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# The assembly of the Milky Way stellar halo

**Anna Curir**[*]

*Astronomical Observatory of Torino (Italy) E-mail:* curir@oato.inaf.it

**Giuseppe Murante**

*Astronomical Observatory of Torino (Italy) E-mail:* murante@oato.inaf.it

**Eva Poglio**

*Astronomical Observatory of Torino (Italy) E-mail:* epoglio@studenti.ph.unito.it

**Álvaro Villalobos**

*Astronomical Observatory of Tireste (Italy) E-mail:* villalobos@oats.inaf.it

The theory of the Milky Way formation, in the framework of the ΛCDM model, predicts galactic stellar halos to be built from multiple accretion events starting from the first structures to collapse in the Universe.

Evidences in the past few decades have indicated that the Galactic halo consists of two overlapping structural components, an inner and an outer halo. We provide a set of numerical N-body simulations aimed to study the formation of the outer Milky Way (MW) stellar halo through accretion events between a (bulgeless) MW-like system and a satellite galaxy. The aim is to explore the orbital conditions of the mergers where a signal of retrograde rotation in the outer part of the halo can be obtained, in order to give a possible explanation of the observed rotational properties of the MW stellar halo.

Our results show that retrograde satellites moving on low inclination orbits deposit more stars in the outer halo regions and therefore can produce the counter-rotating behavior observed in the outer MW halo.

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[*]Speaker.

 

## 1. The Milky Way Stellar Halo and the dynamical friction

According to Carollo et al [1], the inner-halo component of the MW dominates the population of halo stars found at distance up to 10-15 kpc from the Galactic Center. An outer-halo component dominates in the region beyond 15-20 kpc. Inner-halo stars possess generally high orbital eccentricities, and exhibit a modest prograde rotation (between 0 and 50 km $s^{-1}$) around the center of the Galaxy. Outer-halo stars cover a wide range of orbital eccentricities, and exhibit a clear retrograde net rotation (between -40 and -70 km $s^{-1}$) about the center of the Galaxy. These properties indicate that the individual halo components probably formed in different ways through successive dissipational (inner halo) and dissipationless (outer halo) mergers and tidal destruction of proto-Galactic clumps.
In our work we focus on the outer halo. To this purpose, we performed a set of numerical N-body simulations for studying the formation of the outer MW's halo through accretion events.
The dynamical friction has a fundamental role in assembling the final velocity distributions originated by different orbits.
A particle of mass $M_s$ moving through a homogeneous background of individually much lighter particles with an isotropic velocity distribution suffers a drag force [2]:

$$F_d = -\frac{4\pi G^2 M_s^2 \rho_f(< v_s) ln\Lambda}{v_s^2} \tag{1.1}$$

where $v_s$ is the speed of the satellite with respect to the mean velocity of the field, $\rho(< v_s)$ is the total density of the field particles with speeds less than $v_s$ and $\Lambda$ is the Coulomb Logarithm.
From equation (1.1), we expect that the higher is $v_s$, the weaker is the dynamical friction force. Retrograde satellites have higher $v_s$ with respect to prograde one, since in the first case the velocity of the satellite is opposite to that of the disk and to the rotational velocities of the main halo particles. As a consequence, prograde orbits decay faster. Particle stripped from the satellites will remain on the orbit on which the satellite was when they were stripped. How we can see from equation (1.1) the dynamical friction depends upon the satellite mass, so a single star does not feel the effect of this force, due to its to much small mass, and consequently conserves its energy remaining on the same orbit.

## 2. The simulations

We perform two kinds of simulations [3]. In both simulations, we use a primary DM halo with a NFW radial density profile [4], containing a stellar disk. What changes is the satellite: in the first set of simulations we realize a DM+bulge satellite configuration, in which the DM halo contains a stellar bulge, having an Hernquist's radial density profile [5]; in the second set the satellite is an halo with a NFW profile, in which we assume that the DM in the inner region traces the stars.
We simulated minor prograde mergers, in which a satellite co-rotates with the disk spin, and retrograde ones, with a counter-rotating satellite. Stars in the outer halo can be stripped from accreted DM satellites, hosting dwarf galaxies, during their orbits before the final merger. Minor mergers are the most probable sources for these kind of stars, firstly because they do not destroy the galactic disk and can thus happen in all evolutionary phases of the life of a disk galaxy. Moreover, a smaller

