Interactions of Satellite Galaxies in Cosmological Dark Matter Halos

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Abstract

We present a statistical analysis of the interactions between satellite galaxies in cosmological dark matter halos taken from fully self-consistent high-resolution simulations of galaxy clusters. We show that the number distribution of satellite encounters has a tail that extends to as many as 3-4 encounters per orbit. On average 30% of the substructure population had at least one encounter (per orbit) with another satellite galaxy. However, this result depends on the age of the dark matter host halo with a clear trend for more interactions in younger systems. We also report a correlation between the number of encounters and the distance of the satellites to the centre of the cluster: satellite galaxies closer to the centre experience more interactions. However, this can be simply explained by the radial distribution of the substructure population and merely reflects the fact that the density of satellites is higher in those regions.

In order to find substructure galaxies we applied (and present) a new technique based upon the N-body code MLAPM. This new halo finder MLF (MLAPM’s-halo-finder) acts with exactly the same accuracy as the N-body code itself and is therefore free of any bias and spurious mismatch between simulation data and halo finding precision related to numerical effects.

Keywords: methods: n-body simulations – galaxies: clusters – galaxies: kinematics and dynamics – cosmology: dark matter

1 Introduction

Observations

There are several hints indicating that satellite galaxies orbiting within our own Milky Way are interacting with each other. Zhao (1998), for instance, proposed a scenario where the Sagittarius Dwarf galaxy had an encounter with the Magellanic Cloud system some 2-3 Gyrs ago, something that has also been speculated and noted by Ibata & Lewis (1998). Moreover, the two Magellanic Clouds themselves provide the most accurate description of our Universe. Observations point towards a ΛCDM Universe comprised of 28% dark matter, 68% dark energy, and luminous baryonic matter (i.e. galaxies, stars, gas, and dust) at a mere 4% (cf. Spergel et al. 2003). This so-called “concordance model” induces hierarchical structure formation whereby small objects form first and subsequently merge to form progressively larger objects (e.g. White & Rees 1978; Davis et al. 1985). Hence, galaxies and galaxy clusters are constantly fed by an accretion stream of smaller entities starting to orbit within the encompassing dark matter potential of the host. While generally successful, the ΛCDM model does face several problems, one such problem actually being the prediction that one-to-two orders of magnitude more satellite galaxies should be orbiting within galactic halos than are actually observed (Klypin et al. 1999; Moore et al. 1999).

However, there are also indications that the CDM model is in fact correct and does not have a problem with an overabundant population of satellite galaxies. For instance, Benson et al. (2002) carried out a semi-analytical study of satellites in the Local Group and found that an earlier epoch of reionisation was sufficient to suppress star formation in many of the subhalos and thus produce a significant population of “dark galaxies”.

Therefore, if the CDM model is in fact correct and the (overabundant) population of (dark) satellites predicted by it really does exist, it is imperative to understand the discrepancy by investigating the orbital evolution of these objects and their deviation from the background dark matter distribution.

Is Cold Dark Matter still feasible?

There is mounting, if not overwhelming, evidence that CDM provides the most accurate description of our Universe. Observations point towards a ΛCDM Universe comprised of...
the dark matter host halo (Johnston et al. 1996; Hayashi et al. 2003). We stress that each of these studies have provided invaluable insights into the physical processes involved in satellite disruption; our goal is to augment those studies by relaxing the assumption of a static host potential as, in practice, realistic dark matter halos are neither static nor spherically symmetric.

The story continues

The work presented here is based upon a set of numerical simulations of structure formation within said concordance model, analysing in detail the temporal and spatial properties of satellite galaxies residing within host dark matter halos that formed fully self-consistently within a cosmological framework. We focus on interactions between satellite galaxies orbiting within a larger dark matter halo and especially if there is a relation between mutual interplay and distance to the host. The outline of the paper is as follows.

In Section 2 we present our new halo finding algorithms based upon the $N$-body code MLAPM. We then apply it to our set of eight cosmological dark matter halos in Section 3 with a summary of our results given in Section 4.

