Theoretical Predictions of Colors and Metallicity of the Intracluster Light

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Abstract

We study the colors and metallicities of the brightest cluster galaxies (BCGs) and intracluster light (ICL) in galaxy groups and clusters, as predicted by a semi-analytic model of galaxy formation, coupled with a set of high-resolution N-body simulations. The model assumes stellar stripping and violent relaxation processes during galaxy mergers to be the main channels for the formation of the ICL. We find that BCGs are more metal-rich and redder than the ICL, at all redshifts once the ICL starts to form ($z \sim 1$). In good agreement with several observed data, our model predicts negative radial metallicity and color gradients in the BCG+ICL system. By comparing the typical colors of the ICL with those of satellite galaxies, we find that the mass and metals in the ICL come from galaxies of different mass, depending on the redshift. Stripping of low-mass galaxies, $9 < \log M_* < 10$, is the most important contributor in the early stages of ICL formation, but the bulk of the mass/metals contents are given by intermediate/massive galaxies, $10 < \log M_* < 11$, at lower redshift. Our analysis supports the idea that stellar stripping is more important than galaxy mergers in building up the ICL, and highlights the importance of colors/metallicity measurements for understanding the formation and evolution of the ICL.

Key words: galaxies: clusters: general

1. Introduction

The intracluster light (ICL), which was first predicted by Zwicky (1937) and observed in the Coma Cluster by Zwicky (1951), constitutes an important component of baryonic matter in galaxy groups and clusters. Given its intrinsic nature, i.e., diffuse light made up of stars not bound to any galaxy, understanding its formation and evolution is fundamental for understanding the dynamical history of the group/cluster in which it resides. Most of the ICL is concentrated around the brightest cluster galaxy (BCG), but a non-negligible fraction is found around intermediate/massive satellites (Contini et al. 2014, 2018; Presotto et al. 2014), especially in massive ($\sim 10^{15} M_\odot$) clusters at redshift $z = 0$. Despite the physical processes at play for the formation of this diffuse light still being under debate, there is a general consensus that ICL and BCGs are linked in their formation and evolution (Murante et al. 2007; Purcell et al. 2007; Puchwein et al. 2010; Rudick et al. 2011; Contini et al. 2014, 2018; Burke et al. 2015; DeMaio et al. 2015, 2018; Groenewald et al. 2017; Morishita et al. 2017; Montes & Trujillo 2018), in particular after $z \sim 0.7$, during which a clear co-evolution between the two components has been found in our recent study (Contini et al. 2018, hereafter C18).

In C18 we discussed the relative importance of the two main processes that are believed to be responsible for the formation of the ICL, i.e., stellar stripping and galaxy mergers. These two processes have different consequences for the ICL properties, such as colors and metallicities. Qualitatively speaking, if mergers are mainly responsible for the formation of the ICL, we would expect no color/metallicity gradients in the BCG+ICL system, which translates into similar colors/metallicities of BCGs and ICL (as argued in C18, but see also Montes & Trujillo 2014, 2018; DeMaio et al. 2015; Morishita et al. 2017). However, if stellar stripping of satellite galaxies is the main contributor to the ICL, it is reasonable to expect some radial gradients of BCG+ICL colors and metallicity (DeMaio et al. 2015, 2018).

The most recent observations (Iodice et al. 2017; Morishita et al. 2017; DeMaio et al. 2018; Montes & Trujillo 2018, just to quote a few of them) are finding clear radial gradients for both colors and metallicity, in a wide range of redshift, a clue that favors stellar stripping rather than galaxy mergers as the dominant mechanism for ICL formation.

In Contini et al. (2014; hereafter C14) we argued that measurements of the ICL metallicity can help to constrain theoretical models. In recent years, observational measurements of the ICL (or BCG+ICL) have remarkably increased, in such a way that it is now possible to test model predictions. Montes & Trujillo (2014) derived the stellar population properties of the ICL in Abell Cluster 2744, a massive cluster at $z \sim 0.3$. From the rest-frame colors of the ICL, they derived a mean metallicity comparable with the solar value, and a metallicity gradient of the global BCG+ICL system. Similarly, DeMaio et al. (2015) analyzed four galaxy clusters in the redshift range $0.44 < z < 0.57$, and for three of them they found a clear metallicity gradient from supersolar metallicities in the region dominated by the BCG, to subsolar metallicities in the region dominated by the ICL. A few years later, these results were confirmed by other studies (e.g., DeMaio et al. 2018; Montes & Trujillo 2018), thus strengthening the idea that stellar stripping could be the dominant contributor to the ICL.

