BREAKING UP THE MAGELLANIC GROUP INTO THE MILKY WAY HALO: UNDERSTANDING THE LOCAL DWARF GALAXY PROPERTIES

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ABSTRACT

We use a numerical simulation of a loose group containing a Milky Way halo to probe that in the hierarchical universe the Magellanic Clouds and some dSphs have been accreted into the Milky Way halo from a late infalling group of dwarfs. Our simulations show that the tidal breakup of the Magellanic group occurs before it enters the Milky Way halo. Only half of the satellites contributed from the group are predicted to be inside the Milky Way virial radius. Half of its subhalos survive outside the current virial radius in the form of satellites, whereas the remaining material contributes to the diffuse Milky Way halo. At \( z \sim 0 \) the disrupted group contributes less than 10\% to the Milky Way halo mass but 20\% of the brightest dwarf galaxies of the Milky Way have been part of this group. This scenario points out that some dSphs might have been formed away from giant spirals and have accreted already as spheroids, by a late infall group in contrast with the classical picture of tidal stripping of dSph formation models. This would naturally explain several peculiarities of the local dSph: why Draco and the other luminous dSph exist compared to other ultra-faint satellite galaxies, the location of Tucana and Cetus in the outskirts of the Local Group and the mismatch in metallicity between the stellar halo of the Milky Way and the dwarf galaxies that many have suspected dissolved to build it.

Subject headings: cosmology: dark matter – methods: N-body simulations – galaxies: kinematics – galaxies: halos

1. INTRODUCTION

An unequivocal prediction of cold dark matter models (CDM) is that the mass of the Milky Way, in the form of its dark matter halo, builds up hierarchically, by accretion of lower-mass halos. When these sub-systems (often referred to as subhalos) escape the tidal disruption in the Milky Way halo they survive in the form of satellite galaxies until today. Numerical simulations confirmed the theory predicting 500 satellites within 500 kpc from the Milky Way center (Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999). The modest populations of observed dwarf galaxies orbiting the Milky Way and Andromeda, however, seems to conflict with this prediction. Indeed, in the current CDM paradigm of structure formation, dark matter satellites outnumber the known spheroidal by a factor of 10 to 100. This discrepancy between the expected and observed numbers of dwarf galaxies has become widely known as the missing dwarf problem. The newly discovered population of ultra-faint dwarfs around the Milky Way and M31 found in the Sloan Digital Sky Survey (Willman et al. 2005a,b; Belokurov et al. 2006, Zucker et al. 2006) increases of a factor of two in the number of known satellites. It is unclear, however, whether these new discovered low surface brightness satellite galaxies can reconcile the outnumber of subhalos predicted in cosmological simulations and solve the problem (Simon & Geha 2007).

So far a number of mechanisms have been proposed to the substructure problem. Cosmological solutions include modifying the power spectrum at small scales (Kamionkowski & Liddle 2000; Zentner & Bullock 2003) and changing the nature of the dark matter particles, such as assuming a warm dark matter particle (e.g. Colin et al. 2000; Avila-Reese et al. 2001) or invoking a decay from a nonrelativistic particle (Strigari et al. 2007). Alternative solutions typically appeal to feedback effects associated with stellar evolution or including heating from UV radiation in order to suppress the formation of dwarf galaxies by preventing low mass dark matter halos from acquiring enough gas to form stars (e.g., Bullock et al. 2000; Somerville 2002; Benson et al. 2002). An additional scenario has been proposed by Kravtsov, Gnedin & Klypin (2004) suggesting that the dwarf spheroidal we observe today were once much more massive objects that have been reduced to their present mass by tidal stripping processes.

Although these models can reconcile the shallow faint end of the luminosity function of galaxies with the low-mass end of the halo mass function, they did not explain so far the peculiarities of the dwarf spheroidal of the Local Group. For instance, it is known that dSphs of the Local Group tend to cluster tightly around the giant spirals. Proximity to a giant central galaxy prevent them from accreting material and from further star formation and allow for tidal interactions to convert them from dwarf irregulars into spheroids. However, the presence of isolated dSphs found in the outskirts of the Local Group like Tucana or Cetus (Grebel, Gallagher & Harbeck 2003) seem to imply that dSphs might have been formed away from giant spirals and been accreted already as spheroids, in disagreement with the tidal stripping scenario, which is the common picture of dSph formation models (see e.g. Mayer et al. 2007 and reference therein).

