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Satellite galaxies: the infalling pieces of the puzzle of massive galaxies

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Abstract

Accretion of minor satellites has been postulated as the most likely mechanism to explain the significant size evolution of the massive galaxies over cosmic time. A direct way of probing this scenario is to measure the frequency of satellites around massive galaxies at different redshifts. In this contribution, I present the study that we have performed to search for satellites around 629 massive ($M_* \sim 10^{11} M_\odot$) galaxies up to $z \sim 2$ from the near-infrared Palomar/DEEP-2 survey. We find that the fraction of massive galaxies with satellites remains basically constant and close to 30% for satellites with a mass ratio down to 1:100 up to $z = 1$, and ~15% for satellites with a 1:10 mass ratio up to $z = 2$. In addition, at low redshift the satellites are, in average, 1.5 Gyr younger than the massive galaxies that host them. In the minor merging model, this rejuvenated material is likely to be placed in the outskirts of the massive objects, and negative age gradients should be observed in local massive galaxies. Hence, this work gives new clues to explore the minor merging scenario from the study of nearby galaxies.

1 Introduction

Following the discovery of the dramatic increase of the size of the massive galaxies in the last 11 Gyr (a factor of 5 since $z \sim 2$; e.g. [10, 22]), several theoretical scenarios were proposed to explain this huge structural evolution. Among the different ideas that were suggested, the major merger scenario was very early on discarded by the observations (see e.g. [4, 20]). This left room to a growing consensus that the strong size evolution observed among the massive galaxies is mainly dominated by the continuous accretion of minor satellites. However, all the observational evidences compiled so far suggesting that the minor merging is the main route of galaxy size growth it is only indirect, and based on other derived properties of the galaxies like the progressive build-up of their envelopes as cosmic time increases (e.g. [11, 6]) or the mild increase in their velocity dispersions with redshift (e.g. [7, 5]).

A direct way of probing the minor merging scenario is to explore the evolution of the satellites around massive galaxies with cosmic time (e.g.,[25, 14, 24]). Several papers in the last years have calculated the frequency of satellites around massive galaxies and have quantified how this fraction changes with cosmic time. This work has been done in the nearby Universe (see e.g., [8, 16]) and up to $z \sim 1$ using mostly samples of central galaxies less massive than $10^{11}\,\mathrm{M}_\odot$ (e.g., [21, 18]). Here I present our study of satellites around galaxies with $M_{\rm star} \sim 10^{11}\,\mathrm{M}_\odot$ up to $z \sim 2$.

2 Galaxy samples: massive galaxies and catalog of candidates to satellite

The central galaxies were selected from the sample of massive objects published in [23] (hereafter T07) based on the near-infrared Palomar/DEEP-2 survey ([3, 9]) over 710 arcmin^2 in the Extended Groth Strip (EGS).

The satellites around our massive objects were extracted from the EGS IRAC-selected galaxy sample of the Rainbow Cosmological Database[1] published by [1]. This database covers an area of 1728 arcmin^2 centered on the EGS and provides spectral energy distributions (SEDs) ranging from the UV to the MIR regime plus well-calibrated and reliable photometric redshifts and stellar masses ([2]). For the $\sim 10\%$ of the galaxies in this catalog, spectroscopic redshifts are also available. From the Rainbow database we have selected all the galaxies with $z < 2.2$ and an estimated stellar mass $10^8\mathrm{M}_\odot < M_{\rm star} < 10^{12}\mathrm{M}_\odot$. We refer to this resulting sample as the Rainbow catalog.

There are 629 galaxies up to $z = 2$ from T07 for which the Rainbow catalog allows the study of satellites down to a 1:10 mass ratio ($0.10 < M_{\rm sat}/M_{\rm central} < 1$). Down to 1:100 mass ratio ($0.01 < M_{\rm sat}/M_{\rm central} < 1$) and $z < 1$, the number of galaxies that can be explored is 194. These final samples are given by the stellar mass limit (75% complete) at each redshift of the Rainbow database, so that we only consider central galaxies that could have satellites down to 1:10 (and 1:100 for $z < 1$) mass ratio in the Rainbow catalog. More information of this selection is detailed in [17]. The mean stellar mass of our sample is $M_\star = 1.3 \times 10^{11}\mathrm{M}_\odot$ (Kroupa IMF).