Observations focused also on the BCG+ICL colors. DeMaio et al. (2018) extend the analysis done in DeMaio et al. (2015) by studying the ICL properties of 23 galaxy groups and clusters in the redshift range $0.29 < z < 0.89$, and focusing mainly on colors. They found that the color gradients of the BCG+ICL systems become bluer with increasing radial distance, and argue that this cannot be the result of violent relaxation processes during major mergers between satellite galaxies and the BCG. Moreover, they conclude that tidal stripping of massive galaxies ($\log M_*/M_\odot > 10.4$) in the very vicinity of the group/cluster center ($< 100$ kpc) is the likely source of the ICL, in good agreement with our results in C14 and C18.
Similar results have been found in Morishita et al. (2017). These authors investigated the ICL properties of six clusters in the redshift range $0.3 < z < 0.6$ and found negative color gradients with increasing radial distance from the BCG. However, from the typical colors of the satellite population, they concluded that the ICL likely originated from satellites with mass $\log M_*/M_\odot < 10$, in contrast with our results (C14) and DeMaio et al. (2018). Their conclusion is also in contrast with Montes & Trujillo (2018), who used the Hubble Frontier Fields survey to analyze the properties of the ICL in six massive clusters at redshift $0.3 < z < 0.6$. They found that the average ICL metallicity ($\langle \text{Fe}/\text{H} \rangle \sim -0.5$) is compatible with that of the outskirts of the Milky Way, and the mean stellar ages of the ICL are younger (between 2 and 6 Gyr) than the most massive galaxies in the clusters, suggesting that the ICL forms mainly from stripping of intermediate (Milky Way-like) galaxies after $z < 1$.

Very recently, Ko & Jee (2018) analyzed the amount of ICL and its properties in a cluster at $z \sim 1.3$ (which is the highest redshift for which spatial distribution, colors, and quantity of ICL are available, as yet) and they reported no radial dependence of the ICL color.

In this paper we take advantage of the model for the ICL formation described in C14 and C18, and a variation of it, to fully analyze the ICL and BCG colors and metallicity. In the original version of the model, during an episode of stellar stripping we assumed that the same fraction of stellar mass and metals is moved to the ICL component, i.e., we assume no metallicity gradient in satellite galaxies. A modified version of the model presented here assumes a random (negative) metallicity gradient in satellites. Our analysis will focus on addressing the following points:

(i) to make model predictions of colors and metallicities and quantify the difference between the two models;
(ii) to compare our predictions with the available observed data; and
(iii) to study the redshift evolution of ICL colors and metallicity and use the color–color and metallicity–color planes to analyze the contribution to the ICL from satellites of different mass as a function of redshift.

In Section 2, we briefly summarize our model for the formation of the ICL presented in C14 and C18 and its modification. In Section 3, we show the results of our analysis, which will be discussed in detail in Section 4. In Section 5, we give our conclusions. Throughout this paper we adopt a standard $\Lambda$CDM cosmology assuming the following cosmological parameters: $\Omega_m = 0.24$ for the matter density parameter, $\Omega_{\text{baryons}} = 0.04$ for the contribution of baryons, $H_0 = 72 \text{ km s}^{-1} \text{Mpc}^{-1}$ for the present-day Hubble constant, $n_s = 0.96$ for the primordial spectral index, and $\sigma_8 = 0.8$ for the normalization of the power spectrum. Stellar masses (with the assumption of Chabrier 2003 IMF) are given in units of $M_\odot$ (unless otherwise stated), while magnitudes are in the AB system.

2. Methods

In this section we briefly summarize our modeling for the ICL formation and describe its modification, which have been implemented in the semi-analytic model presented in De Lucia & Blaizot (2007). As in C14 and C18, the semi-analytic model has been coupled with the same set of high-resolution N-body simulations (Contini et al. 2012). For further information about the semi-analytic model and the details on the set of simulations, we refer the reader to De Lucia & Blaizot (2007), C14, and C18.

We take advantage of two models: for the sake of simplicity we name them STANDARD and METGRAD. The STANDARD model is formally identical to the Tidal Radius + Merg. model adopted in C14 and the “STANDARD” model adopted in C18. For those readers not familiar with the model, here we provide the necessary information for a full understanding.