Clues to these questions may be gathered from the current observations of the metallicities of a large sample of stars in four nearby dwarf spheroidal galaxies: Sculptor, Sextans, Fornax, and Carina. Recent work from Helmi et al. (2006) shows that all the four systems lack significantly of stars with low metallicity with the dSph metallicity distribution significantly different from that of the Galactic halo. In this context Sales et al. (2007) pointed out that satellite galaxies might be accreted into the main halo as multiple systems and more recently Li & Helmi (2007) showed that subhalos are often accreted in small groups. Lake & D’Onghia (2008) have collected data...
for nearby dwarf associations from Tully et al. (2006) including the list of candidates of dwarf galaxies associated with the Magellanic plane group: LMC, SMC, Sagitarius, Ursa Minor, Draco, Sextans and LeoII (Lynden Bell 1976, Fusi Pecci et al. 1995; Kroupa et al. 2005). The authors showed that seven out of ten dwarfs within ~ 200 kpc from the Milky Way center might well be part of a group of dwarfs recently accreted into the Milky Way showing that there are natural mechanisms that lead to less suppression of satellite galaxies in dwarf galaxy groups and pointing to a resolution for the missing dwarf problem in the Milky Way.

In this paper, we present a simulation of a loose group containing a Milky Way sized halo showing that the Magellanic group likely entered the Milky Way at a redshift 1 and breaks up outside the virial radius. In Lake & D’Onghia (2008) we showed that this picture can naturally explain why galaxy satellites like Draco or Ursa Minor are luminous and why other dwarfs are expected to be dark. Here we focus on the peculiarities of the satellite galaxies of the Local Group and show that they are consistent with the tidal breakup of an infalling group of dwarf galaxies dominated from the LMC and SMC systems.

2. NUMERICAL METHODS

2.1. The Numerical simulation

Our analysis is based on a high-resolution cosmological simulation of a loose group containing a Milky Way sized halo. The target halo of the loose group has a virial mass \(\sim 7 \times 10^{12} h^{-1} M_\odot\) with \(\sim 6\) millions particles within the virial radius. The group was identified in a cosmological simulation of box 90 Mpc (or 67.5 \(h^{-1}\) Mpc) (comoving) on a side of 300\(^3\) particles with cosmological parameters chosen to match the 3-yr Wilkinson Microwave Anisotropy Probe (WMAP3) constraints (Spergel et al. 2006). These are characterized by the present-day matter density parameter, \(\Omega_0 = 0.238\); a cosmological constant contribution, \(\Omega_\Lambda = 0.762\); and a Hubble parameter \(h = 0.73\) (\(H_0 = 100 h\, \text{km s}^{-1}\, \text{Mpc}^{-1}\)). The mass perturbation spectrum has a spectral index, \(n = 0.951\), and is normalized by the linear rms fluctuation on 8 \(h^{-1}\) Mpc radius spheres, \(\sigma_8 = 0.75\). The candidate halo was selected according to the following criteria: (i) Environment location along a filament at least 5 \(h^{-1}\) Mpc far from any rich galaxy group or galaxy cluster at \(z=0\). (ii) The peak velocity of the Milky Way halo inside the group is 206 km s\(^{-1}\).

The group candidate containing the Milky Way halo was selected and resimulated to higher resolution using GRAFIC2 (Bertschinger 2001). The simulation was run with the tree-code PKDGRAV (Stadel 2001). Gravitational interactions between pairs of particles are softened with a fixed comoving softening length of 0.8 \(h^{-1}\) kpc.

2.2. The Analysis

We use SKID (Stadel 2001) to identify subhalos in the high resolution region. SKID finds subhalos within main halos by locating high density regions within the main halo and identifying the bound group of particles associated with each overdensity using a friends-of-friends (FOF) method. Particles which are not bound to their group are removed from the group by an unbinding procedure. We list for our catalog all subhalos with more than 20 particles. The output of SKID is a list of subhalos with their structural properties. We focus on the following satellite properties: (i) the subhalo mass \(M_{\text{sat}}\); (ii) the peak of the subhalo circular velocity profile \(v_{\text{cir}}\); (iii) the location of the subhalo center, identified with the most bound particle, which is the particle with the minimum gravitational potential energy. SKID was run on all snapshot up to \(z=5\), allowing us to track the evolution of individual subhalos.

3. RESULTS

3.1. The Infalling Magellanic Group into the Milky Way

We have identified all the surviving subhalos within the virial radius of the Milky Way halo at present time. Within the virial radius of the simulated Milky Way, there are a total of 70 satellites with circular velocities greater than 10 km s\(^{-1}\) at present time. There are five Magellanic Clouds-sized subhalos inside the Milky Way halo with peak circular velocities between 50 and 62 km s\(^{-1}\). We traced each representative subhalo backwards in time and we searched for the group it belongs to at preceding snapshot. We focused on two target...
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cases like Tucana or Cetus which seem to be located in the

Milky Way. These subhalos may intuitively reproduce the special

properties of the members of the Magellanic group at z=0 (magenta stars). Despite the late infall,

the group becomes unbound through tidal disruption before entering within the Milky Way halo.