3 Search criteria for satellites

We count as satellites those galaxies found in the Rainbow catalog that: (1) are within a projected radial distance to our central galaxies of $R_{\rm search}$=100 kpc (corresponding to 0.3 and 0.2 arcmin for $z = 0.5$ and 2.0, respectively).The search is also restricted to distances larger than 1 arcsec ($\sim$ 8 kpc), which is the deblending limit of sources in the Rainbow database; (2) the difference between their photometric redshifts and the redshift of the central galaxies is lower than the 1σ uncertainty in the estimate of the photometric redshifts of the Rainbow database (using the same uncertainties than in the selection of the sample, i.e., $\Delta z_{\rm phot} = 0.070$ for $0.0 < z < 0.5$, $\Delta z_{\rm phot} = 0.061$ for $0.5 < z < 1.0$, and $\Delta z_{\rm phot} = 0.083$ for $1.0 < z < 2.5$);

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[1] `https://rainbowx.fis.ucm.es/Rainbow_Database/`

and (3) the stellar mass of these objects should be within $0.1 < M_{\mathrm{sat}}/M_{\mathrm{central}} < 1.0$ for the galaxies in the range $0 < z < 2$, and within $0.01 < M_{\mathrm{sat}}/M_{\mathrm{central}} < 1.0$ for the galaxies in the range $0 < z < 1$. We considered different redshift bins to explore the evolution of the fraction, F_{sat}, of massive galaxies with satellites. The width of these bins were chosen to include a similar number of massive galaxies in each bin and have a similar statistics among them.

4 Massive galaxies with satellites

Although redshifts, either from photometric or spectroscopic measurements, are available for all the galaxies in this study, there is a number of objects identified as satellites that are actually contaminants that satisfy the above criteria but are not gravitationally bound to our massive galaxies. We quantify this contamination by placing a number of mock massive galaxies (equal to our central galaxies) randomly through the volume of the catalog. In our simulations, the number of mock galaxies that are within each redshift bin is the same than in our sample and we keep fixed the parameters of the massive galaxies. Once we have placed our mock galaxies through the catalog, we count which fraction of these mock galaxies have satellites around them taking into account the searching criteria explained above. This procedure is repeated one million times to have a robust estimation of the fraction of mock galaxies with satellites. We consider this value, S_{simul}, to be representative of the background affecting our real central sample. In addition, these simulations allowed us to estimate the scatter in the fraction of galaxies that have contaminants. We use this scatter as an estimation of the error of our real measurements.

Since the observed fraction of galaxies with satellites, F_{obs}, is then the sum of the fraction of galaxies with real satellites, F_{sat}, plus the fraction of galaxies which have not satellites but are affected by contaminants $(1 - F_{\mathrm{sat}}) \times S_{\mathrm{simul}}$, we use the following expression:

$$F_{\mathrm{sat}} = \frac{F_{\mathrm{obs}} - S_{\mathrm{simul}}}{1 - S_{\mathrm{simul}}}, \tag{1}$$

where F_{sat} is the final (corrected) fraction of galaxies with satellites obtained from the observed values F_{obs} and the fraction of galaxies with satellites obtained in the simulations S_{simul}.

Our results are illustrated in Fig. 1. The main result is that the fraction of massive galaxies with satellites, within a projected radial distance of 100 kpc, down to a 1:10 mass ratio (corresponding to the range $0.1 < M_{\mathrm{sat}}/M_{\mathrm{central}} < 1$) remains basically constant ($17 \pm 3\%$) in the redshift interval $0 < z < 2$. To have a $z = 0$ comparison, we have added the easurement from [16] using the SDSS sample. They found that at $z = 0$ the fraction of massive galaxies with satellites in the mass range and projected radius explored here is very similar. In the same figure, we show the same analysis up to $z = 1$ for satellite galaxies with 1:100 mass ratio. Although a little bit noisier due to the lower statistics, our findings agree with a relative constant fraction ($31 \pm 6\%$) of massive galaxies having such type of satellites.