This model takes into account the tidal forces between satellite galaxies and the potential well of the group/cluster within which they reside, and violent relaxation during galaxy mergers. The tidal forces are responsible for the stellar stripping, which means that part of the stellar mass (sometimes all) of the satellite galaxy that suffers the tidal force is stripped from the galaxy and gets unbound. This mass is assumed to move to the ICL component associated to the central galaxy at the moment of the stripping. Clearly, this model of stellar stripping allows satellite galaxies to lose mass in a continuous fashion, before merging or being disrupted if the tidal field is strong enough. The stellar density profile of the simulated satellites is approximated by a spherically symmetric isothermal profile, such that the tidal radius can be estimated by means of the equation (see Binney & Tremaine 2008)

$$R_t = \left( \frac{M_\text{sat}}{3 \cdot M_{\text{DM,halo}}} \right)^{1/3} \cdot D,$$

where $M_\text{sat}$ is the satellite mass (stellar mass + cold gas mass), $M_{\text{DM,halo}}$ is the dark matter mass of the parent halo, and $D$ is the satellite distance from the halo center.

An isothermal profile is assumed by the semi-analytic model to derive the tidal radius via Equation (1). However, for a more realistic implementation of stellar stripping, a satellite galaxy is considered to be a two-component system with a spheroidal component (the bulge), and a disk component, when stellar stripping occurs. If $R_t$ is smaller than the bulge radius, the satellite is assumed to be completely destroyed and its stellar and cold gas mass are added to the ICL and hot component of the central galaxy, respectively. On the other hand, if $R_t$ is larger than the bulge radius but smaller than the disk radius, only the stellar mass in the shell $R_t^2 - R_\text{sat}^2$ is moved to the ICL component (as well as a proportional fraction of the cold gas to the hot component of the central galaxy). Since we model the disk component with an exponential profile, $R_\text{sat} = 10 \cdot R_d$ is the radius which contains 99.99% of the stellar mass in the disk, where $R_d$ is the disk scale length. After an episode of partial stripping (no disruption), we update $R_d$ to one-tenth of $R_t$.

It must be noted that our semi-analytic model distinguishes two kinds of satellites, type 1 and type 2 (a.k.a. orphans) satellites. The difference between the two types relies on the dark matter content: type 1 galaxies still own their parent subhalo, while type 2 have lost their parent subhalo or it went under the resolution of the simulation. For type 2 the semi-analytic model applies Equation (1) above directly with no other filter, but for type 1 satellites, the model first requires that the following condition is met:

$$R_{\text{half}}^\text{DM} < R_{\text{half}}^\text{Disk},$$

where $R_{\text{half}}^\text{DM}$ and $R_{\text{half}}^\text{Disk}$ are the half-mass radii for the satellite and its disk component, respectively.
where \( R_{\text{DM}} \) is the half-mass–radius of the parent subhalo, and \( R_{\text{half}}^{\text{Disk}} \) is the half-mass–radius of the galaxy’s disk, that is \( 1.68 \cdot R_d \) for an exponential profile. Central galaxies can also increase their associated ICL through accretion of ICL originally associated with satellite galaxies. This mechanism of ICL accretion works differently depending on the type of satellite involved. Centrals accrete ICL originally associated with satellite galaxies that pass from type1 to type2.\(^3\) Moreover, anytime a type1 satellite is affected by stellar stripping, its associated ICL is added to the ICL component of the corresponding central galaxy. To summarize, a central galaxy acquires its ICL due to stellar stripping through three mechanisms:

1. direct stripping of the stellar mass of satellite galaxies;
2. accretion of ICL associated with type1 satellites that experience a stripping event; and
3. accretion of ICL associated with satellite galaxies that pass from type1 to type2 (i.e., they have lost their dark matter component).

Tidal stripping is not the only channel from which the ICL can form in the STANDARD model. Similar to C14 and C18, we also consider violent relaxation processes that take place during mergers. The “merger channel” is modeled as follows: at each merger, we assume that a fraction \( f_m = 0.2 \) of the satellite stellar mass becomes unbound and is added to the ICL of the corresponding central galaxy. The fraction \( f_m \) has been set to 0.2 by means of numerical simulations of groups (Villalobos et al. 2012). We have verified that such a simple prescription reproduced the result of the simulations, although in reality \( f_m \) is expected to depend on the circularity of the orbit, or other satellite properties such as its stellar mass.

