Semi-analytic model predictions of mass segregation from groups to clusters

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Accepted 2015 July 22. Received 2015 July 22; in original form 2015 March 27

ABSTRACT
Taking advantage of a high-resolution simulation coupled with a state-of-art semi-analytic model of galaxy formation, we probe the mass segregation of galaxies in groups and clusters, focusing on which physical mechanisms are driving it. We find evidence of mass segregation in groups and clusters up to the virial radius, both looking at the galaxy stellar mass and subhalo mass. The physical mechanism responsible for that is consistent with dynamical friction, a drag-force that brings more massive galaxies faster towards the innermost regions of the halo. At odds with observational results, we do not find the inclusion of low-mass galaxies in the samples, down to stellar mass $M_\ast = 10^9 M_\odot$, to change the overall trend shown by intermediate and massive galaxies. Moreover, stellar stripping as well as the growth of galaxies after their accretion, do not contribute either in shaping mass segregation or mixing the radial mass distribution. Beyond the virial radius we find an ‘antimass segregation’ in groups that progressively weakens in clusters. The continuous accretion of new objects and recent merger events play a different role depending on the halo mass on to which accreting material is falling.

Key words: Galaxy: formation – galaxies: evolution.

1 INTRODUCTION

The current scenario of galaxy formation can be divided in two distinct galaxy evolutionary families: the nature scenario, where galaxy properties depend on the state of the galaxies at the time of their formation, and the nurture scenario, where the galaxy properties are instead the product of environmentally driven processes that take place after the galaxy is accreted on large systems, such as groups and clusters. As highlighted by De Lucia et al. (2012), galaxies experience several different kinds of environment during their lifetime, thus leading to the conclusion that the aforementioned scenarios are twisted together. The mass distribution of galaxies in different environments is therefore the result of many physical processes that operate during galaxy evolution, such as gas cooling, star formation, stripping and mergers, and the environment is believed to have a key-role in shaping galaxy properties (e.g. Kauffmann et al. 2004; Tanaka et al. 2004; Blanton et al. 2005; Weinmann et al. 2006; Blanton & Berlind 2007). We now know that galaxy properties such as mass, colour, gas content and age are strongly related to the environment, such that galaxies in denser environments are typically more massive, redder, less gas-rich and older.

Dynamical friction is a key factor in the link between galaxy growth and environment. This has been pointed out by several authors in the context of dark matter (DM) substructures (see e.g. De Lucia et al. 2004; Contini, De Lucia & Borgani 2012) as well as the connection between galaxy stellar mass and subhalo mass (e.g. Gao et al. 2004; Vale & Ostriker 2006; Wang et al. 2006). According to the dynamical friction formula (given by Chandrasekhar 1943), more massive galaxies fall faster towards the innermost region of the cluster, thus leading to a segregation in mass. Under this picture, the characteristic galaxy mass is expected to increase with increasing halo mass (Yang et al. 2005; Zheng et al. 2005; van den Bosch et al. 2008b) because galaxies are more massive in larger objects, and more massive galaxies should preferentially reside in the centre. Hence, if dynamical friction plays an important role, its effect on the distribution of galaxies in large system must be observable. On the other hand, stellar stripping due to tidal forces between galaxies and the cluster potential, as well as ongoing star formation in galaxies as they fall towards the centre, might affect the distribution in mass. Tidal stripping removes part of the stellar mass of galaxies, and is expected to be more effective in massive galaxies (Rudick et al. 2009; Martel, Barai & Brito 2012; Laporte et al. 2013; Watson & Conroy 2013; Contini et al. 2014), while star formation leads to an increase in stellar mass.

