

Cosmic queuing: galaxy satellites, building blocks and the hierarchical clustering paradigm

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Accepted 2009 April 20. Received 2009 April 20; in original form 2009 January 13

ABSTRACT

We study the properties of building blocks (BBs; i.e. accreted satellites) and surviving satellites of present-day galaxies using the semi-analytic model of galaxy formation SAG (‘semi-analytic galaxies’) in the context of a concordance Λ cold dark matter (Λ CDM) cosmology. We consider large number of dark matter (DM) halo merger trees spanning a wide range of masses ($\sim 1 \times 10^{10} - 2.14 \times 10^{15} M_{\odot}$). We find higher metallicities for BBs with respect to surviving satellites, an effect produced by the same processes behind the build up of the mass–metallicity relation. We prove that these metallicity differences arise from the higher peak height in the density fluctuation field occupied by BBs and central galaxies which have collapsed into a single object earlier than surviving satellites. BBs start to form stars earlier, during the peak of the merger activity in Λ CDM, and build up half of their final stellar mass (measured at the moment of disruption) up to four times faster than surviving satellites. Surviving satellites keep increasing their stellar masses rather quiescently down to $z \simeq 1$. The difference between the metallicities of satellites, BBs and central galaxies depends on the host DM halo mass, in a way that can be used as a further test for the concordance cosmology.

Key words: galaxies: evolution – galaxies: formation.

1 INTRODUCTION

Recent times have witnessed a growing discussion regarding the formation of present-day galaxies via the complete disruption of satellites by more massive central objects (e.g. as proposed by Searle & Zinn 1978, hereafter SZ78), in line with the prediction from the cold dark matter (CDM) model of a bottom-up scenario of structure formation. Those disrupted satellites are usually referred to as building blocks (BBs; Ibata, Gilmore & Irwin 1994).

The observational study of the Galactic halo by SZ78 provided hints pointing to a hierarchical galaxy formation scenario. They studied metallicities of the outer Milky Way (MW) stellar halo and inferred that it was formed from infall of small protogalactic fragments characterized by chemical evolution processes similar to the present-day dwarf spheroidal (dSph) MW satellites. Although a hierarchical scenario implies, to some degree, the infall of BBs as suggested by SZ78, it does not imply that BBs are characterized by formation histories (i.e. star formation (SF) rate evolution) similar to those of present-day satellites, as has been suggested by Geisler et al. (2007, hereafter G07).

Several observational facts provide indications that BBs and satellites should be characterized by different formation histories, since

the galaxy population seems to have evolved with time as shown by (i) measurements of the evolution of the stellar mass function up to $z \approx 5$ (Drory et al. 2005) and of the luminosity function (e.g. Faber et al. 2007), (ii) the decline of the SF rate towards $z = 0$ (see e.g. Hopkins, Rao & Turnshek 2005), (iii) the important increase in the frequency of galaxy mergers at high redshift, observed as violent starbursts (e.g. Fontana et al. 2004), and (iv) the differences in galaxy formation epochs, where massive galaxies appear to be older than low-mass objects (e.g. Cowie, Songaila & Cohen 1996). All these arguments indicate that galaxies at high redshift are likely to be different than their present-day counterparts and, therefore, BBs are also probably different from present-day satellites. This is also supported by several studies of our local group which indicate that Galactic halo stars, thought to come from remnants of previous accretion events, are characterized by different abundance patterns than present-day dSph galaxies. Namely, extremely iron poor stars ($[\text{Fe}/\text{H}] < -3$) are not found in dSphs (Helmi et al. 2006), and typical ‘accreted’ halo stars show α -elements-to-iron ratios ~ 0.1 – 0.3 dex higher than stars in dSphs (see G07).