In this study we also consider a slight modification of the STANDARD model that we named the METGRAD model. The STANDARD model does not assume any metallicity gradient in satellite galaxies when they are subject to stellar stripping, which means that the same fractions of stellar mass and metals are stripped from the galaxy. The novelty of the METGRAD model is that it relies on the assumption of a (negative) metallicity gradient in satellites\(^4\) (see, e.g., Tissera et al. 2017), such that the fraction of metals stripped is different from the fraction of stellar mass stripped. In this model, at each episode of stripping we assume that metals in the satellite galaxies follow an exponential profile with \( R_{\text{sl,metals}} = f_R \cdot R_{\text{sl}} \), where \( R_{\text{sl,metals}} \) is the scale length of the distribution of metals, and \( f_R \) is a random fraction assumed to be between 0.5 and 1. Then, in the METGRAD model metals are on average more concentrated in the inner regions of the disk, with respect to the STANDARD model. As a natural consequence, the ICL from the METGRAD model is expected to be less metal-rich than the ICL in the STANDARD model.

3. Results

In this section we present the predictions of our models for the ICL and BCG colors and metallicities. We will focus on these two properties, their variation as a function of redshift, and the differences between the two models that will be tested against available observational data.

3.1. ICL and BCG Metallicities

In C14 we showed that the metallicities of the ICL and BCGs do not depend on the halo mass (see Figure 12 and Figure 13 of C14), and argued that detailed observational data of these properties could help in constraining models. After a few years, a non-negligible amount of data has been collected and it is possible to test our model predictions against them.

However, before testing our predictions with observed data, in Figure 1 we show the metallicity of BCGs (left panel) and the metallicity of the ICL (right panel) as a function of halo mass, as predicted by the STANDARD (black solid lines) and METGRAD (red solid lines) models. The dashed lines represent the 16th and 84th percentiles of the distributions.

\(^3\) Orphans are not allowed to carry any ICL in our model.

\(^4\) Central galaxies are not subject to stellar stripping, i.e., no assumption is made for their metallicity profile.
As expected and anticipated in Section 2, METGRAD predicts slightly higher metallicities for the BCGs, and lower metallicities for the ICL. This is a consequence of the fact that, in METGRAD, metals in satellite galaxies are more concentrated in the inner part of the disk. In this model, the metallicity of the ICL decreases because the stellar mass moved after an episode of stripping is less metal-rich (with respect to the case of the STANDARD model). As time passes and the ICL grows and evolves, less metals are deposited in the ICL. On the other hand, satellites that suffer from stellar stripping but are not destroyed, will survive being more metal-rich. As they merge with the BCG, they bring a higher amount of metals, thus increasing the metallicity of the BCG. It must be noted, however, that the difference between the two models is basically negligible in both cases, BCGs and ICL. In fact, the BCG metallicity on average increases only \( \sim 0.02 \) dex, while the net average decrease in the ICL is \( \sim 0.04 \) dex.

In Figure 2 we plot the radial metallicity profile of BCGs and ICL in six clusters in the redshift range \( 0.3 < z < 0.6 \) (diamonds, triangles, and squares in each panel) by Montes & Trujillo (2018), and compare them with predictions (solid thick lines that represent the regions between the 16th and 84th percentiles) of our two models (top panels for the STANDARD model and bottom panels for the METGRAD model). In semianalytic models we do not have spatial information, which means that radial profiles are not available and must be assumed. To compare our results with observed data, we collect the metallicity of all BCGs (no trend with halo mass, so we can increase the statistic by considering all of them rather than those in halos of similar mass as those observed), and consider them as two-component systems: bulge and disk. In order to place them in the plot, we derived a mass-weighted radius of the galaxy (considering the bulge and disk radii) and concentrated the full amount of metals in it. This avoids assumptions about the radial metallicity profile that would inevitably bias the results. We compute the mass-weighted radius of the BCG as follows:

\[
R_{\text{BCG}} = \frac{R_{\text{bulge}} \cdot M_{\text{bulge}}^* + 1.68 \cdot R_{\text{sl}} \cdot M_{\text{disk}}^*}{M_{\text{BCG}}},
\]

where \( R_{\text{bulge}} \) and \( 1.68 \cdot R_{\text{sl}} \) are the half-mass radii of the bulge and disk, \( M_{\text{bulge}}^* \) and \( M_{\text{disk}}^* \) are the masses of the bulge and disk, respectively.

The ICL is placed in the plot in a similar way (solid thick lines on the right). We assume that the ICL dominates at \( 10 \cdot R_{\text{sl}} \) and place in the plot its metallicity at the distance equivalent to \( 10 \cdot R_{\text{sl}} \). A caveat must be noted. Our predictions are integrated results that consider the metallicity of the whole system (BCG or ICL), while the observed data refer to the metallicity at a given radial distance from the BCG center. Overall, both our model predictions agree reasonably well with observed data, and show little difference (as expected from Figure 1). If we assume that the BCG+ICL systems predicted by our models have some kind of negative gradient, model data would move up in the inner regions and down in the region dominated by the ICL. Thus, our predictions have to be considered as a lower limit in the BCG-dominated region, and as a upper limit in the ICL-dominated region. Our model predictions also agree well with the observed data by DeMaio et al. (2015), who found typical metallicities ranging from \( \sim [0.0, 0.15] \) dex at 10 kpc, and \( \sim [-0.4, -0.1] \) dex at 100 kpc (see their Figure 13), and with data by Montes & Trujillo (2014), who found metallicities similar to those just quoted (see their Figure 2).

