1. INTRODUCTION

The Galactic halo has long been considered a single component. However, evidence in the past few decades has indicated that it may be more complex (Preston et al. 1991; Majewski 1992; Kinman et al. 1994; Carney et al. 1996; Chiba & Beers 1999). The Galactic halo is related to the so-called missing satellites problem; Moore et al. (1999). There is significant evidence of past accretions into the Milky Way (Yanny et al. 2003; Belokurov et al. 2006; Grillmair 2009), and therefore we will accept the scenario that the Milky Way halo contains 300 ± 40 of the main halo, the dynamical friction has a fundamental role in assembling the final velocity distributions resulting from different orbits and 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 Milky Way halo.

Key words: galaxies: kinematics and dynamics – Galaxy: halo – methods: numerical

2. SIMULATIONS

We provide a set of numerical N-body simulations for studying the formation of the outer Milky Ways’ stellar halo through accretion events. After simulating minor mergers of prograde and retrograde orbiting satellite halos with a dark matter main halo, we analyze the signal left by satellite stars in the rotation velocity distribution. The aim is to explore the orbital conditions where a retrograde signal in the outer part of the halo can be obtained, in order to give a possible explanation of the observed rotational properties of the Milky Way stellar halo. Our results show that, for satellites more massive than ~1/40 of the main halo, the dynamical friction has a fundamental role in assembling the final velocity distributions resulting from different orbits and 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 Milky Way halo.

1. INTRODUCTION

The Galactic halo has long been considered a single component. However, evidence in the past few decades has indicated that it may be more complex (Preston et al. 1991; Majewski 1992; Kinman et al. 1994; Carney et al. 1996; Chiba & Beers 2000; Kinman et al. 2007; Miceli et al. 2008). Recently Carollo et al. (2007) confirmed the existence of a two-component halo, analyzing a large sample of calibration stars from the Sloan Digital Sky Survey DR5 (Adelman-McCarty et al. 2007). According to Carollo et al. the Galactic halo consists of two overlapping structural components, an inner and an outer halo. These components exhibit different spatial density profiles, stellar orbits, and stellar metallicities. In particular, the inner halo stars show a small (or zero) net prograde rotation around the center of the Galaxy. Outer halo stars possess a clear retrograde net rotation.

The theory of galaxy formation in a Lambda cold dark matter (ΛCDM) universe predicts galactic stellar halos to be built from multiple accretion events starting from the first structures to collapse (White & Rees 1978; Searle & Zinn 1978). Halos, composed of both dark and baryonic matter, grow by merging with other halos. While the gas from mergers and accretions loses its energy through cooling and settles into a disk, the non-dissipative material (accreted stars and dark matter, DM) forms a halo around the Galaxy. In a ΛCDM universe, a DM halo big enough to host the Milky Way contains 300 ± 100 subhalos (Diemand et al. 2004; such a large number of subhalos is related to the so-called missing satellites problem; Moore et al. 1999).

There is significant evidence of past accretions into the Milky Way (Yanny et al. 2003; Belokurov et al. 2006; Grillmair 2009), and therefore we will accept the scenario that the Milky Way halo has been formed by subhalos accretion and we focus on a possible origin of a retrograde (counter-rotating) outer stellar halo, defined as the set of stars orbiting around the Galaxy at large distance from the disk plane, say z ≥ 15 kpc: Carollo et al. (2007) found that this distance separates the inner and the outer halo. It is expected that such a halo is made of stars stripped from merging or disrupted satellites of low mass (Zolotov et al. 2009; for a detailed study of accreting events onto a Milky Way-like halo, see also Boylan-Kolchin et al. 2009). However, from cosmological simulation, prograde and retrograde mergers are approximately equally likely (Sales et al. 2007; Read et al. 2008).

In order to determine if, and in what condition, we can obtain a retrograde signal in the stellar distribution in the outer halo, we simulate minor mergers of a satellite halo onto a main halo of Galactic mass, with a mass ratio M_{primary}/M_{satellite} ~ 40. We put the satellite on two orbits, one prograde and one retrograde. After the satellite completes its merging/disruption process, we identify stars at distance larger than 15 kpc from the disk plane and simply analyze their rotation velocities. Our main finding is that a counter-rotating stellar halo naturally arises when minor mergers happen on orbits with a low inclination with respect to the disk plane.

The plan of this Letter is the following. In Section 2, we describe our simulations. In Section 3, we give our results on counter-rotating outer halo stars. In Section 4, we draw our conclusions.