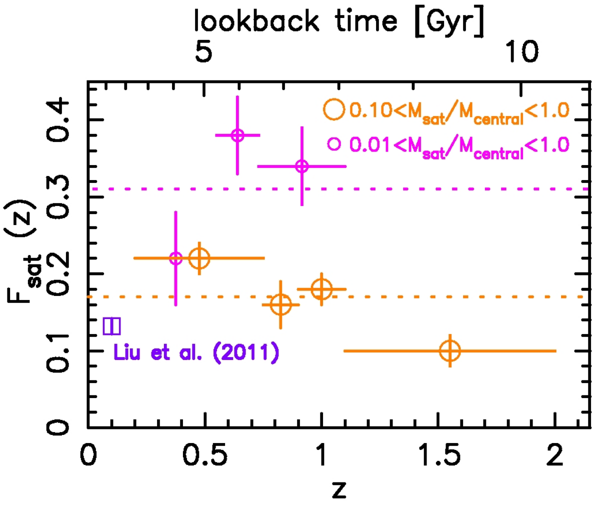

Figure 1: Fraction of massive galaxies with satellites within a projected distance of 100 kpc for different redshifts. The magenta small circles indicate the fraction of massive galaxies with satellites in the mass range $0.1 < M_{\rm sat}/M_{\rm central} < 1$, while the orange big circles indicate the fraction of massive galaxies with satellites in the mass range $0.01 < M_{\rm sat}/M_{\rm central} < 1$. The blue cross indicates the fraction of satellites around massive galaxies in the nearby universe [16].

5 Properties of the satellite galaxies: stellar ages

The available data from the Rainbow catalog allow us to estimate the average properties of the satellites and their central galaxies, as the stellar ages of the galaxies. To estimate these quantity properly, we need to correct statistically by the effect of the contaminants. For doing that, we use the following expression:

$$< Q_{\rm sat} >= \frac{F_{\rm obs}}{F_{\rm sat}} < Q_{\rm obs} > - \frac{S_{\rm simul}}{F_{\rm sat}} < Q_{\rm simul} > \qquad (2)$$

where $< Q_{\rm obs} >$ is the observed mean value of the property Q, $< Q_{\rm simul} >$ is the mean value obtained from the mock massive galaxies (i.e. the values that are found for the contaminants) and $< Q_{\rm sat} >$ is the value after the correction.

We present in Fig. 2 the results obtained for the stellar ages of the galaxies in this study. We find that both satellites and central galaxies at high redshifts present similar average stellar ages, while satellites are younger than their central galaxies when the redshift decreases. A linear fit indicates that satellites at $z = 0$ would be $>$ 1.5 Gyr younger than their central galaxies.

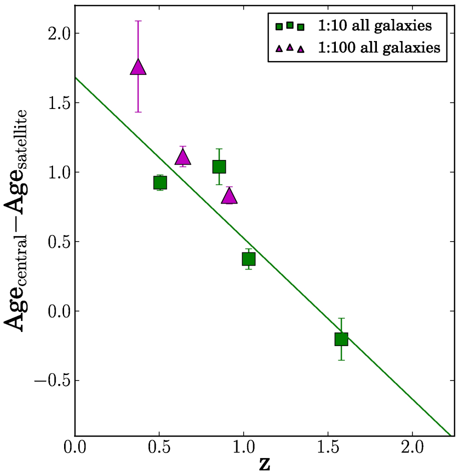

Figure 2: Difference in stellar age between the central galaxies and their satellites. We plot the case of the whole sample exploring satellites down to 1:10 mass ratio (green squares) and down to 1:100 mass ratio (magenta triangles).

6 Summary

In this contribution I present our study of satellites around massive galaxies since $z \sim 2$. We find that $\sim 15\%$ of massive galaxies present satellites down to a 1:10 mass ratio since $z \sim 2$. If we explore satellites down to a 1:100 mass ratio, $\sim 30\%$ of our massive galaxies with $z < 1$ have satellites in this stellar mass range. When exploring the stellar ages of the galaxies, we find that at high redshift, the satellites and their central galaxies have similar stellar ages. When the redshift decreases, we find that satellites are youger than their central galaxies, being > 1.5 Gyr younger at $z = 0$. Since simulations of minor merging suggest that new accreted stars from satellites are mainly added to the outer parts of the central galaxies (e.g., [15, 13, 12]), a (mild) negative age gradient (older stellar populations in the cores than in the outer parts) should be observed in nearby massive galaxies if these satellites are finally accreted by their central galaxies. The challenge to find this age gradient is opened.

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