On the theoretical side, the galaxy population in the currently favoured hierarchical cosmology, obtained via either semi-analytic models or gas dynamic simulations, is also observed to evolve in broad agreement with observations (e.g. De Lucia et al. 2006; Libeskind et al. 2006; Lagos, Cora & Padilla 2008, hereafter LCP08). This galaxy evolution is mainly driven by a changing

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frequency of dark matter (DM) halo mergers which shows a peak activity at redshifts $z \simeq 2-3$ (Okamoto et al. 2005). The particular case of the MW has been studied in a Λ CDM scenario (Bullock & Johnston 2005; Robertson et al. 2005; Font et al. 2006a,b; De Lucia & Helmi 2008) from which it arises that surviving satellites and BBs are characterized by different metallicities, as a result of differences in their formation time-scales.

In this work, we investigate this issue using a considerably larger number of MW-type haloes (a total of 142). Additionally, with the aim to obtain clues about formation scenarios at different mass scales, we also extend the study of BBs and central/satellite galaxy populations to a wide range of DM halo masses. We focus on the systematic differences in metallicity [i.e. $\log_{10}(Z/Z_{\odot})$], age and formation time-scales between central galaxies (those hosted by the largest subhalo in a DM halo), satellites (all other present-day galaxies) and BBs (galaxies that have already merged with a central galaxy). Taking into account the assumption of SZ78, we consider that, as a result of tidal effects, a fraction of the stellar component of the BBs contribute to form the stellar halo of the central galaxy instead of converging to its bulge.

We use the semi-analytic model of galaxy formation ‘semi-analytic galaxies’ (SAG) by LCP08, in combination with a Λ CDM N -body simulation characterized by a periodic box of $60 h^{-1}$ Mpc, with a resolution of $1.001 \times 10^9 h^{-1} M_{\odot}$ per DM particle. The simulation parameters are consistent with the results from *Wilkinson Microwave Anisotropy Probe* data (Sanchez et al. 2006; $\Omega_m = 0.28$, $\Omega_{\Lambda} = 0.72$ and $\sigma_8 = 0.9$; a Hubble constant $H_0 = 100 h$ Mpc $^{-1}$, with $h = 0.72$). As a result of the median size of our comoving box, the maximum halo mass is $M = 5.34 \times 10^{14} M_{\odot}$. We complement our study by using the non-radiative N -body/smoothed particle hydrodynamic simulations of galaxy clusters of masses $M \sim 2.14 \times 10^{15} M_{\odot}$ (Dolag et al. 2005) used in Cora et al. (2008), extending our dynamical range and, consequently, providing a better sampling of the high-mass end of the galaxy population. Because of resolution constraints, our analysis is restricted to galaxies with stellar masses $M_{\text{Stellar}} > 10^7 M_{\odot}$, i.e. none of our conclusions refers to very low-mass objects such as the recently discovered ultra faint dwarfs (e.g. Simon & Geha 2007). In order to distinguish results intrinsic to the Λ CDM scenario, we also use a version of the SAG model where disc instabilities and feedback from active galactic nuclei (AGN) are switched off [maintaining the parameters of the other physical processes fixed, i.e. SF, supernovae (SNe) feedback]. In the remainder of this Letter, we will refer to SAG and its modified version as Models A and B, respectively. Finally, as we are interested in the properties of the MW and its satellites, we mimic such a population by selecting $z = 0$ galaxies with circular velocities in the range $v_c = 210-230$ km s $^{-1}$. Such galaxies are hosted by DM haloes of masses $10^{12} M_{\odot} \lesssim M_{\text{DM}} \lesssim 4 \times 10^{12} M_{\odot}$. In the remainder of this Letter, the 142 haloes selected this way will be referred to as MW-type haloes.