1. INTRODUCTION

The Galactic halo has long been considered a single component. However, evidence in the past few decades has indicated that it may be more complex (Preston et al. 1991; Majewski 1992; Kinman et al. 1994; Carney et al. 1996; Chiba & Beers 2000; Kinman et al. 2007; Miceli et al. 2008). Recently Carollo et al. (2007) confirmed the existence of a two-component halo, analyzing a large sample of calibration stars from the Sloan Digital Sky Survey DR5 (Adelman-McCarty et al. 2007). According to Carollo et al. the Galactic halo consists of two overlapping structural components, an inner and an outer halo. These components exhibit different spatial density profiles, stellar orbits, and stellar metallicities. In particular, the inner halo stars show a small (or zero) net prograde rotation around the center of the Galaxy. Outer halo stars possess a clear retrograde net rotation.

The theory of galaxy formation in a Lambda cold dark matter (ΛCDM) universe predicts galactic stellar halos to be built from multiple accretion events starting from the first structures to collapse (White & Rees 1978; Searle & Zinn 1978). Halos, composed of both dark and baryonic matter, grow by merging with other halos. While the gas from mergers and accretions loses its energy through cooling and settles into a disk, the non-dissipative material (accreted stars and dark matter, DM) forms a halo around the Galaxy. In a ΛCDM universe, a DM halo big enough to host the Milky Way contains 300 ± 100 subhalos (Diemand et al. 2004; such a large number of subhalos is related to the so-called missing satellites problem; Moore et al. 1999).

There is significant evidence of past accretions into the Milky Way (Yanny et al. 2003; Belokurov et al. 2006; Grillmair 2009), and therefore we will accept the scenario that the Milky Way halo has been formed by subhalos accretion and we focus on a possible origin of a retrograde (counter-rotating) outer stellar halo, defined as the set of stars orbiting around the Galaxy at large distance from the disk plane, say z ≥ 15 kpc: Carollo et al. (2007) found that this distance separates the inner and the outer halo. It is expected that such a halo is made of stars stripped from merging or disrupted satellites of low mass (Zolotov et al. 2009; for a detailed study of accreting events onto a Milky Way-like halo, see also Boylan-Kolchin et al. 2009). However, from cosmological simulation, prograde and retrograde mergers are approximately equally likely (Sales et al. 2007; Read et al. 2008).

In order to determine if, and in what condition, we can obtain a retrograde signal in the stellar distribution in the outer halo, we simulate minor mergers of a satellite halo onto a main halo of Galactic mass, with a mass ratio M_{primary}/M_{satellite} ~ 40. We put the satellite on two orbits, one prograde and one retrograde. After the satellite completes its merging/disruption process, we identify stars at distance larger than 15 kpc from the disk plane and simply analyze their rotation velocities. Our main finding is that a counter-rotating stellar halo naturally arises when minor mergers happen on orbits with a low inclination with respect to the disk plane.

The plan of this Letter is the following. In Section 2, we describe our simulations. In Section 3, we give our results on counter-rotating outer halo stars. In Section 4, we draw our conclusions.
We simulated prograde mergers, in which a satellite co-rotates with respect to the disk spin, and retrograde ones with a counter-rotating satellite. We chose two orbits used in Read et al. (2008) for studying the thickening of the disk due to the same kind of minor merger: a low-inclination one with a 10° angle with the disk plane and a high-inclination one with a 60° angle. Initially, the center of the primary halo stays in the origin of our coordinate system and the satellite is in $(x, y, z) = (80.0, 0.27, -15.2)$ kpc for the low-inclination orbit and in $(15.0, 0.12, -26.0)$ kpc for the high-inclination one. The $(x, y, z)$ components of the velocity of the satellite are, in the prograde case, $(6.3, -0.35, 5.7 \times 10^{10})$ km s$^{-1}$ for the low-inclination orbit and in $(15.0, 0.12, -26.0)$ kpc for the high-inclination one. The retrograde orbits have the $y$-component of the velocity inverted.

The secondary has always a spin parameter $\lambda = 0$, where we define $\lambda = J/(\sqrt{2} M V R)$, with $M$ being the mass inside a radius $R$ and $V = GM/R$ being the circular velocity, as in Bullock et al. (2001). We use simulations with a primary halo with spin parameters $\lambda = 1$ (simulations “A”) and $\lambda = 0$ (simulations “B”). We assign the angular momentum to DM particles using a rigid body rotation profile. The angular momentum of DM particles is always aligned with that of the stellar disk.

