SATELLITES AROUND MASSIVE GALAXIES SINCE $z \sim 2$: CONFRONTING THE MILLENNIUM SIMULATION WITH OBSERVATIONS

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ABSTRACT

Minor merging has been postulated as the most likely evolutionary path to produce the increase in size and mass observed in the massive galaxies since $z \sim 2$. In this Letter, we directly test this hypothesis, comparing the population of satellites around massive galaxies in cosmological simulations versus the observations. We use state-of-the-art, publicly available, Millennium I and II simulations, and the associated semi-analytical galaxy catalogs to explore the time evolution of the fraction of massive galaxies that have satellites, the number of satellites per galaxy, the projected distance at which the satellites locate from the host galaxy, and the mass ratio between the host galaxies and their satellites. The three virtual galaxy catalogs considered here overproduce the fraction of galaxies with satellites by a factor ranging between 1.5 and 6 depending on the epoch, whereas the mean projected distance and ratio of the satellite mass over host mass are in closer agreement with data. The larger pull of satellites in the semi-analytical samples could suggest that the size evolution found in previous hydrodynamical simulations is an artifact due to the larger number of infalling satellites compared to the real universe. These results advise us to revise the physical ingredients implemented in the semi-analytical models in order to reconcile the observed and computed fraction of galaxies with satellites, and eventually, it would leave some room for other mechanisms explaining the galaxy size growth not related to the minor merging.

Key words: dark matter – galaxies: evolution – galaxies: formation – galaxies: halos

Online-only material: color figures

1. INTRODUCTION

Accretion of minor satellites has been postulated as the most likely mechanism to explain the significant size evolution (Daddi et al. 2005; Trujillo et al. 2006) of the massive galaxies over cosmic time. This idea fits with much of the observational indirect evidence: the progressive growth of the wings of the profiles of the massive galaxies with time (Bezanson et al. 2009; Hopkins et al. 2009; van Dokkum et al. 2010; Carrasco et al. 2010), the ($\sim 1.5$) larger velocity dispersion of the massive galaxies at high-$z$ compared to present-day equally massive objects (e.g., Cenarro & Trujillo 2009; Cappellari et al. 2009; Onodera et al. 2010; Newman et al. 2010; van de Sande et al. 2011), and the expected mass growth by a factor of two of the massive galaxies with time suggested by the observations (see, e.g., Trujillo et al. 2011).

On the theoretical side, Naab et al. (2009) conducted pioneer work on exploring the minor merging effect on a cosmologically motivated evolution of a massive galaxy since $z \sim 3$. Their study supported the idea that minor merging can explain simultaneously the size and velocity dispersion evolution, as well as a moderate increase of the stellar mass by a factor of two. This work has been confirmed by many other authors (e.g., Sommer-Larsen & Toft 2010; Feldmann et al. 2010; Oser et al. 2012). Nonetheless, although both the observational and theoretical side seem to converge in a unique solution to the problem of the size evolution of the massive galaxies, a direct confrontation of both the theory and the observations has not yet been conducted.Inferring the merger rate (e.g., López-Sanjuan et al. 2011) from the observations is not straightforward due to the large uncertainties in the determination of the merging timescales. Alternatively, an immediate way of testing the model with the data is counting the number of satellites around the massive galaxies. These objects will likely be involved in the growth of the massive objects. Observations have matured enough to allow a robust determination of the fraction of massive galaxies with satellites at different redshifts and for different mass ratios (e.g., Newman et al. 2012; Mármol-Queraltó et al. 2012; López-Sanjuan et al. 2012). On the other hand, present cosmological simulations are large enough to permit the estimation of this fraction with accuracy.

In this Letter, we explore the model predictions about the properties of the satellites surrounding massive galaxies and their evolution with cosmic time. In particular, we compare the changes with redshift of the fraction of satellites, the radial projected distances, and the stellar mass ratio of three different semi-analytical models (Bower et al. 2006; De Lucia & Blaizot 2007; Guo et al. 2011) based on the Millennium simulation with the data taken by Mármol-Queraltó et al. (2012). We find that although the general trends with redshift are reproduced (i.e., the fraction of massive galaxies with satellites only changes moderately with cosmic time in the simulations), all the models tend to overpredict this fraction.

2. GALAXY CATALOGS

We use the public release of two very large $N$-body simulations, Millennium I (Springel et al. 2005) and Millennium-II (Boylan-Kolchin et al. 2009). The cosmology assumed in both simulations is a $\Lambda$CDM with the following parameters: $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_L = 0.75$, $n = 1$, $\sigma_8 = 0.9$, and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. The two simulations use the same
number of particles, $2160^3$, but cover different volumes and, therefore, they have different numerical resolutions. Thus, the computational boxes have sides of 685 Mpc and 137 Mpc, and particles masses of $1.18 \times 10^9 M_\odot$ and $9.45 \times 10^6 M_\odot$ for the Millennium I and II simulations, respectively.