Our models show similar results, but if compared to the observed data, the assumption of a radial metallicity gradient in satellites makes the model predictions go to the right, i.e., higher metallicities for the BCGs and lower metallicities for the ICL. We will come back to this in Section 4.

3.2. ICL and BCG Colors

In this section we analyze the ICL and BCG colors in the BVJgriz system. As seen in Section 3.1, the predictions of our models are very similar. In the analysis that follows we find negligible differences between the two models; then, for the sake of shortness, we show the results from our STANDARD model only.

In Figure 3 we plot the histogram of \( B-V \) (left panels) and \( z-J \) (right panels) colors of BCGs (red lines) and ICL (black lines), at redshifts \( z = 1 \) (top panels), \( z = 0.5 \) (middle panels), and \( z = 0 \) (bottom panels). Similarly, in Figure 4 we plot \( g-r \) and \( i-J \) colors. The distributions of the four colors show that BCGs are redder than the ICL, at any redshift once the ICL starts to form (which we consider to be \( z \sim 1 \) as shown in C14 and C18). However, in all cases the color difference between BCGs and ICL is less than \( \sim 0.1 \) mag, translating to a mild color gradient that does not weaken with decreasing redshift.

Our results are consistent with several observational data. DeMaio et al. (2018) studied the color gradient of 23 galaxy groups and clusters in the redshift range \( 0.3 < z < 0.9 \) and found that the BCG+ICL color gets bluer toward the region dominated by the ICL, indicating that the ICL is bluer than the BCG. In their Figure 5 they plot the BCG+ICL color profiles ordered by increasing redshift. That plot shows mild gradients in most of the cases and no clear dependence on redshift, consistent with what we find in Figures 3 and 4.

Morishita et al. (2017) investigated the ICL in six clusters at redshifts \( 0.3 < z < 0.6 \) (the same clusters analyzed by Montes & Trujillo 2018 and shown in Figure 2) and found clear negative color gradients (see their Figure 4). Qualitatively speaking, their results compared well with ours. We found similar \( B-V \) colors (~0.7 mag), but our \( z-J \) ICL colors are comparable with theirs only at large distances, around 300 kpc. As stated above, we do not have spatial information, and as in the case of the metallicity, radial color profiles are possible only by making assumptions that would bias the results. If we focus the attention on the innermost regions, their ranges in \( B-V \) are consistent with ours, but again, our \( z-J \) colors are bluer. The comparison with observed data in \( g-r \) and \( i-J \) colors is very similar. Our \( g-r \) ICL colors are consistent with the color \( g-r = 0.68 \pm 0.04 \) mag of the Abell Cluster 2744 at \( z = 0.3 \) (Montes & Trujillo 2014), and with \( g-r \sim 0.7 \) mag of the Fornax cluster (Iodice et al. 2017), but our \( i-J \) colors are bluer by around 0.2 mag when compared with \( i-J \sim 0.55 \) of the Abell Cluster 2477 (Montes & Trujillo 2014).

For a more simplistic representation and a more quantitative comparison of the results cited above, we show in Figure 5 the \( BVJr \) (left panel) and \( gJr \) (right panel) color diagram, collecting the predictions of the STANDARD model for galaxy groups (log \( M_{\text{halo}} < 14.5 \), diamonds), galaxy clusters (log \( M_{\text{halo}} \geq 14.5 \), triangles), observed data by Morishita et al. (2017; color lines and squares in the left panel), and data by Montes & Trujillo (2014; black lines and squares in the right panel). Data by Morishita et al. (2017) cover a wide range both
in $B-V$ and $z-J$, while the observation by Montes & Trujillo (2014) in $g-r$ is narrower. As stated above, our predictions agree fairly well with observed data in $B-V$ and $g-r$, while there is a non-negligible offset between models and observations in $z-J$ ($\sim 0.15$ mag), and $i-J$ ($\sim 0.2$ mag). We will come back to this issue in Section 4.