2 Identifying Satellite Galaxies

Cosmological Simulations

Over the last decades great advancements have been made in the development of $N$-body codes. We have seen the rise of tree based gravity solvers (Barnes and Hut 1986), mesh based techniques (Klypin & Shandarin 1983), and combinations of direction summation techniques and grid based Poisson solvers (Efstathiou et al. 1985). However, simulating the Universe in a computer and producing the data is only the first step in a long journey; the purpose of these codes is their predictive power, thus the ensembles of millions of dark matter particles used with such (dissipationless) $N$-body codes need to be interpreted and then compared to the observable Universe. This task requires analysis tools to map the phase-space, which is being sampled by the particles, back to "real" objects in the Universe, the traditional way has been through the use of "halo finders".

Identifying Dark Matter Halos

Halo finders mine the $N$-body data to find locally overdense gravitationally bound systems. Under the assumption that all galaxies and galaxies clusters are centered about local over-density peaks in the dark matter density field they are usually found just using spatial information of the particle distribution. To identify objects in this fashion, the halo finder is required in some way to reproduce the work of the $N$-body solver in the calculation of the density field or the location of its peaks. The major limitation, however, will always be the appropriate reconstruction of the density field. Normally this task is performed after the simulation has finished using an independent method to derive a) the density field and b) to smooth it on a certain scale.

With that in mind, we are using a new method for identifying gravitationally bound objects that utilizes the adaptive meshes of the open source $N$-body code MLAPM (Knebe, Green & Binney 2001). It is called MHF (MLAPM’s Halo Finder) and naturally works on-the-fly, but has also been adapted to deal with single outputs of any $N$-body code. However, in order to understand the functionality of MHF it is important to gain insight into the mode of operation of MLAPM first.

MLAPM’s Mode of Operation

MLAPM reaches high force resolution by refining high-density regions with an automated refinement algorithm. These adaptive meshes are recursive: refined regions can also be refined, each subsequent refinement having cells that are half the size of the cells in the previous level. This creates a hierarchy of refinement meshes of different resolutions covering regions of interest. The refinement is done cell by cell (individual cells can be refined or de-refined) and meshes are not restricted to have a particular symmetry. The criterion for (de-)refining a cell is simply the number

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1MLAPM can be downloaded from the webpage http://astronomy.swin.edu.au/MLAPM
Thus, the grid structure naturally surrounds the satellites; therefore follow the density distribution by construction. The density field with the cosmological background density) drops below the virial value set by the background cosmological model, i.e. $\Delta_{\text{vir}} = 340$ for $\Lambda$CDM at redshift $z = 0$. This defines the virial radius $R_{\text{vir}}$ and provides us with a list of particles associated with that dark matter halo.

We then need to prune that list and remove (in an iterative procedure) all gravitationally unbound particles, respectively. Starting with the potential centre again, we calculate the kinetic and potential energy for each individual particle in the respective reference frame and all particles faster than two times the escape velocity are removed from the halo. We then recalculate the centre (as well as the virial radius) and proceed through the process again. This iteration stops once no further particles are removed or if there are fewer than eight particles left in which case the potential centre will be removed from the halo list completely.

In the end we are left with not only a list of appropriate halo positions but we also derived canonical properties for all credible objects, e.g. virial radius, virial mass, velocity dispersion, density profile, etc. A more elaborate description of our technique can be found elsewhere though (Gill, Knebe & Gibson 2004a).

### 3 Quantifying Interactions in simulated Galaxy Clusters

**The Dark Matter Host Halos**

We created a set of eight high-resolution galaxy clusters each consisting of order more than a million dark matter particles. These clusters formed in dissipationless $N$-body simulations of the so-called "concordance" ($\Lambda$CDM) cosmology ($\Omega_0 = 0.3, \Omega_{\Lambda} = 0.7, \Omega_b h^2 = 0.022, h = 0.7, \sigma_8 = 0.9$). The runs have a mass resolution of $m_p = 1.6 \times 10^8 h^{-1}$ $M_\odot$ and achieved a force resolution of $\approx 2h^{-1}$ kpc allowing us to resolve the host halos down to about the central 0.25% of their virial radii $R_{\text{vir}}$.

The halos were specifically selected to investigate the evolution of satellite galaxies and its debris in an unbiased sample of host halos thus analysing the influence of environment in the evolution of such systems. To achieve this goal high temporal information was required to track the development of the satellites. We therefore stored 17 outputs from $z = 2.5$ to $z = 0$ equally spaced with $\Delta t \approx 0.35$ Gyrs. From $z = 0.5$ to $z = 0$ we have 30 outputs spaced $\Delta t \approx 0.17$ Gyrs. A summary of the eight host halos is presented in Table 1.