Our primary halo has $10^6$ DM particles inside the virial radius ($\sim 2.5 \times 10^6$ in total) and one million star particles in the exponential disk, with mass $M_{DM} = 10^6 M_\odot$ and $M_{*} = 5.97 \times 10^4 M_\odot$, respectively. Our DM+bulge secondary halo has $1.1 \times 10^4$ DM particles and $10^5$ bulge star particles, with masses $M_{gal} = 1.95 \times 10^4 M_\odot$ and $M_{bulge} = 2.38 \times 10^4 M_\odot$.

We use Plummer-equivalent softening lengths $\varepsilon = 0.5$ kpc and $\varepsilon = 0.25$ kpc for bulge star particles. We run all our simulation using the public parallel Treecode GADGET2 (Springel 2005).

To test the convergence of our results with resolution, we run our set “A” with 10 times more particles in the satellite halo. We also changed the spin parameter of primary and secondary halos, its radial distribution using the profile from Bullock et al. (2001) and their coupling.

We analyze positions and kinematics of the bulge stars, once the satellite completes it merging with the primary halo. We run all our simulations for $t = 4.63$ Gyr, corresponding to $\sim 16$ dynamical timescales of the main halo.

3. RESULTS

In all cases, in our simulations the satellite is slowed down by dynamical friction exerted on it by both disk and halo particles. At the first pericenter, tidal forces deform the satellite, redistributing its particle’s energy (violent relaxation), and strip away some stellar particles (tidal stripping). The process continues at each subsequent passage to the pericenter, until no recognizable self-gravitating structure is present anymore. Stripped star particles track the orbital pattern of the satellite. The spatial distribution of stars depends upon the dynamical history of the satellite to which they belonged, i.e., how quickly it loses its orbital energy, how strongly it gets disrupted by tidal forces, and how these effects modify the orbit itself during the merger process.

We rotate our coordinate system so that the stellar disk lies in the $X-Y$ plane. The origin is in the disk center of mass. To detect a rotation signal in the outer halo stars, we simply took all the star particles initially belonging to our satellite and having a coordinate $Z > 15$ kpc or $Z < -15$ kpc. We then calculate the rotation velocity of such particles in the disk plane.

3.1. Distributions of $v_\phi$

In Figure 1, we show histograms of the rotation velocity obtained in the four simulations of set A: the satellite is either co-rotating or counter-rotating with respect to the disk, and the orbit has either a low or a high inclination with respect to the disk plane. In the upper panels, we show histograms at the final
time of our simulations; in the lower ones, we performed an average over five consecutive snapshots (~100 Myr) to get rid of possible sampling effect on the particle orbits which can rise using a particular instant of time. We show both the distribution of stars from single simulations and the one resulting from taking together star particles from prograde and retrograde orbits having the same initial inclination. The latter gives us a hint on the possible rotation signal origin, in case a similar number of prograde and retrograde minor accretion events happen during the formation history of a galaxy, under the hypothesis that their inclination is the same.

It is immediately clear from the figure that our couple of low-inclination orbits show an excess of counter-rotating stars in the outer halo.

Table 2 reports the number of satellite star particles in the positive and negative peaks in all of our cases and the number of Outer Halo Satellite Star Particles having Rotation Velocities \( v_{\text{rot}} < -10 \, \text{km s}^{-1} \) and \( v_{\text{rot}} > 10 \, \text{km s}^{-1} \) in Our Low-inclination Run.

| Distribution | \( \lambda = 1 \) Counter | \( \lambda = 1 \) co | \( \lambda = 0 \) Counter | \( \lambda = 0 \) co |
|--------------|-----------------|-----------------|-----------------|-----------------|
| 10° total \( v_{\text{rot}} \) > | 20292 | 10237 | 146670 | 13033 |
| 10° peak | 6510 (−54) | 1917 (−54) | 4455 (−54) | 3419 (54) |
| 60° peak | 3581 (+6) | 4010 (64) | 2741 (−6) | 3071 (78) |

Notes. Results are for the final time of our simulations. For each inclination, we considered prograde and retrograde mergers together. First row: the numbers of satellite star particles having rotation velocities smaller than \(-10 \, \text{km s}^{-1}\) or higher than \(10 \, \text{km s}^{-1}\), for the low-inclination case. Second row: the number of star particles in the positive and negative peaks, for the low-inclination case. Third row: the number of star particles in the positive and negative peaks, for the high-inclination case. Column 2: the number of counter-rotating satellite stars when the DM halo has a spin \( \lambda = 1 \). Column 3: the number of co-rotating satellite stars when the DM halo has a spin \( \lambda = 1 \). Column 4: the number of counter-rotating satellite stars when the DM halo has no spin, \( \lambda = 0 \). Column 5: the number of co-rotating satellite stars in the same \( \lambda = 0 \) cases.