Despite the large amount of observations and effort spent on the topic, there is not yet a common agreement in the literature. There is evidence in favour of mass segregation in large systems (Lares, Lambas & Sánchez 2004; McIntosh et al. 2005; van den Bosch et al. 2008a; Presotto et al. 2012; Balogh et al. 2014; Roberts et al.
but at the same time there is significant evidence for a lack of mass segregation in clusters (von der Linden et al. 2010; Vulcani et al. 2013; Ziparo et al. 2013). Thus, the controversy over mass segregation remains unsolved.

Recently, Roberts et al. (2015), using group catalogues derived from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al. 2009), find evidence for mass segregation out to $2 \times R_{200}$, with strength that scales inversely with halo mass. These authors argue that the conflicting results in the literature might be reconciled by considering that mass segregation appears more evident once low-mass galaxies are included in the sample, and that it is a function of halo mass, with clusters showing little or no segregation. This points-out the need to probe a large range of halo mass and different thresholds in galaxy stellar mass, and the need of timely investigations using theoretical models.

Theoretical models have not sufficiently contributed to the debate. Only very recently Vulcani et al. (2014, hereafter V14), by means of semi-analytic models of galaxy formation (De Lucia & Blaizot 2007; Guo et al. 2011), investigate the galaxy stellar mass function as a function of the environment. Although they do not explicitly focus on mass segregation, these authors find that the stellar mass function does not strongly depend on the cluster-centric distance, although there is a hint of mass segregation in low and intermediate halo masses.

In this Letter, we focus on the role played by dynamical friction on the observed mass segregation in groups and clusters. We take advantage of a state-of-art semi-analytic model which includes a refined treatment of stellar stripping that can be switched on/off. Our simulation allows us to achieve the goals highlighted above, since we can probe a large range of halo mass and use different thresholds in stellar mass in order to: (a) investigate the dependence of mass segregation with halo mass; (b) understand if it is driven by the inclusion of low-mass galaxies in the sample; (c) isolate the role of stellar stripping; and (d) isolate the growth of galaxies after accretion.

Table 1. Our simulated haloes have been split in four samples, according to the halo mass. In the first column, we give the name of the sample, the second column indicates the range of $M_{200}$ values corresponding to each sample, while the third gives the number of haloes in each sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass range ($M_{200}$)</th>
<th>Numb. of haloes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small groups</td>
<td>$[10^{13.5} - 5 \times 10^{13}] M_{\odot} h^{-1}$</td>
<td>2286</td>
</tr>
<tr>
<td>Large groups</td>
<td>$[5 \times 10^{13} - 10^{14}] M_{\odot} h^{-1}$</td>
<td>275</td>
</tr>
<tr>
<td>Small clusters</td>
<td>$[10^{13} - 5 \times 10^{13}] M_{\odot} h^{-1}$</td>
<td>146</td>
</tr>
<tr>
<td>Large clusters</td>
<td>$&gt;5 \times 10^{14} M_{\odot} h^{-1}$</td>
<td>9</td>
</tr>
</tbody>
</table>

3 RESULTS

In order to examine environmental dependences we study four samples of haloes, ranging from small groups (with mass $M_{200}$ in the range $[10^{13} - 5 \times 10^{13}] M_{\odot} h^{-1}$), to large clusters (with mass larger than $5 \times 10^{13} M_{\odot} h^{-1}$). Details of the samples are given in Table 1.

In the top panels of Fig. 1 we plot the mean stellar mass of galaxies as a function of radial distance considering the mass at redshift $z = 0$ (solid lines) and at the time of accretion1 (dotted lines) for our four samples of haloes (different colours), considering all satellite galaxies (explicitly excluding centrals) with stellar mass larger than $10^{10} M_{\odot}$ belonging to the FOF-group. We find a clear mass segregation up to the virial radius, with more massive galaxies preferentially located in the innermost regions, close to the centre. To better quantify the strength of the segregation we compute a linear fit to the virial radius for all samples and show the result in Table 2. The zero-point ($b$) decreases from small groups to big clusters of about 0.2 dex, while the slope ($a$) flattens significantly from $-0.678$ in small groups to $-0.227$ in big clusters. Moreover, none of the slopes are consistent with zero even within $3 \times \sigma$.