satellite suffers less dynamical friction, and can deposit stars at larger distances from the galactic center, for a longer period of time.
We run all our simulation using the public parallel Treecode GADGET2 [6].
Into the main halo, we embed a truncated stellar disk supported by rotation, having an exponential surface density law.
In the first set of simulations, in which we used a DM+ (Hernquist's bulge) satellite configuration, we performed the numerical experiments only in high resolution. In the second one, in which the satellite is a DM halo with a NFW profile, we run a suite of numerical experiments, varying the force and mass resolution of both the primary and the secondary. We choose our minor mergers with a mass ratio $M_{prim}/M_{sat}\approx 40$, similar to the estimated mass ratio of the Large Magellanic Cloud (LMC) to the MW halo.
We choose two orbits: a low-inclination one, with a 10 degree angle with the disk plane, and a high inclination one with a 60 degree angle. The satellite coordinates and its components of the velocity are listed in Table 1.
We use simulations with a primary halo with a spin parameter $\lambda = 1$ (A case) and $\lambda = 0$ (B case).

| | Orbit | $x$ | $y$ | $z$ | $v_x$ | $v_y$ | $v_z$ |
|---|---|---|---|---|---|---|---|
| Pro1 | Prograde-1 (10°) | 80.0 | 0.27 | -15.2 | -6.3 | 62.5 | 0.35 |
| Ret1 | Retrograde-1 (10°) | 80.0 | 0.27 | -15.2 | -6.3 | -62.5 | 0.35 |
| Pro2 | Prograde-2 (10°) | 29.5 | 0.27 | -5.2 | -6.3 | 89.3 | 0.35 |
| Ret2 | Retrograde-2 (10°) | 29.5 | 0.27 | -5.2 | -6.3 | -89.3 | 0.35 |
| Pro | Prograde (60°) | 15.0 | 0.12 | -26.0 | -1.2 | 80.1 | 2.0 |
| Ret | Retrograde (60°) | 15.0 | 0.12 | -26.0 | -1.2 | -80.1 | 2.0 |

**Table 1:** In the first three columns, are listed the initial satellite coordinates in *kpc*, while in the last three the components of velocity in $km/s$. At low inclination, we simulate mergers with two different departures, one further from the disk center (1) and one nearer to the disk center (2).

We assign the angular momentum to DM particles using a rigid body rotation profile.
In our second set of simulations, we repeated our experiments using a Bullock's rotational profile