2 BUILDING BLOCKS OF PRESENT-DAY GALAXIES

As a first step, we analyse the way in which galaxy metallicities¹ and stellar ages depend on the host DM halo mass; stellar ages are calculated using the stellar-mass-weighted mean. Fig. 1 shows the results for Models A (left-hand panels) and B (right-hand panels),

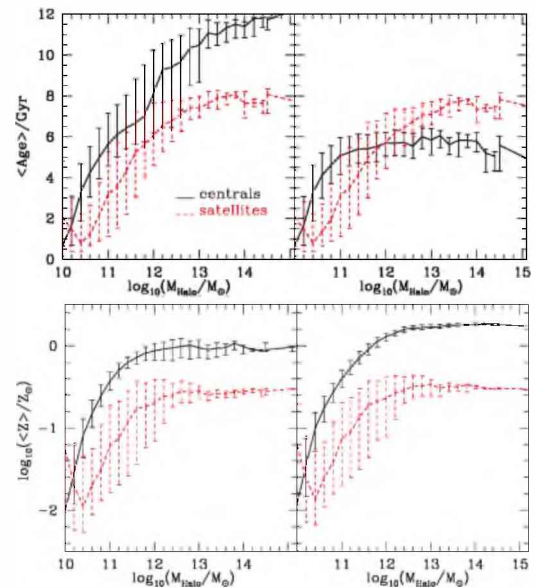


Figure 1. Average age and metallicity, in terms of the solar values (Asplund et al. 2005), for the satellite galaxy population (dashed lines) and central galaxies (solid lines), as a function of their host DM halo mass. Results for Models A and B are shown in the left- and right-hand panels, respectively. Error bars correspond to 20 and 80 percentiles.

where dashed and solid lines represent, respectively, the average properties of satellite and central galaxies for each DM halo. Model A shows a shift in galaxy ages between central and satellite galaxies (upper-left panel), where the latter are usually at least $\sim 1-2$ Gyr younger. The magnitude of this shift depends on the DM halo mass, where more massive haloes show larger age differences. These are a consequence of the AGN feedback, which reduces or even stops gas cooling in massive central galaxies at low redshifts, thus improving the agreement of galaxy luminosities and colours with observational results (see LCP08). In Model B, central galaxies are younger than their satellites for DM halo masses $M_{\text{DM}} \gtrsim 10^{12} M_{\odot}$ as a result of the absence of this heating source. Both models show a clear correlation between galaxy metallicity and DM halo mass (lower panels of Fig. 1), with central galaxies being more chemically enriched than their surviving satellites. AGN feedback is not decisive for the build up of the relation between metallicity and halo mass for both central and satellite galaxies, as becomes evident from Model B. This tight relationship is a direct consequence of the hierarchical clustering process, where more massive galaxies sit in initially higher density peaks and, as a consequence, start to form earlier on average,² allowing them to acquire higher amounts of metals. Thus, a hierarchical scenario is prone to produce less chemically enriched satellites with respect to their central galaxies, regardless of the AGN feedback modelling (also suggested by Tissera, De Rossi & Scannapieco 2005). Note that the differences in metallicity between central and satellite galaxies become larger as the halo mass increases. In the case of MW-type haloes, this difference is on average ≈ 0.8 dex, and can be as high as ≈ 1.3 dex.

The different metallicities of central and satellite galaxies arise from the combination of the stellar mass–metallicity relation

¹The detailed implementation of metal enrichment in SAG [i.e. yields from core collapse SNe (SNe CC), Type Ia Supernovae (SNe Ia) and low-intermediate-mass stars] is described in Cora (2006).

²Assuming a linear evolution for density fluctuations proportional to the scalelength of the Universe, a , and non-linear fluctuation for collapsed objects $\propto a^3$.