Interestingly, at $r \sim R_{200}$ we find an upturn, and the mean stellar mass starts to increase again up to $2 \times R_{200}$, from small groups to small clusters. As shown by the plot, the result still holds when considering the stellar mass at the time of accretion. In this case, the trend is the same, but the mean stellar mass at each radial distance is slightly lower. This means that galaxies have had time to grow in mass by redshift $z = 0$, but also that the effects of stellar stripping and star formation do not drive trends in mass segregation, suggesting that the main driver is of dynamical nature. We compare our results with results of V14 given by the De Lucia & Blaizot (2007) model (black symbols in the top panels of Fig. 1). Despite these points are shifted-low with respect to ours, they clearly show the same trend

1 The time of accretion of a given galaxy is defined as the last time the galaxy is central.
Figure 1. Mean stellar mass of galaxies as a function of radial distance considering the mass at redshift $z = 0$ (solid lines) and at the time of accretion (dotted lines). Dashed lines represent 1σ statistical errors computed for the mass at redshift $z = 0$ (we omit the scatter around the mean mass at accretion for a more readable plot). All galaxies having stellar mass larger than $10^{10} M_\odot$ belonging to the FOF-group are considered (top panels), for halo masses within $[10^{13} - 5 \cdot 10^{13}] M_\odot h^{-1}$ (blue lines), $[5 \cdot 10^{13} - 10^{14}] M_\odot h^{-1}$ (red lines), $[10^{14} - 5 \cdot 10^{14}] M_\odot h^{-1}$ (green lines), and masses $> 5 \cdot 10^{14} M_\odot h^{-1}$ (purple lines). Symbols represent data points of V14, which are predictions of De Lucia & Blaizot (2007) model. The bottom panels show the same information for the same samples of haloes, but considering all galaxies within a sphere of radius $2 \times R_{200}$ centred on the halo centre.

Table 2. Slopes, zero-points and their errors obtained with a linear fit, $\log M_\ast = a (R/R_{200}) + b$, done out to the virial radius, for all samples shown in the upper panels of Fig. 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$a$</th>
<th>$\sigma_a$</th>
<th>$b$</th>
<th>$\sigma_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Groups</td>
<td>−0.678</td>
<td>0.012</td>
<td>10.797</td>
<td>0.005</td>
</tr>
<tr>
<td>Large Groups</td>
<td>−0.483</td>
<td>0.023</td>
<td>10.728</td>
<td>0.011</td>
</tr>
<tr>
<td>Small Clusters</td>
<td>−0.339</td>
<td>0.021</td>
<td>10.665</td>
<td>0.011</td>
</tr>
<tr>
<td>Large Clusters</td>
<td>−0.227</td>
<td>0.045</td>
<td>10.681</td>
<td>0.023</td>
</tr>
</tbody>
</table>

and a hint of upturn in the external regions in small and large groups, while they suggest neither mass segregation within the virial radius nor upturn in large clusters.

In the bottom panels of Fig. 1 we show the same information plotted in the top panels, now considering all galaxies within a sphere centred in the centre of the halo and having a radius equal to $2 \times R_{200}$. This procedure results in a sample including all of those galaxies in the top panels of Fig. 1, as well as all galaxies within the sphere that are not gravitationally bound to the group/cluster, and results in a sample that is more comparable to observational samples. A comparison between the top and bottom panels indicates that adding galaxies not belonging to the FOF-group, but within $2 \times R_{200}$, attenuates the steepness of the stellar mass–radial distance relation beyond $R_{200}$ in groups, and basically flattens it in clusters.

