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A numerical study on the distribution of the debris of the Milky Way satellites

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Abstract. We perform six N-body simulations reproducing the interaction between the Milky Way and its satellite galaxies, in order to address the deposit of satellite debris in the Galactic environment. We find that most of the baryons survive inside their host satellites and that most of the baryonic debris ends up in the inner regions of the Milky Way, in contrast to the more uniform distribution of dark matter debris. We also look at the debris Inertia tensor in the inner regions of the Milky Way and find a lower minor-to-major axis ratio for baryons than dark matter. We plan to explore the phase-space distribution of the debris ending in the Galactic disk and bulge. We also plan further simulations including gas dynamics to study the impact of gas on the process.

Keywords. methods: n-body simulations, Galaxy: kinematics and dynamics, galaxies: dwarf

1. Introduction

Within the cosmological model of galaxy and structure formation (e.g. White & Rees 1978), galaxies like the Milky Way (MW hereafter) are evolved in a Dark Matter (DM) halo that is expected to be surrounded by a number of smaller halos (subhalos). These in turn are home to satellite galaxies that orbit in the host MW environment and interact with it during their evolution. The properties and scale relations of DM halos and subhalos have been studied by means of pure N-Body simulations like the Aquarius (Aq) cosmological simulations (Springel *et al.* 2008). In a recent work, Moetazedian & Just 2016; MJ16) obtained the parameters describing the final MW-like halos and their subhalos at redshift $z = 0$ in the Aq A2-to-F2 simulations. For each of these simulations, they performed an N-body study of the interaction of a corresponding disk-bulge-halo MW model with its most massive satellites. They concluded that these DM-only satellites do not impact strongly on the MW disk thickening and vertical heating. From a cosmological point of view, the physical properties of the dwarf galaxies that merge with the MW are well understood when looking at full hydrodynamical N-body simulations, like in the case of Macciò *et al.* 2017; M+17). M+17 studied the properties of a set of N-body dwarf galaxies evolved until redshift $z = 1$ in isolation, before interacting with any MW-like galaxy. In this work we take advantage of the library of N-body dwarf galaxies from M+17, that contain both baryonic and DM particles, and we inject them into the six above simulations from MJ16, replacing their DM-only satellites. The goal is to study how do baryonic and DM debris distribute in the MW environment when they are stripped from their host satellites because of MW tidal forces.

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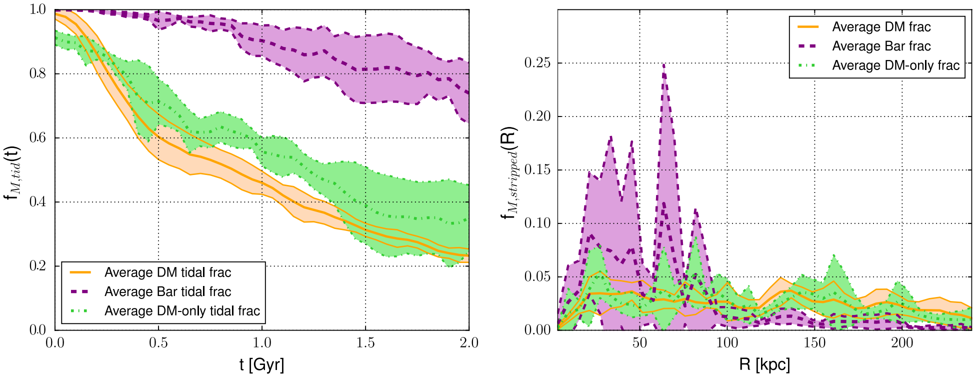

Figure 1. *Left panel*: Evolution in time of the average fraction $f_{M,tid}$ of total matter inside the tidal radii of the satellites. Purple dashed lines are for satellite baryons, orange full lines are for satellite DM and green dot-dashed lines are from the same calculations for the satellites in the corresponding MJ16 simulations. For each color, the central line is for the average between the six simulations, the upper and lower lines are the average +/- the root-mean-square (rms) scatter between the six simulations, while the shaded areas cover the corresponding regions in between. *Right panel*: Average fraction of stripped matter $f_{M,stripped}$ as a function of GCd. Color codes are as in the left panel.

2. Numerical simulations

We run a total of six N-body simulations reproducing the interaction of the MW with its satellite galaxies. For the MW models we adopt the same six models created after Aq, as described in MJ16. Each model consists of a disk (10M particles), a bulge (500K particles) and a halo (4M particles)†. The candidate baryonic-and-DM (hybrid) satellites are chosen among the sample of M+17 dwarf galaxies according to a criterion to match the original satellites used in MJ16. We require that the hybrid dwarf galaxy models minimize the distance from the MJ16 satellites in the logarithmic M_{200}-(v_{max}/r_{max}) plane, where v_{max}/r_{max} is an estimator of the central satellite density, and where v_{max} and r_{max} are the satellite maximal velocity and radius of maximal velocity, respectively. We stress that, despite we did not have other good solutions to match the two distributions of satellites (they come from different kind of simulations and are evolved until different redshift values), this new selection led to a final sample of hybrid dwarf galaxies that have lower and similar concentrations compared to the MJ16 satellites, that are more spread in the M_{200}-(v_{max}/r_{max}) plane. The initial positions of the selected satellites are as in MJ16. We run each simulation for 2 Gyr using the code `GADGET-4` (see `GADGET-2`, Springel 2005).