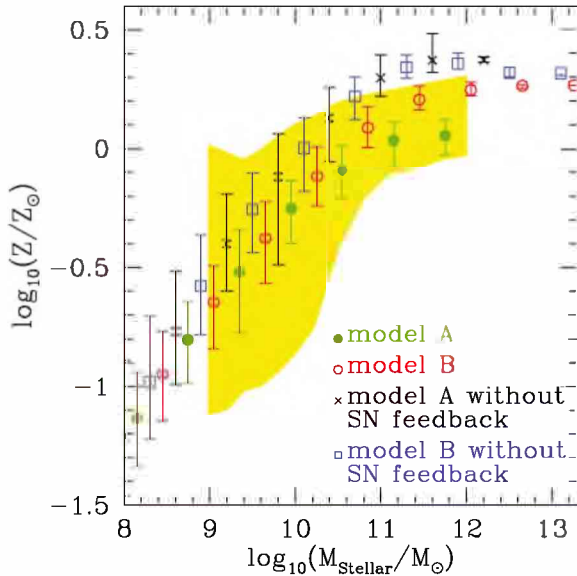


Figure 2. SMMR at $z = 0$ of the full galaxy population for Model A, Model B, and Models A and B without SNe energy feedback (symbols are indicated in the figure key). Error bars correspond to 10 and 90 percentiles. The observational relation determined by Gallazzi et al. (2005) is represented by the shaded area.

(SMMR), and the lower increase of the median stellar mass of satellites compared with that of their central galaxy as the mass of the DM halo increases (e.g. stellar masses for satellites are 1.03 dex lower for $M_{\text{Halo}} \approx 3 \times 10^{11} M_{\odot}$, and 1.35 dex lower for $M_{\text{Halo}} \approx 10^{12} M_{\odot}$, on average). Fig. 2 shows the SMMR for the full galaxy population in Model A (filled circles), Model B (open circles), and Models A and B without SNe energy feedback (crosses and open squares, respectively). As can be seen, SNe feedback is essential to provide a good agreement with the observed data (shaded area; Gallazzi et al. 2005); neglecting to include it produces significantly higher metallicities. However, the increasing trend of the SMMR is obtained independently of the details of the heating sources that affect the evolution of the baryonic component, including SNe energy feedback. The SMMR of the individual populations of central and satellite galaxies follows closely that of the global population, with only minor differences at the low-mass end.

Note that the previous metallicities correspond to the full stellar content of galaxies. Therefore, we cannot directly compare these results to measurements of metallicities of the MW stellar halo. As was mentioned above, we take the BBs at the time of the merger as a representative population of the stellar halo. This assumption imposes that, in order to be able to compare the properties of both populations, our analysis includes all simulated galaxies which have experienced at least one merger (with a BB) during their lifetime and have at least one surviving satellite.

A first comparison shows that the stellar masses of BBs (just before the accretion) are only slightly lower than that of $z = 0$ surviving satellites, and that BBs have slightly higher $M_{\text{ColdGas}}/M_{\text{Stellar}}$ fractions (differences of a factor of ~ 2 for MW-type haloes). Fig. 3 shows, for Model A, the average metallicity of surviving satellites (dashed line) and BBs (solid line) as a function of the host DM halo mass. Important differences between both populations arise for DM halo masses $M_{\text{DM}} \gtrsim 6 \times 10^{11} M_{\odot}$: at lower values, the metallicities between satellites and BBs are rather similar, as a result of the smaller differences between formation epochs for BBs and satel-

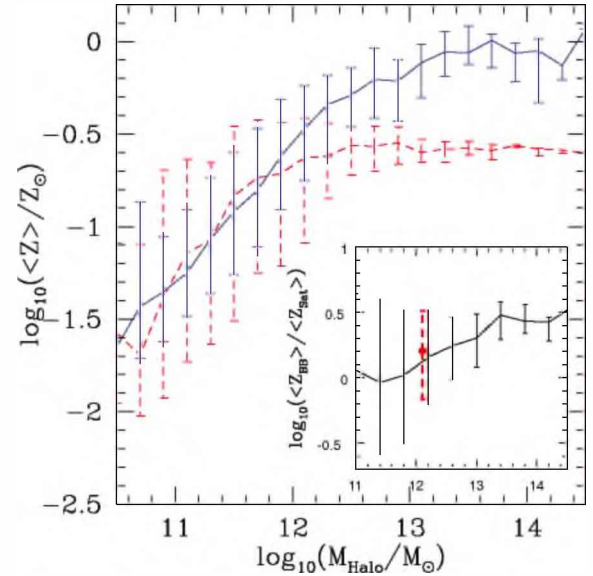


Figure 3. Average metallicity for the present-day satellite galaxy population in individual DM haloes (dashed line) and for the BBs of central galaxies (solid line), as a function of the host DM halo mass, for Model A. Error bars correspond to 20 and 80 percentiles. The inset shows the difference between the average metallicities of BBs and satellites as a function of DM halo mass. The filled circle represents MW-type haloes.