From Table 2, the counter-rotating excess signal is 1.60 at peaks and 1.59 overall in the low-inclination case, and 1.17 at peaks and 1.02 overall in the high-inclination one.

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 particles stripped from satellites that can reach the outer halo.

The lower row of Figure 2 shows that our result does not depend on the mass resolution of our satellite halo. Even using 10 times more particles in the secondary, only our low-inclination couple of mergers shows an excess of counter-rotating stars in the outer halo.

### 3.2. Description of the Mergers

Two effects are acting on the satellite halo in these kinds of mergers: dynamical friction and tidal disruption. The first one is exerted both by the main halo DM particles and by the disk star particles. The second is most important near the center of the main halo, where the gravitational potential is stronger. But, dynamical friction depends upon the details of the satellite orbits. It is already known (Quinn & Goodman 1986; Walker et al. 1996; Huang & Carlb erg 1997; Velazquez & White 1999; Villalobos & Helmi 2008) that prograde orbits tend to decay faster than retrograde ones. The dynamical friction force goes as \( F_{\text{fr}} \propto 1/v_{\text{rot}}^2 \) (Binney & Tremaine 2008), where \( v_{\text{rot}} \) is the velocity of the satellite relative to the field particles; retrograde satellites have higher \( v_{\text{rot}} \) with respect to prograde ones, since in the first case the rotation velocity of the satellite is opposite to that of the disk and the main DM halo particles. Particles stripped from the satellites will remain on the orbit on which the satellite was when they were stripped. Therefore, retrograde satellites “deposit” more star particles in the outer halo regions, producing the signal we observe in our simulations, since their orbits have
a longer decay time. Obviously, to obtain this effect, the orbital velocity must lie on the disk plane,\(^5\) which is almost the case for our low-inclination orbits. High-inclination encounters do not show such a behavior.

In Figure 3, we plot the position of the center of mass of all the star particles belonging to the satellite as a function of time. Left panel shows the result for our low-inclination orbits, right panel for the high-inclination ones. The center of mass position makes sense only until the satellite is disrupted; this happens after \(\sim 3\) Gyr in our low-inclination prograde simulation, \(\sim 4\) Gyr in our low-inclination retrograde one, while in the high-inclination cases the satellite is disrupted already after \(\sim 1\) Gyr.

\(^2\) our 60° mergers with our 1:40 mass ratio are not able to give a significant counter-rotating signal, also owing to the disk tilt produced by the merger itself; and

\(^3\) the fraction of counter-rotating to co-rotating satellite stars in the outer stellar halo is higher if the DM has a spin.

From our controlled experiments, we now have an indication of the possible origin of the counter-rotation of stars observed in the Galactic outer halo in the context of a hierarchical \(\Lambda\)CDM model of galaxy formation, in which many major mergers happen during the history of the Galaxy. Even if, statistically, the number of prograde and retrograde minor mergers are 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 (see, e.g., Brunino et al. 2007); from our results, we expect that if the galactic disk were perpendicular to the main accretion streams, no counter-rotating signal would be observed in the outer halo star distribution.

Our orbits are not cosmologically motivated, since the aim of our experiment is to determine if and in what cases an excess of counter-rotating stars in the outer halo can be produced. Of course, in a realistic case mergers will occur with orbits having a number of different inclinations, giving rise to a velocity distribution which will not show such a clear, double peaked signal as that detected in the present work. A detailed study of the orbital parameters of minor mergers in a statistically significant set of cosmological Galaxy-sized halo cosmological accretion histories is needed before a quantitative comparison between theory expectations and observation can be performed.