The dark matter merger trees are extracted from the simulations using a combination of friends-of-friends (Davis et al. 1985) and SUBFIND (Springel et al. 2001) halo finders. The dark matter halos are converted into galaxies according to different semi-analytical models which can differ in the phenomenological recipes to introduce the gas and stellar components in such halos. In this Letter, we consider three semi-analytical models available in the Millennium database web (Lemson & the Virgo Consortium 2006).

The first one is a version of the Durham semi-analytical model (Bower et al. 2006) that implements feedback due to active galactic nuclei (AGNs) as a manner to stop or delay the formation of cooling flows. The other two models are the ones by De Lucia & Blaizot (2007) and Guo et al. (2011). Both are very similar, the second one being an improvement of the earlier version that modifies or extends some of the semi-analytical recipes. The new features implemented in the model by Guo et al. (2011) are the separate evolution of sizes and orientations of gaseous and stellar disks, the size evolution of spheroids, tidal and ram-pressure stripping of satellite galaxies, and the disruption of galaxies to produce intracluster light. The effect of AGN feedback was already included in the earlier version by De Lucia & Blaizot (2007). The initial mass function (IMF) used to estimate the stellar masses of the simulated galaxies were from Chabrier (2003) for Guo et al. (2011) and De Lucia & Blaizot (2007) and Kennicutt (1983) for Bower et al. (2006).

The models by Bower et al. (2006) and De Lucia & Blaizot (2007) use the Millennium I simulation, whereas the third model by Guo et al. (2011) is based on the higher resolution Millennium-II simulation.

## 3. RESULTS

We have generated three galaxy catalogs using the Millennium web application. Each catalog corresponds to one different semi-analytical model as previously discussed. For each of the catalogs, we select all the massive galaxies—which we call host galaxies—as those objects with stellar masses, $M_\ast$, between $10^{11} M_\odot$ and $10^{13} M_\odot$. For each host galaxy, and for the sake of comparison with the data by Máról-Queralto et al. (2012), we consider a spherical region of a radius of 100 kpc (physical units). Within this region, we compute the number of satellites with stellar masses of $0.1 < M_\ast/M_\odot < 1$ and projected distances smaller than 100 kpc. Once the satellites fulfilling such mass ratio and separation conditions are identified, we calculate the projected distance of each satellite and the mass ratio with respect to their host galaxy. In order to study different mass scales, this process is repeated for smaller satellites with stellar masses in the range of $0.1 < M_\ast/M_\odot < 1$.

Possible bias effects due to the use of different host masses or galaxy-type-dependent number of satellites are minimized by using the same mass criteria for simulated and observed galaxies and by comparing both samples globally, without distinguishing between galaxy types.

In Figures 1 and 2, we present the results of the previous analysis on the three considered galaxy catalogs. The figures are organized in three columns, each one showing the results of one particular catalog. For all the columns in Figure 1, and from top to bottom, we display the fraction ($\langle f \rangle$) of massive galaxies that have at least one satellite and the mean number of satellites ($N_s$) for those host galaxies that have them. The

![Figure 1](image_url)
average projected distance of the satellites ($D_s$) and the average ratio of the satellite stellar mass over the host galaxy stellar mass ($M_s/M_h$) are presented in Figure 2 and organized as in Figure 1. The full circles (triangle) stand for the simulated satellites with mass ratios of $0.1 < M_s/M_h < 1$ ($0.01 < M_s/M_h < 1$). The error bars are computed as one standard deviation. The observational data from Mármol-Queraltó et al. (2012) are overplotted as red (blue) open circles (diamonds) for mass ratios of $0.1 < M_s/M_h < 1$ ($0.01 < M_s/M_h < 1$) in both figures. The IMF used in this work was from Chabrier (2003). These data are representative of the results found for different authors (see, e.g., Figure 6 of López-Sanjuan et al. 2012), and for this reason we use it here as a basis of comparison with the simulations.

Figure 1 clearly shows that all the semi-analytical models explored in this Letter systematically overpredict at every redshift the fraction of massive galaxies having satellites in their vicinity. The model expectation is larger than what is currently measured by a factor ranging between 1.5 and 6 depending on the mass ratio considered to probe the satellite population (either $1:10$ or $1:100$).

The average projected distance of the satellites to the host galaxy in Figure 2 is well reproduced (within the errors) for the case of $1:10$ ratio: $\sim 40$ kpc. However, in the case of the $1:100$ ratio, the observed satellites are closer to the massive objects than what simulations predict. Finally, in relation to the typical average mass of the satellites within each mass ratio displayed in Figure 2, the models are closer to the observations, particularly in the case of Bower et al. (2006). Another important aspect of the observations which agree broadly with the models is the fact that all the properties of the satellites explored here, the fraction of massive galaxies with satellites, their average distance to the host object, and the average mass ratio of the satellite, depend weakly on the redshift.