In Fig. 2, we show the DM mass in subhaloes associated with galaxies with stellar mass larger than $10^{10} M_\odot h^{-1}$, for our samples of haloes. In our semi-analytic model we keep following the so-called orphan-galaxies, i.e. those galaxies that have lost their subhalo after accretion in a larger system. In Fig. 2, we take the samples of galaxies considered in the bottom panels of Fig. 1, without the orphan galaxies. The trend of mass with radius shown by DM is the same found for stellar mass, a clear mass segregation up to the virial radius and an upturn beyond it, in all samples except for the small groups. This suggests that mass segregation might be driven mostly by DM rather than by physical processes involving only stellar mass.

The prediction of our model is then consistent with observations that find evidence for mass segregation in groups and clusters (van den Bosch et al. 2008a; Presotto et al. 2012; Balogh et al. 2014; Roberts et al. 2015), at least up to the virial radius. The upturn beyond the virial radius disappears on cluster scales, particularly when the sample includes non-FOF galaxies. We repeated the same analysis including low-mass galaxies (down to $10^9 M_\odot$). The inclusion of low-mass galaxies only changes the mean stellar mass at each radial distance, but does not significantly change the overall trend.

4 DISCUSSION

Mass segregation in evolved objects is generally believed to be a consequence of dynamical friction, which causes more massive galaxies to fall to the centre of haloes more quickly. Nevertheless, the assembly history of haloes, as well as other physical processes taking place in dense environments, might play an important role. Galaxies can grow in stellar mass via star formation or mergers, and the rate of the growth could depend on their stellar mass. In addition, tidal forces in groups and clusters cause stellar stripping. Although
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Figure 2. Mean DM mass in subhaloes of galaxies with mass larger than $10^{10} \ M_\odot h^{-1}$ in the same samples of haloes shown in the bottom panels of Fig. 1. Due to the presence of ‘orphan’ galaxies in our model (see text), this population of galaxies are missed here.

Figure 3. Residual merging time at $z = 0$ (derived as the dynamical friction time-scale minus the time elapsed since accretion) as a function of their radial distance from the halo centre. All galaxies within a sphere centred on the halo centre and having a radius equal to $2 \times R_{200}$ are considered.

dynamical friction brings massive galaxies towards the centre, this is also the environment in which tidal stripping gets stronger (Contini et al. 2014). It is possible that tidal stripping could be strong enough to mix the population of galaxies and no mass segregation would be present. We investigated on this switching-off our stellar stripping and merger channels for the formation of the intrahalo light, and found similar results as those reported in Fig. 1 (plots not shown), meaning that stellar stripping is not enough for mixing the galaxy distribution. This is confirmed by V14’s data, that are predictions of De Lucia & Blaizot (2007) models, which does not have any prescription for stellar stripping.

As seen in Section 3, the top panels of Fig. 1 show that beyond $R_{200}$ the stellar mass–radial distance relation changes slope until it flattens in clusters. When considering all galaxies (bottom panels of Fig. 1) in the sphere centred on the centre of the halo, the slope flattens at lower halo mass, in large groups. This may be due to pre-processing and accretion of new galaxies by the FOF-group, which could reduce the strength of ‘antimass segregation’ found outside the virial radius, that progressively weakens from small groups to large clusters. This is supported by the result found in Fig. 2 for DM subhaloes. Accretion of smaller haloes and mergers of objects with comparable mass during the assembly of each halo have different consequences depending on the virial mass of the object that they are infalling on to or merging with. Large groups and clusters form later, and this may lead to the upturn due to recent mergers of DM haloes. In terms of stellar mass we do not find an upturn on cluster scales due to the non-linear relation between DM and stellar mass. This means that, in our model, the stellar mass growth in massive haloes is not as steep as the DM mass growth, and that the star formation efficiency is higher in low-mass haloes with respect to larger ones. This is consistent with the predicted stellar mass function, from which it is clear that semi-analytic models find more low-mass galaxies than observed (see, e.g. Guo et al. 2011 and references therein).