### 3.3. Color–Color and Color–Metallicity Planes

The color–color plane has been used in the past to understand from what kind of satellite galaxies the ICL acquires its mass, just by comparing the typical colors of the ICL with those of satellites in different ranges of stellar mass (Morishita et al. 2017). In the left panels of Figure 6 we plot the $B-V$ and $z-J$ colors of the ICL (triangles), and satellite galaxies in different mass ranges, $9 < \log M_\odot < 10$ (red stars), $10 < \log M_\odot < 11$ (green diamonds), and $\log M_\odot > 11$ (magenta squares), as a function of redshift (different panels). The plots clearly show that satellites in the stellar mass range $9 < \log M_\odot < 10$ have colors similar to those of the ICL at $z = 1$, suggesting that they are the systems that contribute the most to the ICL at the beginning of its formation.\(^5\) Quantitatively and qualitatively speaking, this result is in good agreement with the recent observation of the ICL F105W-F140W color of a galaxy cluster at $z \sim 1.2$ by Ko & Jee (2018), who found

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\(^5\) Very recently, Ko & Jee (2018) found an observational hint of an earlier formation of the ICL in a galaxy cluster at redshift $z = 1.24$. However, this cluster might be one of the exceptional cases and more statistics at these redshifts is needed.
F105W-F140W ∼ 0.7 mag. Although we do not show it, at the same redshift we find $g-r = 0.62 \pm 0.03$ mag for the ICL, and $g-r = 0.63 \pm 0.05$ mag for satellites in the stellar mass range $9 < \log M_\ast < 10$.

As time passes (see middle panel), the colors of the ICL get much closer to those of more massive galaxies, in the stellar mass range $10 < \log M_\ast < 11$. At the present time (bottom panel), intermediate/massive satellites are still the major contributors to the ICL.

The same conclusions can be drawn by looking at the color–metallicity plane (right panels). At $z = 1$, both the colors and the metallicities of low-mass galaxies are very close to the colors and metallicities of the ICL, but at lower redshifts and down to the present time, these ICL properties get closer and closer to those of intermediate/massive galaxies. Colors and metallicity then confirm the prediction made in C14, i.e., intermediate/massive galaxies are responsible for the bulk of the stellar mass and metals in the ICL.

Morishita et al. (2017), in a similar way, compared the $B-V$ and $z-J$ colors of the ICL in six clusters at an average redshift $z \sim 0.5$ with the typical colors of satellite galaxies in different stellar mass ranges. In tension with our predictions, they found that low-mass, $\log M_\ast \lesssim 10$ galaxies are likely the most important source for the ICL, as its colors are more consistent with the colors of those galaxies. However, as noted by the authors themselves, the tension can be explained by the presence of strong color gradients in massive galaxies. We will fully discuss this important point in Section 4.

4. Discussion

The primary goal of this study is to focus on the colors and metallicities of the ICL and BCGs and show how our model predictions compare with observational data. The standard version of the model adopted here has been developed in C14, where we have shown the basic properties of the ICL, including its metallicity at the present time. At that time not many observational measurements of colors and metallicities were available, and a combined (theory and observation) analysis focused on using observed data to constrain theoretical models was not possible, or completely reliable. Since then, an important amount of data have been collected, and not only at the present time where we focused our attention in the analysis done in C14, but at higher redshifts. Currently, observations have already reached $z \sim 1$ and promising
campaigns are starting to go further, beyond $z = 1$. Having full coverage of observed properties of the ICL from $z \sim 1$ and down to the present time is strictly necessary for solid comprehension of the formation and evolution of the ICL, and it is, at the same time, extremely helpful for setting theoretical models of galaxy formation.

In Section 3 we presented a series of results aimed at testing our models against available observations. As stated in C14 and mentioned in this paper, colors and metallicities are important quantities that can tell us more about the ICL formation and its evolution, and then on the dynamical state and history of the cluster in which the ICL is found (Feldmeier et al. 1998; Durrell et al. 2002; Williams et al. 2007; Loubser et al. 2009; Coccato et al. 2011; Montes & Trujillo 2014, 2018; DeMaio et al. 2015). In the following we discuss in detail our results and their implications for the general picture of the ICL formation that the collection of different works is shaping.

The metallicities of BCGs and ICL have been studied by several authors (e.g., Feldmeier et al. 1998; Durrell et al. 2002; Williams et al. 2007; Loubser et al. 2009; Coccato et al. 2011; Montes & Trujillo 2014, 2018; DeMaio et al. 2015). Overall, these studies find the stellar ages of the ICL to be between 2 and 13 Gyr and subsolar ICL metallicities in the range $-0.8 < \log Z/Z_\odot < -0.2$, and hints of the presence of radial metallicity gradients in the BCG+ICL system. An important question is: what can the radial metallicity profile tell us? The answer to this question has been discussed several times and by several authors (e.g., Montes & Trujillo 2014, 2018; DeMaio et al. 2015, 2018; Morishita et al. 2017; Contini et al. 2018 and others) and the key point relies on the main mechanism responsible for the formation of the ICL.