Summarizing, model predictions agree qualitatively well with the observations, except for the fact that they overpredict on average the fraction of massive galaxies with satellites around them by a factor of two.

4. DISCUSSION

The most striking of our results is the overabundance of simulated satellites around massive galaxies by a factor between 1.5 and 6 compared to the observations. At $z = 0$, this is quite surprising as the stellar mass function of the Millennium galaxies (Guo et al. 2011) is perfectly compatible with the observations (Pérez-González et al. 2008). Guo et al. (2011) use the same observational database as in Mármol-Queraltó et al. (2012), so the origin of this discrepancy cannot be explained as a consequence of a different data set. The slightly high power spectrum normalization in Millennium ($\sigma_8 = 0.9$) is also irrelevant, as no important effects are expected at the scales studied in this work (see, for instance, Zentner & Bullock 2003). The only way to reconcile both results is by considering that the spatial distribution of less massive galaxies is not the same in the real and in the virtual universe. In particular, the satellite galaxies are more clustered (a factor of two on average) around the massive galaxies in the semi-analytical samples than what the observations suggest. It is worth noting that at $z > 0$, the semi-analytical models considered here do not match the observed mass functions, and, indeed, they overproduce the number of low mass galaxies.

The fact that semi-analytical satellites appear to be on average a factor of two more common around the massive galaxies than in the observations could point to a factor of two larger merger timescale in the models than in the real universe (a scenario already discussed in the literature and which has so far eluded a conclusive answer, see, e.g., the discussion in López-Sanjuan et al. 2012). Other possible sources of the discrepancy between the abundance of real and virtual satellite galaxies could be related to numerical resolution effects or the use of an unrealistic modeling of the galaxy formation processes—for moderate and small masses—in the semi-analytical models considered in this Letter. In order to discard possible resolution effects, we have performed an extra analysis using two galaxy catalogs produced by the same semi-analytical model described in Guo et al. (2011) on both Millennium I and II simulations.
results are extremely similar for all the analyzed quantities in both cases. This fact discards uncontrolled effects due to the numerical resolution and stresses the crucial role of the considered semi-analytical model. In particular, the different treatment for identifying the central galaxies and for the gas stripping between the models by Guo et al. (2011) and De Lucia & Blaizot (2007) should enhance the satellite galaxy population in Guo’s model as is proved by the results shown in Figure 1. We note, however, that even with such differences, the three models considered here show a clear excess in the fraction of satellites around massive galaxies.

Another remarkable result of the observations is the constancy of the fraction of massive galaxies with satellites at all redshift. This suggests that the number of satellites per host is in equilibrium, leading to a constant accretion of stellar mass by the host galaxy (Nierenberg et al. 2012). This is in contrast with the decline of this fraction since $z \sim 1.2$ in the higher resolution Millennium II simulation. We remark, however, that in the lower resolution Millennium I simulations this fraction seems also not to change with cosmic time, in better agreement with the observations. We can link this finding with the radial distribution of the satellites. In all the three semi-analytical catalogs, the projected average distance of the satellites is almost constant. This trend is perfectly consistent with the observations, although the actual values for the average projected distance are only similar between data and models for the larger satellites. A constant average radial distance of the satellites indicates no significant evolution in the radial profile of satellites, in agreement with the result found by Budzynski et al. (2012).

Finally, it is important to discuss the results found here in relation to the role of minor merging in the evolution in mass and size of the massive galaxies as commented in the Introduction. Both observations and hydrodynamical simulations agree on the important role played by the satellites at feeding the host massive galaxies and producing an unavoidable increase in their sizes and masses. In fact, such hydrodynamical simulations as the ones presented in Oser et al. (2012) are able to fully explain the evolution in size of the massive galaxies by the effect of minor merging. However, the results presented in this work indicate that these findings should be taken with caution, since these simulations do not include AGN feedback and, therefore, even a larger number of satellites should be expected. In particular, simulations showing that the full size evolution can be explained by minor merging alone must also be able to reproduce the number of satellites found observationally. Thus, the larger pull of satellites in the simulations could suggest that size evolution found in the hydrodynamical simulations (although in agreement with the observations) is an artifact due to the larger number of infallen satellites compared to the real universe. This would leave some room for other mechanisms of galaxy size growth not related to the minor merging. However, the ambiguities in the physical processes modeled in the simulations lead to uncertainties in crucial issues like the merger timescales or the efficiency in the size growth that prevent us from concluding this result with full certainty.

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