Satellite galaxies in cosmological dark matter halos

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Abstract. We present preliminary results from a series of high-resolution $N$-body simulations that focus on 8 dark matter halos each of order a million particles within the virial radius. We follow the time evolution of hundreds of individually tracked satellite galaxies and relate their physical properties to the differing halo environmental conditions. Our main science driver is to understand how satellite galaxies lose their mass and react to tidal stripping. Unlike previous work our results are performed in a fully self-consistent cosmological context. The preliminary results demonstrate that while environment may vary considerably with respects to formation time and richness of substructure, the satellites evolve similarly.

1. The Simulations

Four standard $\Lambda$CDM cosmological simulations with side length $64 h^{-1}$ Mpc were run at low mass resolution ($128^3$ particles), with 8 halos selected sampling a range of environments. In this contribution we present results for our oldest (8.3 Gyr) and youngest (3.4 Gyr) dark matter halos, halo # 1 and # 8 respectively. These halos were re-simulated at 64 times higher mass resolution giving an effective mass per particle of $10^9 h^{-1}$ M$_\odot$, and a force resolution of approximately 1 $h^{-1}$ kpc. The $N$-body simulations were carried out using the publicly available adaptive mesh refinement code MLAPM (Knebe, Green & Binney 2001). The code solves Poisson’s equation on a hierarchy of nested grids: the whole computational volume is covered by one cubic domain grid whereas refined regions are of arbitrary shape and adjusted to the actual density field at each major step in order to follow the real distribution of particles at all times. An example of MLAPM in action is shown in the left panel of Figure 1. These two images show the density field of our youngest halo superimposed by the refinement grids. The top image shows the 5th refinement level with grid resolution $4096^3$, the bottom the 6th level of refinement. As the grids follow the over-densities in the simulations they by definition encompass the satellites. Hence, we can build a hierarchy of nested isolated MLAPM grids into a ”grid tree”, and then generate a list of potential satellite centers by treating the densest grid at the end of each branch as a ”potential” halo center. We further check the validity of the center by assigning physical properties to the adjacent radial density distribution. The details can be found elsewhere (Gill, Knebe & Gibson 2003).
2. Dark Matter Halo Environment

Following Lacey & Cole (1994) the formation time of the halo \( z_{\text{form}} \) is defined to be the time when the halo contains half of its present day mass. From \( z_{\text{form}} \) to \( z=0 \) we track all satellites in the vicinity of the host halo. The number of satellites within the virial radius of our 8 halos (of mass \( > 2 \times 10^{10} \, h^{-1} \, M_\odot \)) ranges from 50 – 250. The right panel of Figure 1 shows the orbits of the tracked satellites for two sample host halos highlighting the differing halo environments. The top image shows a halo developing in a rich region fed by three filaments, whereas the figure directly below shows a host halo in a relatively isolated region that saw early rapid collapse.

3. Satellite Disruption

Figure 2 shows the number of satellites within a 2 \( h^{-1} \) Mpc sphere (physical coordinates), as a function of redshift normalized by the number of satellites within the sphere at redshift \( z_{\text{form}} \). The thin line (always on top) shows the total number of satellites within that sphere, while the bottom (thick) line shows the number of "disrupted" satellites subtracted from the number of satellites at \( z_{\text{form}} \). The rise in the thin lines from \( z_{\text{form}} \) to \( z=0 \) reflects the richness of the immediate environment around the halo. Halo #1 is in a particularly rich
"filament fed region". These filaments are a source of significant satellite infall (recall the right panel of Figure 1).

As the satellites orbit within the halo they experience dynamical friction causing them to sink towards the centre of the halo's potential, undergo tidal stripping, and gradually lose mass. For each satellite, its particle distribution becomes increasingly diffuse. Our criterion for calling a satellite "disrupted" is linked to its tidal radius; assuming that the average density of the satellite has to be at least a factor of three above the density of the host halo at the distance of the satellite we iteratively calculate the tidal radius and the mass $m(< r_{\text{tidal}})$ enclosed by solving:

$$r_{\text{tidal}} = \left( \frac{m(< r_{\text{tidal}})}{3M(< D)} \right)^{\frac{1}{3}} D = 0 ,$$  

The distance $D$ of the satellite to the host and $M(< D)$, the mass of the host halo interior to $D$, are fixed. As soon as there are fewer than 15 particles within the tidal radius we classify the satellite as being disrupted. Note that we are unable to separate numerical resolution disruption and real physical disruption of a satellite. It is not clear if we had infinite mass resolution that the satellite would still actually survive.

In Figure 2, the right panel shows the difference of the satellite's mass at $z_{\text{form}}$ and $z=0$ divided by its mass at $z_{\text{form}}$ and the number of orbits as a function of eccentricity of the satellite orbit. Thus as the satellite does get disrupted in
general it losses at least 30 percent of its mass each orbit. Further, for seven of the eight halos, satellites on high eccentricity orbits are losing more mass (per orbit) than spherical ones, (such as halo # 8). However, this is not strictly true for all environments; e.g. in halo # 1, satellites on spherical orbits lose more mass - in this case the satellite orbits are on average closer to the halo core.

4. Properties of the Satellites in the Halos

Because of the high temporal resolution of the outputs of our simulations ($\Delta t \sim 0.2$ Gyr) we are able to track accurately the orbital and other characteristics of the satellites. We present here a few preliminary results:

- For each of the 8 halos the mean eccentricity was consistently around 0.6, where eccentricity was measured as $e = 1 - \frac{\text{pericentre}}{\text{apocentre}}$.
- For each of the 8 halos the mean pericentre distance was approximately 30 percent of the host virial radius.
- The apocentres of the satellite orbits are aligned with the principle axis of the host galaxy cluster.
- In general a satellite loses at least 30 percent of its mass each orbit. Further, for the majority of the eight halos, satellites on high eccentricity orbits are losing more mass (per orbit) because they penetrate deeper into the host's potential.
- Satellite-Satellite interactions are not negligible.

A fuller and quantitative analysis is being prepared (Gill, Knebe & Gibson 2003). There, we address additional characteristics concerning satellite evolution: e.g. how does a satellite actually react to its tidal disruption?

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References

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MLAPM is available at http://astronomy.swin.edu.au/MLAPM/