lites of galaxies in lower density peaks. We define the formation epoch as the time when a galaxy has acquired 10 per cent of its final stellar mass, thus avoiding ambiguities arising from the resolution limit. The inset shows the difference between average metallicities of BBs and satellites, $\log_{10}(\langle Z_{\text{BB}} \rangle / \langle Z_{\text{Sat}} \rangle)$, in individual systems: the filled circle shows MW-type haloes for which the difference in the average metallicities is ≈ 0.2 dex. This measurement is consistent with results for the MW, where the abundance patterns shown by dSphs and the Galactic halo are suggestive of higher metallicities for the MW BBs (e.g. Tolstoy et al. 2004). In our sample, 70 per cent of the MW-type haloes show $\log_{10}(\langle Z_{\text{BB}} \rangle / \langle Z_{\text{Sat}} \rangle) \gtrsim 0.0$, which indicates that the MW stellar content would be rather typical for its host halo mass. For Model B, we find a very similar behaviour, indicating that the difference between metallicities of BBs and surviving satellites is an intrinsic feature of the Λ CDM scenario. This claim is also supported by the similarity of our results for different dynamical friction time-scales; we use the two alternative recipes implemented in SAG, as described in LCP08. Our results confirm those found for MW-type haloes in numerical simulations (e.g. Robertson et al. 2005), but this is the first time such an analysis is performed using an unbiased sample of merger trees (with at least one galaxy merger and one surviving satellite) extracted from a fully non-linear cosmological numerical simulation.

It is important to remark that our model predicts that the majority of the stars in galaxies hosted by MW-type haloes are formed *in situ* since BBs only contribute with ≈ 15 per cent of the $z = 0$ stellar mass. In contrast, more than 50 per cent of the $z = 0$ stellar mass of central galaxies hosted by DM haloes with masses $M_{\text{DM}} \gtrsim 10^{13} M_{\odot}$ come from the accretion of BBs.

By analysing the details of their formation (i.e. formation epoch and history), we can explain the gap in metallicity between BBs and surviving satellite galaxies. We estimate their formation time-scales by taking into account the look-back time (LBT) to the moment in which they acquire 10 and 50 per cent of their final stellar mass.

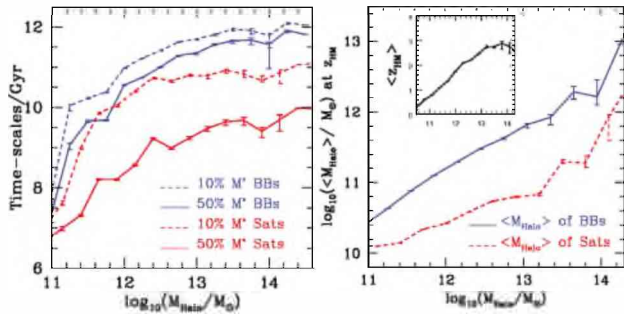


Figure 4. Left-hand panel: average LBT to the formation of 10 and 50 per cent of the final stellar mass of BBs and surviving satellites as a function of DM halo mass (line types are indicated in the figure key), for Model A. Right-hand panel: central halo mass at the redshift of merger with the parent haloes of BBs and the average mass of parent haloes of surviving satellite galaxies at the same redshift. The average redshift for the merger is shown in the inset. Error bars show the uncertainty on the mean.