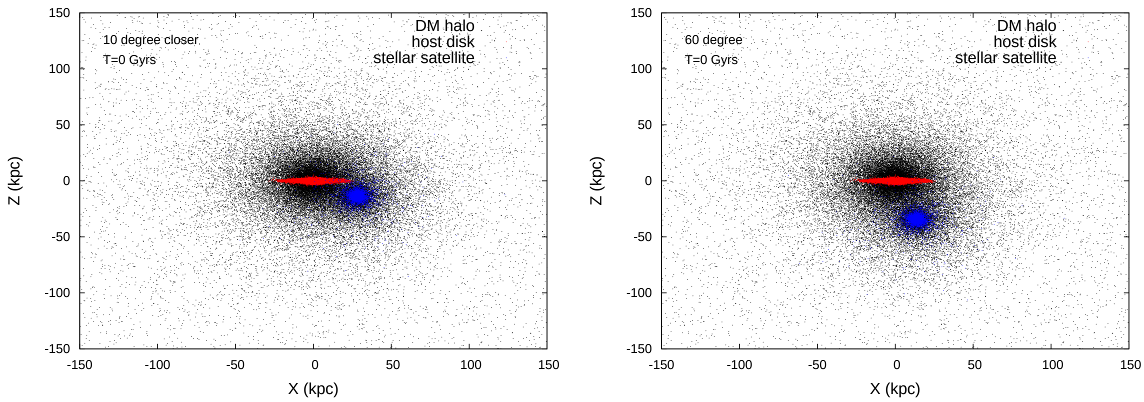


**Figure 1:** Initial morphologies of the system halo+disk and satellite

[7] instead of a rigid rotation one for the DM rotation velocity. In this case, we set $\lambda = 0.06$, a value suggested by cosmological simulations.
In the DM-only simulations the satellite is a DM halo with a NFW radial density profile. In this set of simulations, we follow the evolution of the inner region of the satellite: a central sphere of 8 kpc radius, and we assume that the DM particles in this inner regions trace the stars. The choice of such a value is due to the fact that, the gravitational mass contained within 8 kpc radius, is comparable with the gravitational mass of the LMC. We run our DM-only numerical experiments, varying the mass and force resolution in both the primary and the secondary: the low resolution case has $10^4$ particles within the virial radius of the DM satellite, whereas in the high resolution case we have $10^5$ particles within the same virial radius. We run all our simulations for 4.6 Gyrs, corresponding to $\sim$ 16 dynamical time of the main halo.
The simulations were carried out at CASPUR, with CPU time assigned with the "Standard HPC grant 2009", and at the CINECA, Bologna, with CPU time assigned under an INAF/CINECA grants.

## 3. Results and conclusions

In Figure 2, we show histograms of the rotation velocity $v_\Phi$ obtained in the four simulations of the set A. It is immediately clear from the Figure2 that our pair of low inclination orbits show an excess of counter-rotating stars in the outer halo. Also in our set B, low inclination retrograde orbits produce more counter-rotating star particle than co-rotating stars produced by prograde orbits. This is not the case for high inclination orbits. Therefore, both disk rotation and halo spin contribute to the slowing-down of prograde orbits and to the consequent smaller amount of high-energy star particle stripped from satellites that can reach the outer halo. However, disk rotations appear to be the main driver of such an effect.
Our main results are the following:

- low inclination mergers do produce an excess of counter-rotating satellite stellar particles in the outer halo, independently on the spin of the DM;
- high inclination orbits do not seem to produce a significant counter-rotating signal;
- the fraction of counter-rotating to co-rotating satellite stars in the outer stellar halo is higher if the DM has spin.

In the ΛCDM model, there is no reason for expecting an excess of retrograde mergers. Thus, if such an excess was needed to produce a counter-rotating signal in the outer stellar halo, we should require a peculiar accretion history for the MW. The main result of this work shows that such a fine-tuning in the MW history is not needed. Even if, statistically, the number of prograde and retrograde minor merger is the same, still a counter-rotating signal can arise *if such mergers predominantly happen along low inclination orbits*. Since matter accretion, in a CDM dominated Universe, mainly occurs along filaments, this will be the case *if the galaxy disk is co-planar* to the (majority of) filaments. The disk-filament alignment issue is still debated [8]: from our results, we expect that if the galactic disk were perpendicular to the main accretion streams, no counter-rotating signal should be observed in the outer halo star distribution.

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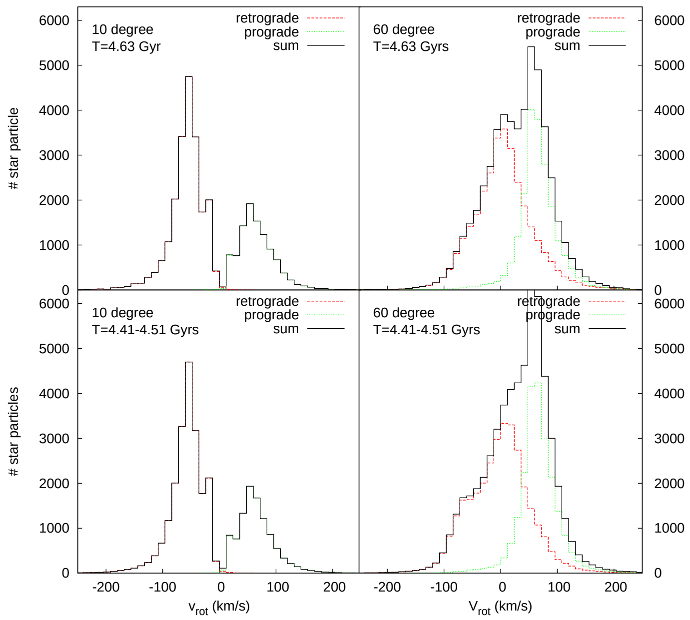


**Figure 2:** Histograms of rotation velocities for star particles in the outer halo, at the end of the set A of merger simulations. Upper panels show the histograms at the final time, lower panel show the same histograms, averaged over five simulation snapshots. In red, we plot the histogram obtained for our retrograde orbits; in green, those for our prograde orbits. In black we show the sum of the two. Left column is for the low inclination orbits, right column for the high inclination ones. We used 50 velocity class, equispaced, between -300 and 300 km/s in all histograms.