The quality of our halo finder and our data, respectively, can be viewed in Figure 2. There we show the orbits of four sample satellite galaxies orbiting within their respective host halo. This Figure nicely demonstrates how we are very accurately tracking the orbits of the satellites within the area of trade of the host halos. In a companion paper (Gill et al. 2004) we are presenting a thorough analysis of the dynamics of these satellite galaxies. There we

![Image](image_url)
also present the number distribution of orbits of the sub-
structure population which peaks at about 1–2 orbits with
a tail extending to as many as 5 orbits in the older systems.
However, in this study we like to focus on one particular
aspect, namely satellite-satellite encounters.

Quantifying Encounters

As a first order approximation for quantifying encounters
between substructure galaxies we calculated the tidal radius
of a given satellite induced by one of the other satellites.
This means that the tidal radius is defined to be the radius
where the gravitational effects of the companion satellite
are greater than its self-gravity. When approximating both
satellites as point masses and maintaining that the mean
density within the satellite has to be three times the mean
density of the "perturber" at distance \( D \) (Jacobi limit) the
definition for tidal radius reads as follows

\[
\tau_{\text{tidal}} = \left( \frac{m}{3M} \right)^{1/3} D, \tag{1}
\]

where \( m \) is the mass of the actual satellite and \( M \) is the
mass of the perturbing satellite at distance \( D \).

Whenever the tidal radius becomes smaller than the virial radius\(^2\) of the satellite we increased a counter for that
particular satellite. This counter now keeps track of the
number of (perturbing) interactions with companion satel-
lite galaxies. As some of the satellites may have had more
interactions simply because they spent more time orbiting
the host we are normalising the number of encounters by the
number of orbits for each individual satellite. The distribu-
tion of this (normalised) counter is presented in Figure 3.
The well pronounced peak at zero encounters shows that in
most cases the interactions between satellites is negligible.
However, we also observe that (in our simplistic treatment
for satellite-satellite interactions) we do find as many as 3-4
encounters per orbit for individual satellites. This, in fact,
indicates that with sufficient spatial resolution (as it is the
case with our data) one is able to decipher the influence of
the dominant host halo from the (minor) interactions with the
companion satellite galaxies. We, however, leave a
detailed analysis of this phenomenon to a companion paper
(Gill, Knebe & Gibson 2004b), where we individually select
satellite galaxies and resimulate them in static and evolving
analytic host potentials as opposed to their evolution in the
live potential used for this study.

We complement Figure 3 with Table 2 where we give the
percentage of satellites that had one or more encounters
per orbit. The average percentage amounts to 30% of the
whole substructure population. We also observe a clear
trend for the interactions to become more prominent in youn-
ger systems. This is basically a reflection of the fact
that the younger systems are still in the process of digesting
their last major merger and have not reached an equilibrium
state yet, respectively.

\(^2\)We are tracking each satellite galaxy individually from the
formation time of the host halo using its initial particle content
and hence we are in the unique position to accurately calculate
its virial radius as the radius where the mean averaged density
(measured in terms of the cosmological background density \( \rho_b \))
drops below \( \Delta_{\text{vir}}(z) \).

Table 1: Properties of the eight dark matter host ha-
os. Distances are measured in \( h^{-1}\) Mpc, velocities in
\( \text{km s}^{-1}\), masses in \( 10^{14}\) \( h^{-1}\) \( \text{M}_\odot \), and the age in
Gyrs. We applied a mass-cut of \( M > 10^{10}\) \( h^{-1}\) \( \text{M}_\odot \)
(100 particles) which explains the rather 'low' number for \( N_{\text{sat}}(<R_{\text{vir}}) \).

| Halo | \( R_{\text{vir}} \) | \( M_{\text{vir}} \) | \( z_{\text{form}} \) | age | \( N_{\text{sat}}(<R_{\text{vir}}) \) |
|------|----------------|----------------|----------------|-----|----------------|
| # 1  | 1.34           | 2.87           | 1.16           | 8.30| 158            |
| # 2  | 1.06           | 1.42           | 0.96           | 7.55| 63             |
| # 3  | 1.08           | 1.48           | 0.87           | 7.16| 87             |
| # 4  | 0.98           | 1.10           | 0.85           | 7.07| 57             |
| # 5  | 1.35           | 2.91           | 0.65           | 6.01| 175            |
| # 6  | 1.05           | 1.37           | 0.65           | 6.01| 85             |
| # 7  | 1.01           | 1.21           | 0.43           | 4.52| 59             |
| # 8  | 1.38           | 3.08           | 0.30           | 3.42| 251            |