These are represented for Model A in the left-hand panel of Fig. 4 by dashed and solid lines, respectively, for BBs (blue) and surviving satellite galaxies (red), as a function of the host DM halo mass. As can be seen, regardless of environment, BBs assemble their stellar mass in considerably shorter times (~ 0.25 Gyr to increase their stellar mass from 10 to 50 per cent of its final value) than surviving satellites (~ 1.5 Gyr), implying that the former will naturally show enhanced α -element abundances in comparison to the latter. During short and intense SF events, such as those characteristic of BBs, a stellar population achieves large $[\alpha/\text{Fe}]$ ratios since stars are formed from gas polluted by SNe CC products: the onset of SNe Ia occurs ~ 1 Gyr after the first SF episode, when the bulk of SF activity has already occurred. A detailed study of α -element abundances will be tackled in a forthcoming paper. Additionally, BBs also finish acquiring 50 per cent of their final stellar mass substantially earlier (~ 2 Gyr) than surviving satellites as a result of their different initial environments. BBs are aggregated into more massive objects earlier than surviving satellites, i.e. their initial location could be part of a higher density fluctuation than that of satellites and, therefore, collapse earlier, as already discussed in the literature (e.g. Helmi et al. 2006). In Model B, we consistently find that BBs form both earlier and faster than surviving satellites regardless of their host DM halo mass, indicating that these two effects are natural in a hierarchical universe.

These results indicate that the formation epoch of BBs in MW-type haloes corresponds to $z \simeq 2.7$ (with $\simeq 8$ per cent dispersion in LBT in our model) and that they acquire 50 per cent of their stellar content by $z \simeq 2.25$, whereas MW satellites show formation epochs at $z \simeq 2.1$ (with $\simeq 5$ per cent dispersion in LBT for MW-type haloes) and acquire 50 per cent of their stellar mass by $z \simeq 1.25$. In the concordance cosmology, the peak in the merger activity of galaxies occurs at $z \approx 2-3$ (e.g. LCP08), which coincides with the formation epoch of BBs, and only partially overlaps the epoch when surviving satellites start acquiring their stellar mass. Therefore, the cosmological peak merger activity, which is directly linked to the maximum SF activity in the Universe, may be partly responsible for the different properties of BBs and satellites and would explain the fact that their properties are more similar at lower host DM halo masses (see Fig. 3), for which most of the SF activity occurs at later times when the cosmic SF activity is already in its declining phase. Note that at fixed DM halo mass, the populations of BBs on the one hand and of surviving satellites on the other show very

homogeneous properties; the relative 1σ dispersion in ages and metallicities is of the order of 10 per cent, or smaller.

The right-hand panel of Fig. 4 shows in a solid line the mass of the central DM halo at the moment of the accretion of the parent DM haloes of BBs (when the collapse of the density peak has just occurred and before dynamical friction starts the merging process between the BBs and the central galaxy) as a function of the $z = 0$ host halo mass. The average DM halo mass hosting the $z = 0$ surviving satellites at the same LBT is shown by a dashed line. Additionally, the average redshift of acquisition of the host haloes of BBs is shown in the inset. We can see that, at the accretion epoch of BBs and regardless of environment, the mass of haloes hosting BBs is larger than that of the surviving satellites. This result proves that BBs are embedded in higher initial fluctuation peaks than surviving satellites. This way, a cosmic queuing picture emerges where the progenitors of the most massive present-day objects start their formation process earlier than lower mass systems. Lower present-day mass objects need to wait longer to reach this collapse threshold (see e.g. Press & Schechter 1974).

In summary, the Λ CDM cosmology predicts that central and satellite galaxies represent two distinct populations with different age and metallicity distributions. Even though satellite galaxies, in general, cannot be expected to resemble the original galactic BBs, they can still be used to probe the assumptions behind galaxy formation models by comparing their metal content to that of the halo stars of their central galaxy.

