtenidos de las principales propiedades de las galaxias son adecuados para el uso subsiguiente. En este trabajo, realizamos un análisis estadístico de la contribución relativa a la masa estelar y a la metalicidad de las galaxias en la RCM, de los procesos de formación y evolución sufris-
dos por estas galaxias (formación estelar pasiva, inestabilidad de disco y fusiones de galaxias). Nuestros resultados muestran que una mezcla de fusiones menores y mayores de tipo seco (con poco contenido de gas), es determinante en la evolución de las galaxias más luminosas de la RCM, ya que agregan material estelar de baja metalicidad a las galaxias remanentes, de forma tal que su masa crece pero los colores no se ven afectados significativamente. Los mismos resultados han sido hallados en todos los cúmulos simulados, apoyando la idea de la universalidad de la RCM, en concordancia con trabajos observacionales.

1. **Introduction**

The colour–magnitude relation (CMR) is usually understood as a mass–metallicity relation: more luminous and massive galaxies in this relation have deep potential wells capable of retaining the metal content released by supernovae events and stellar winds. Generally, a linear relation has been used to fit the correlation between luminosity and colour of cluster galaxies lying in the CMR. However, different fits have been suggested (e.g. Janz & Lisker 2009), consistent with a change of slope from the bright to the faint ends. Additional evidence of a tilt towards bluer colours at the bright end of the CMR arises from studies of large samples of early-type galaxies in the Sloan Digital Sky Survey (Baldry et al. 2006, Skelton et al. 2009). This observed trend has been reproduced by Skelton et al. (2009) using a simplified model in which dry mergers of galaxies already on the CMR mildly change the slope of this relation at higher luminosities. This detachment of the bright end of the CMR, motivates our study. We use a semi-analytic model of galaxy formation and evolution that includes the effect of feedback active galactic nuclei (Lagos et al. 2008), and an improved estimation of the scalelength of galactic discs (Tecce et al. 2010). Our aim is to explain how minor mergers influence the evolution of the most massive galaxies in the CMR, since several authors consider dry mergers as the prime candidates to account for the strong mass and size evolution of the stellar spheroids at \( z < 2 \), and they are supposed to increase the stellar mass of galaxies, without changing the colours (Bernardi et al. 2007).

2. **Comparison between simulated and observed**

We extend the study performed by Jiménez et al. (2009), considering two sets of simulated galaxy clusters, C14 and C15, with virial masses in the ranges \( \simeq (1.1 - 1.2) \times 10^{14} h^{-1} M_\odot \) and \( \simeq (1.3 - 2.3) \times 10^{15} h^{-1} M_\odot \), respectively (see Dolag et al. 2005 for details), and construct the CMRs in three different colour–magnitude planes. Minimum square fits to the simulated CMRs are estimated in each magnitude system, for all clusters. The average slopes of these fits are \( b_{(B-R)} = -0.0426 \) in the \( (B-R) \) vs. \( R \) plane, \( b_{(V-I)} = -0.035 \) in the \( (V-I) \) vs. \( I \) plane (\( R \) and \( I \) magnitudes are in the Cousins system), and \( b_{(C-T_1)} = -0.0740 \) in the \( (C-T_1) \) vs. \( T_1 \) plane (Washington photometric system). We compare these slopes with observed ones. In the \( (B-R) \) vs. \( R \) plane, López-Cruz et al. (2004) studied the CMRs of 57 low-redshift cluster galaxies, obtaining an
3. Physical processes involved in the development of the CMR

We find an interesting aspect from our simulations. In all colour–magnitude planes, the most massive and luminous galaxies present a detachment from the general trend denoted by fainter galaxies. This break occurs at approximately the same magnitude in the different filters ($M^\text{break}_R \sim M^\text{break}_V \sim M^\text{break}_{T1} \approx -20$), being more evident in the Washington T1. In order to understand the physical reasons that lead to the bluer colours of the brightest galaxies in our simulations, we divide the simulated CMR at $z = 0$ in bins of one magnitude from $M_{T1} = -17$ to $M_{T1} = -24$ and analyze the evolution of mass and metallicity of the stellar component contributed by different processes: quiescent star formation (QSF) and starbursts during major wet, major dry, minor wet and minor dry mergers, and disc instability (DI) events (for details on the classification of these processes in our model, see Jiménez et al. 2009).

