The Color-Magnitude Relation of Cluster Galaxies: Observations and Model Predictions

N. Jiménez\textsuperscript{1,2}, A. Smith Castelli\textsuperscript{1,2}, S. A. Cora\textsuperscript{1,2} & L. P. Bassino \textsuperscript{1,2}

\textsuperscript{(1)} Facultad de Ciencias Astronómicas y Geofísicas (FCAG, UNLP)
\textsuperscript{(2)} Instituto de Astrofísica de La Plata (CCT La Plata, CONICET - UNLP) and CONICET, Argentina

Abstract. We investigate the origin of the color-magnitude relation (CMR) observed in cluster galaxies by using a combination of cosmological $N$-body/SPH simulations of galaxy clusters, and a semi-analytic model of galaxy formation (Lagos, Cora & Padilla 2008). Simulated results are compared with the photometric properties of early-type galaxies in the Antlia cluster (Smith Castelli et al. 2008). The good agreement obtained between observations and simulations allows us to use the information provided by the model for unveiling the physical processes that yield the tight observed CMR.

1. Introduction

Early-type galaxies residing in groups and cluster of galaxies define a sequence in the colour-magnitude diagram, being bright galaxies redder than fainter ones. This colour-magnitude relation (CMR) seems to be universal in nearby clusters of galaxies. Smith Castelli et al. (2008, hereafter SC08) have recently obtained a linear fit to the CMR of the Antlia cluster with a slope in agreement with those found in Virgo (Lisker et al. 2008), Fornax (Mieske et al. 2007), Perseus (Conselice et al. 2002) and Coma (López-Cruz et al. 2004). Such universality lead several authors to suggest that the build up of this relation in galaxy clusters is more related to galaxies internal processes than to the influence of the environment (SC08; Misgeld et al. 2008).

The understanding of the building of the CMR displayed by elliptical galaxies is a key test for galaxy formation models. Using hydrodynamical simulations...
of groups and clusters of galaxies, Saro et al (2006) and Romeo et al. (2008) have tried to reproduce the observed slope and normalization of the CMR. Semi-analytic models have also been used for this kind of study (De Lucia et al. 2004; Kaviraj et al. 2005). None of these galaxy formation models considers the effect of feedback from active galactic nuclei (AGN), which is essential to avoid the formation of too massive and blue cluster dominant galaxies.

We present a study on the origin of CMR in galaxy clusters by applying a semi-analytic model of galaxy formation to the outputs of hydrodynamical non-radiative N-body/SPH numerical simulations of clusters of galaxies. We compare the results obtained from this model with the galaxy properties of the Antlia cluster (SC08). The Antlia cluster is the third nearest well populated galaxy cluster after Virgo and Fornax ($D = 35.2$ Mpc).

2. The Model

We use a combination of cosmological adiabatic N-body/SPH simulations of clusters of galaxies and the SAG (acronym for ‘Semi-Analytic Galaxies’) semi-analytic model of galaxy formation (Lagos et al. 2008). This model follows the formation and evolution of galaxies including gas cooling, star formation, feedback from supernovae explosion and galaxy mergers, a detailed implementation of the metal enrichment of the baryonic component, and feedback from AGN. We consider two simulated galaxy clusters, having virial masses in the range $\sim (1-13) \times 10^{14} h^{-1} M_{\odot}$ (Dolag et al. 2005). These clusters have been initially selected from a Λ cold dark matter simulation of a cosmological box of $479 h^{-1}$ Mpc of size, characterized by $\Omega_m=0.3$, $\Omega_{\Lambda}=0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_b = 0.039$ for the baryon density parameter, and $\sigma_8 = 0.9$ for the normalization of the power spectrum. The mass resolution is $m_{dm} = 1.13 \times 10^9 h^{-1} M_{\odot}$ and $m_{gas} = 1.69 \times 10^8 h^{-1} M_{\odot}$, for dark matter and gas particles, respectively.

3. Color-Magnitude and Luminosity-Metallicity Relations

In order to compare simulations with observations, we apply a morphological criterium to select elliptical galaxies from the model. Ellipticals are those bulge dominated systems where the ratio between the bulge mass and the total stellar mass, $r = M_{\text{Bulge}}/M_*$, satisfy the condition $r > 0.95$.

X-ray observations have revealed that the Antlia has an average temperature of $kT \sim 2.0$ keV (Pedersen et al. 1997, Nakazawa et al. 2000). The virial temperature of the least massive cluster considered ($kT \sim 1.3$ KeV) is quite similar to that of the Antlia cluster. However, since the general trends of the results are similar for both simulated clusters, we show here the CMR and luminosity-metallicity relation for the more massive one, which contains a larger population of galaxies.