2.1 Why are all the MW satellites so similar?

The observational result that MW satellites are similar between themselves in terms of metallicity properties (G07) and different from their host – the MW galaxy – has been a subject of intense debate. In this Letter, we suggest that the latter is a consequence of the same processes behind the build up of the SMMR: regarding the former, we find that the dispersion in the stellar mass and age for satellites seldom exceeds 23 and 10 per cent, respectively. In particular, MW-type haloes show dispersions below 5 per cent for the formation LBT and 20 per cent for the stellar mass of surviving satellites. Such narrow spreads in masses and ages also result in narrow metallicity dispersions within DM haloes, providing a plausible explanation for the similarities between the different MW dSphs.

3 SUMMARY AND CONCLUSIONS

In this work, we have used the semi-analytic model described by LCP08 in combination with a cosmological N -body simulation of the concordance Λ CDM cosmology and hydrodynamical simulations of galaxy clusters, to study the populations of surviving satellites and BBs of central galaxies hosted by DM haloes of various masses (Model A). In order to isolate the effects arising from the hierarchical growth of structures alone, we also considered a model without AGN feedback and disc instabilities (Model B).

Our main results are summarized as follows.

- (i) On average, massive DM haloes host more chemically enriched galaxies than low-mass haloes, regardless of the inclusion of AGN or SNe feedback. In Model A, central galaxies are older than the surviving satellite population for all the halo masses considered. In Model B, central galaxies of the most massive haloes can be younger than their satellites. The latter effect arises as a result of

the lack of the AGN feedback, which suppresses the SF in massive galaxies at low redshift.

(ii) Halo stars (analysed via the stellar content of BBs) and present-day satellite galaxies show clear differences in age and metallicity; the former are found to be more chemically enriched than the latter, regardless of the inclusion of energy feedback sources as AGN and SNe. We find that these results arise from the earlier formation epochs and faster formation time-scales experienced by BBs with respect to satellites. The epoch of assembly of BBs for MW-type galaxies roughly corresponds to the peak merger activity in a Λ CDM universe.

(iii) With respect to MW-type DM haloes in SAG, we find that, in 70 per cent of the cases, the metallicities of BBs are higher than those of surviving satellites, as is thought to be the case of the MW (e.g. G07). This indicates that the MW stellar content would be rather typical for its host DM halo mass. This particular result does not depend on the implementation of AGN feedback and disc instabilities. However, it should be borne in mind that the observational data may still be subject to selection biases as has been proposed by Bullock & Johnston (2005).

Our conclusions do not depend on the detailed physical assumptions adopted in the semi-analytic model but are rather a natural consequence of the hierarchical growth of structures. To conclude, we remark that the differences between BBs and surviving satellites can be thought of as a consequence of the existence of a SMMR, which is found both in observations and in models of galaxy formation. This relation indicates that objects with higher stellar masses, corresponding to higher peaks in the density field, are characterized by higher metallicities. Therefore, it is not surprising that central galaxies and BBs (which collapsed early into massive objects and populate high peaks) are characterized by higher metallicities than satellite galaxies. The latter only recently began their merging process with their host galaxy and come from lower peaks in the density fluctuation field. This explains their lower metal abundances. In this picture, satellite galaxies are simply waiting for their turn to become BBs to imprint their signature in the continuously evolving relation between the properties of surviving satellites and their host galaxy stellar halo.

ACKNOWLEDGMENTS

We thank Carlton Baugh, Manuela Zoccali, Doug Geisler and Amina Helmi for helpful discussions and comments. We also thank Klaus Dolag and Roberto González for providing the cosmological simulations. We acknowledge the anonymous referee for useful remarks which helped to improve this work. NP was supported by

Fondecyt grant no. 1071006. The authors benefited from a visit of SAC and Carlton Baugh to Santiago de Chile supported by Fondecyt grant no. 7080131. This work was supported in part by the FON-DAP Centro de Astrofísica, by Basal project PFG0609, and by PIP 5000/2005 from Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.

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