Figure 1 shows the evolution with redshift of the accumulated mass contributed by different sets of processes (QSF and DI: left panel; minor mergers: middle panel) normalized to the total stellar mass acquired within each magnitude bin. In this way, we have an estimation of the relative importance of these processes on the formation of galaxies with different luminosities. It can be seen that for a set of very luminous galaxies ($-24 < M_{T1} < -20$), the mass fraction contributed by QSF and DI decreases at low redshifts (from $z \approx 2 - 3$) as the galaxy is being formed. Note that values larger than unity are reached because the total stellar mass of galaxies is reduced as a result of mass recycled by the stellar population due to mass loss and dying stars, following the whole
evolution traced by the semianalytic code; this is not taken into account by the individual mass contributions. As the stellar mass of galaxies increase, QSF and DI lose importance at expense of the effect of mergers. In particular, the role of minor mergers becomes relevant, as it is evident by the fractions presented in the middle panel of Fig. 1, characterized by a steep increase since $z \approx 2 - 3$. This increment is less pronounced for less luminous galaxies (grey lines), although the relative contribution of this process to the galaxy mass already acquired is larger than for brighter galaxies. Besides, these fainter galaxies keep forming stars through QSF and DI as indicated by the almost constant values depicted by grey lines since $z \approx 3$ (left panel), being consistent with the fact that the stellar mass keep growing as it consumes the available reservoir of cold gas. As shown by Jiménez et al. (2009), minor mergers involved in the evolution of the brightest galaxies are mainly dry mergers (fraction of gas cold gas content in the central galaxy less than 0.6). Major dry mergers also affect their formation but are less important in terms of the contributed mass fraction. On the other hand, fainter galaxies also suffer SF associated to starbursts occurring during minor wet mergers.

The total metallicity achieved at $z = 0$ by the most luminous galaxies in the CMR, considering all physical processes, lies within the range $-0.2 \leq [\text{Fe/H}]_{\text{Total}} \leq 0.15$ (not shown here). Taking into account that mergers (mainly minor dry ones) play a significant role in the evolution of these galaxies, we explore the evolution of the metallicity of the stars accreted and formed during these events. This is shown in the right panel of Figure 1, where different line types depict the results obtained for galaxies in different magnitude bins. At $z = 0$, the metallicity contributed by these components to the most luminous galaxies ranges within $-0.4 \leq [\text{Fe/H}]_{\text{Mergers}} \leq -0.15$. Then, accreted stars in merger events contribute with metals having subsolar abundances. Hence minor and major dry mergers suffered by the most luminous galaxies of the CMR since $z < 2$ lead to the increase of their stellar mass without strongly affecting their metallicities. Thus a break in the bright end of the CMR arises with galaxies rising their total luminosities but without changing their colours. The same results are found for C14 and C15 clusters, suggesting that the CMR is universal, in concordance with previous observational works (e.g. López Cruz et al. 2004).

References

Bernardi, M., Hyde, J. B., Ravi, S. K., Miller, J. C., Nichol, R. C., 2007, ApJ, 133, 1741
Baldry, I. K., Balogh, M. L., Bower, R. G., et al., 2006, MNRAS, 373, 469
Dolag, K., Vazza, F., Brunetti, G., Tormen, G., 2005, MNRAS, 364, 753
Janz, J., Lisger, T., 2009, ApJ, 696, 102L
Jiménez, N., Cora, S. A., Bassino L. P., Smith Castelli, A., 2009, BAAA, 52, 197
Lagos, C., Cora, S. A., & Padilla N. D., 2008, MNRAS, 388, 587
López-Cruz O., Barkhouse W. A., Yee H. K. C., 2004, ApJ, 614, 679
Skelton, R. E., Bell, E. F., Somerville, R. S. 2009, ApJ, 699, 9L
Smith Castelli, A. V., Bassino, L. P., Richtler T., et al., 2008, MNRAS, 386, 2311
Tecce T. E., Cora S. A., Tissera P. B., Abadi M. G., Lagos C. del P., 2010, MNRAS, 408, 2008