The left panel of figure 1 shows the CMR of early-type galaxies of the Antlia cluster obtained by SC08 from CCD wide-field (MOSAIC-CTIO) photometry in the Washington photometric system ($T_1$ and $C$ filters). This relation is defined by 51 early-type galaxies from the Ferguson & Sandage (1990) Antlia Group catalogue and 21 new early-type dwarf galaxy candidates and members. The CMR spans 11 mag in brightness with no change of slope.
The semi-analytic model provides galactic magnitudes in the Johnson photometric system. They were converted to the Washington one through the transformations given by Forbes & Forte (2001) for globular clusters, assuming that early-type galaxies are old stellar systems. Additional conversions were obtained from Fukugita et al. (1995). The right panel of figure 1 shows the simulated photometric properties of early-type galaxies compared to the mean CMR of early-type members of the Antlia cluster. The slope denoted by the red side of the locus occupied by the simulated galaxies is in very good agreement with the mean observed CMR.

The observed $M_V$ magnitude versus [Fe/H] relation for the Antlia galaxies (SC08) and Local Group dwarfs (Grebel et al. 2003) is shown in the left panel of figure 2. Antlia galaxies metallicities were obtained by transforming $(C - T_1)$ colors to [Fe/H] values through the Harris & Harris (2002) relation for globular clusters. The right panel of figure 2 shows the corresponding relation obtained from the larger simulated cluster which is compared to the mean observed relation. We find an excellent agreement for [Fe/H] > $-1$. The spread of lower luminous objects towards lower metallicities is due to the presence of late-type galaxies, missclassified as ellipticals by the rather uncertain threshold in the adopted morphological criterium. This set of simulated galaxies also populate the blue side of the color-magnitude diagram.

The similar trends found in the colour-magnitude and metallicity-luminosity relations between observations and simulations are encouraging. We plan to extend this study in order to explain the physical origin of the dispersion of the observed CMR, thus evaluating the influence of the star formation history and the chemical enrichment of the involved galaxies.

Acknowledgments. This work was supported by grants from Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Agencia Nacional
Figure 2. **Left:** Observed luminosity-metallicity relation for the Antlia cluster. **Right:** The same relation for the simulated cluster compared with the mean observed relation for Antlia (solid line).

de Promoción Científica Tecnológica and Universidad Nacional de La Plata, Argentina.

References

Conselice, C.J., Gallagher, J.S. III & Wyse, R.F.G. 2002, AJ, 123, 2246
De Lucia, G., Poggianti, B.M., Aragón-Salamanca, A., et al. 2004, ApJ, 610, L77
Dolag, K., Vazza, F., Brunetti, G. & Tormen, G.G. 2005, MNRAS, 364, 753
Ferguson, H.C. & Sandage, A. 1990, AJ, 100, 1
Forbes, D.A., Forte, J.C. 2001, MNRAS, 322, 257
Fukugita, M., Shimasaku, K. & Ichikawa, T. 1995, PASP, 107, 945
Grebel, E.K., Gallagher, J.S. & Harbeck, D. 2003, AJ, 125, 1926
Harris, W.E. & Harris, G.L.H. 2002, AJ, 123, 3108
Kaviraj, S., Devriendt, J. E. G., Ferreras, I. & Yi, S. K. 2005, MNRAS, 360, 60
Lagos, C., Cora, S.A. & Padilla, N.D. 2008, MNRAS, 388, 587
Lisker, T., Grebel, E.K. & Binggeli, B. 2008, AJ, 135, 380
López-Cruz, O., Barkhouse, W.A. & Yee H.K.C. 2004, ApJ, 614, 679
Mieske, S., Hilker, M., Infante, L. & Mendes de Oliveira, C. 2007, A&A, 463, 503
Misgeld, I., Mieske, S. & Hilker, M. 2008, A&A, 486, 697
Nakazawa, K, Makishima, K., Fukazawa, Y. & Tamura T. 2000, PASJ, 52, 623
Pedersen, K., Yoshii, Y. & Sommer-Larsen, J. 1997, ApJ, 485, L17
Romeo, A.D., Napolitano, N.R., Covone, G., et al. 2008, MNRAS, 389, 13
Saro, A., Borgani, S., Tornatore, L., et al. 2006, MNRAS, 373, 397
Smith Castelli, A., Bassino, L., Richtler, T., et al. 2008, MNRAS, 386, 2311 (SC08)