3. Matter distribution

We look first at the fraction of mass that is tidally stripped from the satellites during the 2 Gyr (Figure 1, left panel). For each satellite, we define the tidal radius r_{tid} at each time following the Ernst & Just (2013) approximation:

$$r_{tid} = \left(\frac{GM_{sat}}{\omega^2 - \frac{d^2\Phi(R)}{dR^2}} \right)^{\frac{1}{3}} \tag{3.1}$$

where G is the gravitational constant, M_{sat} is the satellite mass, ω is its orbital angular speed and Φ is the gravitational potential at galactocentric distance (GCd) R.

† (We were provided the models already evolved in isolation for 2 Gyr by R. Moetazedian, as described in MJ16)

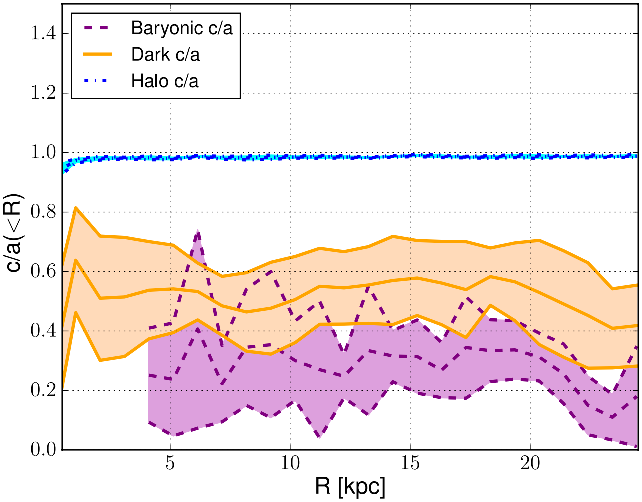

Figure 2. Average minor-to-major axis ratio c/a of the Inertia tensor of the stripped debris within GCd R, $I(<R)$, as a function of R for the six simulations. This is a zoom into the first 25 kpc of GCd. As in Figure 1, purple dashed lines are for baryons, orange full lines are for DM. Blue dot-dashed lines are for the host MW halo. For each color (i.e. component), the lighter shaded areas cover again the region between the average, central line and the average +/- the rms scatter.

Most of the satellite baryonic matter ($\sim 80\%$) is still within the tidal radii of the satellites, while most of the DM is stripped out of the satellites. This is because originally baryons reside well inside their host dwarf galaxies, so they are stripped less efficiently by the MW. Then, we address the radial distribution in the host halo of the stripped baryons and DM (Figure 1, right panel). We find that, within 242.8 kpc (the virial radius of these MW models), baryons end mostly in the inner regions of the MW, while DM is more uniformly distributed. The reason is that stronger tidal forces are needed to strip baryons from their host satellites, and this can happen only when the satellites approach the Galactic center. In Figure 1 we also plot the time evolution of the fraction of total DM inside the satellites tidal radii (left panel) and the radial distribution of stripped DM (right panel) from MJ16 simulations. We find no significant differences from the behaviour of DM in our simulations. We zoom in the inner 25 kpc of GCd and we consider the minor-to-major axis ratio of the debris Inertia tensor. For all the matter falling within a given GCd, the Inertia tensor within that GCd is calculated with components:

$$I_{jj} = \sum_i \sum_{k \neq j} x_{i,k}^2 m_i; \quad I_{jk} = -\sum_i x_{i,j} x_{i,k} m_i, \tag{3.2}$$

where i stands for the i-th particle, m_i is its mass and $x_{i,j}, x_{i,k}, x_{i,l}$ stand for its cartesian coordinates. We then define $c < b < a$ as the three main axes of the Inertia tensor.

At the end of the simulations, the baryonic debris has a lower c/a (Figure 2). This indicates a flatter distribution. This may be an effect of the higher concentration of baryonic debris in the inner regions of the Galaxy (J.F. Navarro, private suggestion). Another possibility may be that since only radially elongated satellite orbits can reach the MW core regions in order to allow them to strip baryons efficiently, these turn to be less spherically distributed than DM debris (A.V. Macciò, private suggestion). This requires future investigation by addressing the orientation of the principal axes of the Inertia tensor, in order to see the possible differences between baryonic and DM debris. We note that on average the MW host halo remains spherical.

4. Conclusions and future work

From our N-body simulations we find that satellite baryonic debris is stripped less efficiently than DM debris, it is more focused in the inner regions of the MW and it is predicted to be flatter than DM debris. Next, we plan to explore in more detail the distribution of baryons and DM in the disk and in the bulge, considering also their kinematics in order to cover their full phase-space distribution. We also plan to re-simulate the process with a new set of simulations including gas dynamics. This will allow us to see the impact of gas on perturbations induced in the MW disk and on the survival of satellites after their encounters with the MW. Recent surveys (e.g. Gaia DR-2) may provide useful data for testing our simulation results.(†)

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