According to the main literature on the topic, a handful of processes have been invoked, but currently only two are considered to be important sources of ICL: galaxy mergers and stellar stripping. The relative importance of each of them in contributing to the ICL stellar mass as a function of time has different consequences on the ICL properties, such as the metallicity (as well as colors). In fact, if we assume that mergers between satellites and the BCG are the main channel, we would not expect a clear metallicity (or color) gradient in the BCG+ICL system, simply because major or multiple minor mergers would mix the stellar populations, thus flattening the pre-existing gradient. On the other hand, if we assume that stellar stripping is the most important channel, we do expect some gradient, from supersolar metallicities in the BCG, to
substantial metallicity gradients in the ICL (i.e., a negative gradient). This is because stellar stripping removes stars from the outskirts of the satellites, which are more metal-poor than the average system, and typical values strongly depend on what kinds of galaxies (in terms of stellar mass) contribute most. BCGs lie on the right side of the mass–metallicity relation, so they are, on average, more metal-rich than satellites. Ergo, if ICL stars come from stripping of satellites that are more metal-poor, and we add the fact that stripping acts on the outskirts of the satellites, the net result would be an ICL more metal-poor than BCGs.

These arguments have been used by several authors in the last few years. Montes & Trujillo (2014; but see also Montes & Trujillo 2018), based on the colors of the Abell Cluster 2744, derived a mean metallicity of the ICL that was slightly subsolar. According to the properties of the stellar population in the ICL, they concluded that most of it formed via disruption of galaxies with masses and metallicities comparable to those of the Milky Way. Similarly, DeMaio et al. (2015) used stellar population synthesis models to convert the observed colors to the metallicity of four clusters at $z \sim 0.5$. They found negative metallicity gradients from supersolar (BCGs) to subsolar (ICL), which they explained as the result of tidal stripping of $L^*$ galaxies, thus ruling out major mergers as the main contributors. In a later study, DeMaio et al. (2018), with a more numerous sample of galaxy clusters (23) in a wider range of redshifts ($0.3 < z < 0.9$), strengthened their previous conclusion by ruling out the contribution to the ICL from dwarf galaxies as the major channel. In fact, as discussed also in C18, in order to reproduce the observed luminosity of the ICL, the number of disruption events of these kinds of galaxies would considerably flatten the faint-end slope of the luminosity/stellar mass functions after $z < 1$ (when the ICL starts forming), at odds with observations (e.g., Manccone et al. 2012; Ilbert et al. 2013; Muzzin et al. 2013; Tomczak et al. 2014 and others).

Observational clues in favor of the major merger scenario are also present in the recent literature, albeit strengthened by theoretical arguments. Burke et al. (2015) focused on the BCG stellar mass growth from $z \sim 0.9$ to $z \sim 0.1$ and assumed that, at each merger between the BCG and the satellite, 50% of the stellar mass of the satellite galaxies goes to the ICL, thus finding that BCG and ICL grow factors in line with the expectations from theoretical models (C14, Murante et al. 2007). Similarly, Groenewald et al. (2017) addressed the same point, between $0.1 \lesssim z \lesssim 0.5$. These authors made the same assumption for the percentage of mass that moves to the ICL (50%) and concluded that major mergers can explain the growth rate of BCGs, and at the same time they bring enough stellar mass to the ICL down to the present day. As noted in C18, they make use of the stellar mass growths published in C14, which consider both stellar stripping and mergers. Although their method is inconsistent, their find a similar growth factor.

Our models favor the stellar stripping channel rather than mergers (C14, C18), and their predictions are in line with the picture described above. One key point of this work relies on the importance of a metallicity gradient in satellite galaxies (our METGRAD model). As shown in Section 3, assuming a metallicity gradient in satellites that contribute to the stellar mass and metals in the ICL has just a little effect on the ICL and BCG metallicities (see Figures 1 and 2). Nevertheless, this assumption brings the predictions toward the right direction, that is, BCGs more metal-rich and ICL more metal-poor. However, a caveat is worth noting. As argued in C14, the mass–metallicity relation predicted by our models is offset low with respect to the observed one (e.g., Gallazzi et al. 2005) at the massive end. In particular, the observed BCG metallicities, which are similar to those of the most massive galaxies, are expected to be at least 0.2–0.3 dex higher (e.g., Von Der Linden et al. 2007). Modeling the ICL does not substantially improve the disagreement in the massive end, despite it going...
to the right direction (higher metallicities for more massive galaxies).