We investigate the relationship between dynamical friction and halo mass in Fig. 3, where we plot the residual merging time at $z = 0$ versus the radial distance, for the same samples of haloes and considering all galaxies in the sphere centred on the centre of the halo and having a radius equal to $2 \times R_{200}$, as done in the bottom panels of Fig. 1. The residual merging time is simply derived as the dynamical friction time-scale minus the time elapsed since accretion. The dynamical friction time-scale has been evaluated at the time of accretion and following Jiang et al. (2008) formula (equation 5 of their paper). Two interesting features arise from this plot. First, galaxies that are closer to the centre are also those with the smallest residual merging time and, overall, the relations fit well with the behaviour shown in the bottom panels of Fig. 1. Secondly, the residual merging times increase from groups to clusters. This means that mass segregation in groups can be explained by invoking dynamical friction, which has enough time to bring massive galaxies in the innermost regions of the group. This still applies in clusters, where the typical dynamical friction time-scale is long enough to distribute galaxies according to their mass, but on average much longer than in groups (even longer than a Hubble time).

We are aware that the ‘antimass segregation’ we find beyond the virial radius is not observed (e.g. Roberts et al. 2015). There might
be several reasons for that, including contamination of foreground and background galaxies. We do not have any contamination of such objects by construction. On the other hand, when we include unbound galaxies as done in the bottom panels of Fig. 1 instead of FOF galaxies only (as done in the top panels of the same figure), the relation considerably flattens. As argued above, this might be due to recent mergers between DM haloes, which could reduce the strength of antimass segregation found outside the virial radius. The upturn beyond $R_{200}$ is remarkably sharp in groups, and appears sensitive to the inclusion of unbound galaxies. A full explanation of the upturn deserves a more detailed analysis, which must takes into account the merging histories of the haloes considered. We plan to address this point in a future paper.

5 CONCLUSION

In this Letter, we focus on the mass segregation in simulated groups and clusters coupled with a state-of-art semi-analytic model of galaxy formation that accounts for the physics of baryons.

We find a non-negligible mass segregation in groups and clusters up to the virial radius, and the level of segregation is statistically significant at all halo masses. The strength of the segregation is found to be a function of halo mass, such that it is weaker at higher halo mass. This can be explained by invoking dynamical friction, which brings more massive galaxies faster towards the innermost regions of the halo. The mass segregation trends are insensitive to both the inclusion of low-mass galaxies in the sample (down to stellar mass $M_\star = 10^9$ $M_\odot$) and stellar stripping.

Moreover, beyond the virial radius we find an ‘antimass segregation’ in groups that progressively weakens in clusters. The upturn beyond the virial radius highlights that these galaxies are intrinsically more massive than those in the inner regions. Galaxies in the outskirts have been recently accreted and thus have been centrals for a longer time. They then had more time and more chance to grow in mass, due to cooling and enhanced star formation. Considering all galaxies in a sphere centred on the centre of the halo and having a radius equal to $2 \times R_{200}$ (i.e. not only those belonging to the FOF-group), the trend beyond the virial radius weakens, approaching observational findings.

Interestingly, mass segregation is found also by looking at the DM in subhaloes, with similar features shown by the stellar mass. This result, along with the fact that neither stellar stripping nor star formation (nor both together) shape mass segregation after accretion, points out that the main driver of the radial distribution of galaxies has a dynamical nature. We showed that dynamical friction is the most likely candidate, but, in order to quantify its relative contribution in shaping mass segregation and confirm the nature of the upturns beyond the virial radius, a more detailed analysis is needed.

ACKNOWLEDGEMENTS

The authors thank Benedetta Vulcani for providing us her data, Alessio Romeo for helpful comments, and the anonymous referee for improving the content of this Letter. EC and XK acknowledge financial support by NSF of Jiangsu Province (no. BK20140050), 973 programme (no. 2015CB857003, 2013CB834900), the NSFC (no. 11333008) and the Strategic Priority Research Program the emer-

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