Relations to Observations

If we now assume that such interactions might be held re-
ponsible for star formation bursts, i.e. if encounters trig-
ger star formation, it raises the question whether we can
explain the observed correlation between star formation activity in the Local Group Dwarfs and distance to the
centre of the Milky Way. Van den Bergh (1994), for in-
stance, reported that Dwarf spheroidals located close to
the Galaxy only experienced star formation early in their
lifetimes. Dwarf spheroidals at intermediate distances un-
derwent significant star formation more recently whereas
the most distant ones do show ongoing star formation at
the present time. Do encounters with other satellites trig-
ger star formation bursts? To this extent we present the
relation between the number of encounters (per orbit) as
a function of distance to the centre of the host at redshift
\( z = 0 \). The result can be viewed in Figure 4. Unfortu-
nately we do not observe a clear trend for all our halos,
even though most of them actually show the reverse cor-
relation, namely the closer a satellite to the host galaxy
the more encounters with other substructure. This rela-
tion is even more prominent when not normalising by the
number of orbits. Only halo #7 does show a trend that
agrees with the observational finding for star formation ac-
tivity and distance to the centre, even though we show in
Gill et al. (2004) that halo #7 does otherwise have no out-
standing differences to the other halos. Anyway, as we see
in Gill, Knebe & Gibson (2004a) the radial satellite density
distribution roughly declines like \( \rho_{\text{sat}} \propto r^{-2} \) and hence the
mild (anti-)correlation between number of encounters and
distance can be interpreted as a "volume effect": closer to
the centre of the host lives approximately the same num-
ber of satellites in a spherical shell as farther out, but as
the volume of that shell is smaller it is more likely for the
satellites to interact.

4 Summary

We used a set of eight high-resolution cosmological simula-
tions to investigate and quantify interactions between satel-
ite galaxies orbiting within a common dark matter halo.
Figure 3: Distribution of number of encounters for all satellite galaxies more massive than $10^{10} h^{-1} M_\odot$ at redshift $z = 0$.

Table 2: Percentage of satellites that had one or more encounters per orbit.

| Halo | percentage |
|------|------------|
| # 1  | 14         |
| # 2  | 18         |
| # 3  | 12         |
| # 4  | 31         |
| # 5  | 27         |
| # 6  | 22         |
| # 7  | 58         |
| # 8  | 58         |

Figure 4: Encounters per orbit as a function of distance to the host halo’s centre for redshift $z = 0$. 

Using our definition for encounter, which is based upon the mutually induced tidal radius, we showed that on average 30% of the substructure population had had more than one encounter per orbit with another satellite galaxy orbiting within the same host halo. There is, however, a clear trend for interactions to be more common in young galaxy clusters. We furthermore showed that satellite galaxies closer to the centre of the host halo had had more interactions with companion satellites, not because they simply orbited for longer in the underlying host potential but most likely because of the universal radial distribution of satellite galaxies found in cosmological dark matter halos (Gill et al. 2004). Even though satellite-satellite interactions are unimportant for the majority of satellite galaxies, there exists a sub-population for which this needs to be investigated in more detail and more carefully, respectively.

We also noted that there is a degeneracy between the influence of the host halo and the interactions with the companion satellites which can only be disentangled with an appropriate resolution for both the actual N-body-simulation and the halo finding technique. We therefore applied a new method for identifying gravitationally bound objects in cosmological N-body simulations. This new technique is based upon the adaptive grid structures of the open source adaptive mesh refinement code MLAPM (Knebe, Green & Binney 2001). The halo finder is called MHF and acts on the same accuracy level as the actual simulation. A more thorough study of the functionality of MHF is presented in Gill, Knebe & Gibson (2004a). A detailed analysis of the degeneracy between influence of the host halo and interactions with companion satellites can be found in a companion paper, too (Gill, Knebe & Gibson 2004b).

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