For the first time in semi-analytics we present predictions of the ICL colors. As discussed in Section 3.2, $B-V$ and $g-r$ colors are in good agreement with the observed ones, and we find BCGs to be slightly redder than the ICL, as observed. Nevertheless, our $z-J$ and $i-J$ colors are bluer compared with observations. In both colors we find an offset of around 0.2 mag, which probably depends on the response of the J filter, considering that in all the other bands our results agree fairly well with observational data. However, despite the offset (which propagates from the stars in galaxies to the stars in the ICL), our models predict mild radial color gradients in the BCG + ICL system at any redshift since $z \sim 1$, in agreement with observations (e.g., Montes & Trujillo 2014; DeMaio et al.

Colors are a useful tool to understand the channels that contribute most to the ICL. In C14 we showed that most of the ICL comes from intermediate/massive galaxies and its metallicity is very similar to that of these galaxies. In that study we focused our attention on the present time, when all the ICL was formed. Here, as shown in Figure 6, we present the same information as a function of redshift by comparing the colors/metallicity of the ICL with those of satellite galaxies in different ranges of stellar mass, similar to Morishita et al. (2017).

At the beginning of its formation the ICL was mainly built-up by relative low-mass galaxies ($9 < \log M_* < 10$), but already at $z \sim 0.5$ and down to the present time, more
massive ($10 < \log M_\bullet < 11$) satellites play the most important role. If we compare our results at $z \sim 0.5$ with the observed data by Morishita et al. (2017) at similar redshifts, we find a disagreement. In fact, Morishita et al. (2017) showed that low-mass satellites ($\log M_\bullet < 10$) have colors closer to those of the ICL, and concluded that these are the main contributors to the ICL. However, the presence of color gradients in massive satellites might reconcile (at least partly) our disagreement, because stripping acts mainly in the outskirts of satellites, regions typically bluer than the integrated colors (see, e.g., Morishita et al. 2015). Then, although they found ICL colors closer to those of relative low-mass satellites, the main contribution came from stars stripped from the outskirts of massive satellites. As discussed in C14, dynamical friction arguments fully support this picture, as they are more massive satellites that more rapidly reach the innermost regions of the halo and are more likely to be subject to stellar stripping than low-mass galaxies.

5. Conclusions

We have coupled a semi-analytic model of galaxy formation with a set of N-body simulations to make predictions of colors and metallicitities of BCGs and ICL. In the analysis we took advantage of the prescription for the formation of the ICL presented in C14 and C18, and a modification of it that considers a metallicity gradient in satellite galaxies that are subject to stellar stripping. We compared the results presented in Section 3 and discussed in Section 4 to test our model against current theories for the formation and evolution of the ICL. In light of our results and their implications, we conclude the following:

1. BCGs are more metal-rich than the ICL. Moreover, the assumption of a metallicity gradient in satellite galaxies subject to stellar stripping brings predictions to the right direction (BCGs more metal-rich and ICL more metal-poor), but does not have a significant impact on the results, quantitatively speaking (Figure 1).

2. Both prescriptions predict a negative metallicity gradient and mild color gradients of the BCG+ICL system, in good agreement with observed data (Figures 2–4). $B-V$ and $g-r$ ICL colors are well reproduced, but our $z-i$ and $i-J$ ICL colors are offset low with respect to observations by $\sim 0.2$ mag (Figure 5).

3. The contribution to the ICL in terms of stellar mass and metals comes from galaxies of different masses, depending on the redshift. At the beginning of its formation, the ICL acquires most of the mass from galaxies in the stellar mass range $9 < \log M_\bullet < 10$, but already at $z \sim 0.5$ and down to the present time intermediate/massive galaxies with mass in the range $10 < \log M_\bullet < 11$ contribute most (Figure 6).

Future observational campaigns designed to measure the colors and metallicity of BCG+ICL in a wide range of redshifts can put some constraints on the formation and evolution of the ICL. In C18 we argue that a possible solution to the debate over stellar stripping/mergers as the main channel can be found on cluster scales in the local Universe, by separating the ICL associated with the BCG from that formed and somehow linked to satellite galaxies. For the reasons discussed above, we conclude this study by highlighting the importance of radial colors and metallicity gradients in support of stellar stripping as the main channel. The first measurements are suggesting this picture, but we need more data to finally confirm it or prove it wrong.

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