We acknowledge useful discussions with Daniela Carollo, Stefano Borgani, Gabriella De Lucia, Antonaldo Diaferio, and Alessandro Spagna. The simulations were carried out at CASPUR, with CPU time assigned with the “Standard HPC grant 2009” call and at the “Centro Interuniversitario del Nord-Est per il Calcolo Elettronico” (CINECA, Bologna), with CPU time assigned under an INAF/CINECA grant. A.C. acknowledges the financial support of INAF through the PRIN 2007 grant no. CRA 1.06.10.04 “the local route to galaxy formation.”

4. CONCLUSIONS

We performed controlled numerical simulations of minor merger events. Our aim was to determine if an excess of counter-rotating stars in the outer stellar halo can be produced by couples of mergers having orbits with identical inclination and opposite initial rotation. Our primary halo has an exponential stellar disk and its DM has an NFW radial density profile; our satellite’s DM has an NFW density profile and contains a stellar spheroid with a Hernquist density profile. The mass ratio of our merger is \(M_{\text{primary}}/M_{\text{satellite}} \sim 40\). We simulate low-inclination encounters, in which the angle of the satellite’s orbit with the disk plane is 10°, and high-inclination ones (60°). We use prograde and retrograde orbits and also vary the DM spin parameter of the main halo. DM spin is aligned with the disk rotation. Here, we define all stars having a distance \(z > 15\) kpc from the disk plane as belonging to the outer stellar halo.

Our main results are the following:

1. low-inclination mergers do produce an excess of counter-rotating satellite stellar particles in the outer halo, independently on the spin of the DM;

\(^5\) DM spin is parallel to the disk spin: also the effect of the DM halo spin is maximum in such a case.

REFERENCES

Adelman-McCarthy, J. K., et al. 2007, ApJS, 172, 634
Belokurov, V., et al. 2006, ApJ, 642, L137
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd ed.; Princeton, NJ: Princeton Univ. Press)
Boylan-Kolchin, M., Springel, V., White, S. D. M., & Jenkins, A. 2009, arXiv:0911.4484
Brunino, R., Trujillo, I., Pearce, F. R., & Thomas, P. A. 2007, MNRAS, 375, 1381
Bullock, J. S., Dekel, A., Kolatt, T. S., Kravtsov, A. V., Klypin, A. A., Porciani, C., & Primack, J. R. 2001, ApJ, 555, 240
Carney, B. W., Laird, J. B., Latham, D. W., & Aguilar, L. A. 1996, AJ, 112, 668
Carollo, D., et al. 2007, Nature, 450, 1020
Chiba, M., & Beers, T. C. 2000, AJ, 119, 2843
Curti, A., & Mazzell, P. 1999, A&A, 352, 103
Diemand, J., Moore, B., & Stadel, J. 2004, MNRAS, 352, 535
Grillmair, C. J. 2009, ApJ, 693, 1118
Hernquist, L. 1993, ApJS, 86, 389
Huang, S., & Carlberg, R. G. 1997, ApJ, 480, 503
Kinman, T. D., Cacciari, C., Bragaglia, A., Buzzoni, A., & Spagna, A. 2007, MNRAS, 375, 1381
No. 2, 2010

ASSEMBLY OF THE OUTER GALACTIC STELLAR HALO

L.119

Kinman, T. D., Suntzeff, N. B., & Kraft, R. P. 1994, AJ, 108, 1722
Majewski, S. R. 1992, ApJS, 78, 87
Miceli, A., et al. 2008, ApJ, 678, 865
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Press, W. H., Flannery, B. P., & Teukolsky, S. A. 1986, Numerical Recipes: The Art of Scientific Computing (Cambridge: Cambridge Univ. Press)
Preston, G. W., Shectman, S. A., & Beers, T. C. 1991, ApJ, 375, 121
Quinn, P. J., & Goodman, J. 1986, ApJ, 309, 472
Read, J. I., Lake, G., Agertz, O., & Debattista, V. P. 2008, MNRAS, 389, 1041
Sales, L. V., Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2007, MNRAS, 379, 1464
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Springel, V. 2005, MNRAS, 364, 1105
Velazquez, H., & White, S. D. M. 1999, MNRAS, 304, 254
Villalobos, À., & Helmi, A. 2008, MNRAS, 391, 1806
Walker, I. R., Mihos, J. C., & Hernquist, L. 1996, ApJ, 460, 121
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Yanny, B., et al. 2003, ApJ, 588, 824
Zolotov, A., Willman, B., Brooks, A. M., Governato, F., Brook, C. B., Hogg, D. W., Quinn, T., & Stinson, G. 2009, ApJ, 702, 1058