The basic properties of the members of the Magellanic group at z=0 are presented in Table 1. The group has roughly only 23 members surviving as satellites which contribute to the total budget of subhalos of the Milky Way at present time. Table 1 lists the total number of subhalos found with similar peak of the circular velocity, $v_{\text{max}}$ and the mass associated to the members.

Figure 2 shows the spatial distribution of all the satellites within the virial radius of the Milky Way (blue filled circles) as compared to the subhalos of the disrupted Magellanic group at z=0 (magenta stars). Despite the late infall, this particular group appears very well mixed, however almost half of the surviving subhalos of the group (10 subhalos) are at present time located outside the virial radius of the final Milky Way. A few of them are in the outskirts of the Milky Way. These subhalos may intuitively reproduce the special cases like Tucana or Cetus which seem to be located in the outskirts of the Local Group (Grebel, Gallagher & Harbeck 2003). In particular one of the satellite of the destroyed group is almost 1 Mpc away from the Milky Way center (see table 1). Out of 23 surviving subhalos of the LMC group the remaining subhalos and material of the group is destroyed and contributes to the diffuse Milky Way halo. We traced back-

wards in time the other representative Magellanic systems and found that they belong to infalling multiple systems. Figure 3 shows the peak circular velocity cumulative distribution of the satellites contributed by the simulated infalling Magellanic group measured at z=0 compared to the observed Magellanic group measured at z=0 (filled squared symbols) (see also Figure 2 in Lake & D’Onghia 2008). The Magellanic plane group includes: LMC, SMC, Sagittarius, Ursa Minor, Draco, Sextans and Leo I is displayed with black filled squared. The little filled circles shows the velocity cumulative distribution of satellite galaxies in the Milky Way inferred from Simon & Geha (2007).

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Figure 3.— The peak circular velocity cumulative distribution of the satellites contributed by the simulated infalling Magellanic group measured at z=0 inside the virial radius of the Milky Way halo (blue filled points) and outside the virial radius (open magenta symbols). The velocity cumulative distribution of the observed Magellanic group including LMC, SMC, Sagittarius, Ursa Minor, Draco, Sextans and Leo I is displayed with black filled squared. The little filled circles shows the velocity cumulative distribution of satellite galaxies in the Milky Way inferred from Simon & Geha (2007).
4. DISCUSSION AND CONCLUSION

We performed a simulation of a Milky Way halo in the $\Lambda$CDM models focusing on the properties of the satellite population at the present day. Our simulation probes that in the cosmological context of the hierarchical universe the Magellanic Clouds might have been accreted into the Milky Way from an infalling group and that the LMC and SMC became unbound only recently. This results is consistent with the recent findings from Kallivayalil et al. (2006), Besla et al. (2007) who argue that the LMC fell into the Milky Way halo only 2 Gyrs ago and is moving at nearly the escape velocity at its radius approaching its orbital pericenter for the first time. One might argue that the time of the accretion of Magellanic Clouds is $z \sim 1$ in this specific simulation, much earlier than the observational results but groups with 10% of the Milky Way mass may infall any time.

Our main results may be summarized as follows. (i) The tidal break up of the Magellanic group occurs outside the current virial radius of the Milky Way and spreads its surviving satellites over 2 or 3 virial radii. Half of its satellites survive outside the current virial radius of the Milky Way in the form of satellites, whereas the remaining material contributes to the diffuse Milky Way halo. (ii) At $z=0$ the disrupted Magellanic group contributes less than 10% to the Milky Way mass but 20% of the brightest dwarf galaxies of the Milky Way have been part of this group. (iii) The circular velocity cumulative distribution of the satellites of the simulated Magellanic group matches the function of the observed Magellanic plane satellites the in the Local Group, suggesting that the gas physics in dwarf groups plays a key role in keeping dwarf galaxies luminous and might be the key to solve the missing dwarf problem as already discussed in Lake & D’Onghia (2008). (iv) Elongated tidal streams are formed as remnants of the breakup of the Magellanic group well outside the traditional virial radius estimate, reinforcing the idea that the traditional estimates of the virial masses around galaxies might be underestimated of a factor of 2 when an infall is happening. A remarkable consequence of the last result is that our models predict a great amount of low mass satellites to be discovered well outside the virial radius of the Milky Way. It predicts groups of dwarf galaxies to be in the neighborhood of the Local Group. Some associations of dwarf galaxies within 5 Mpc from the Milky Way have been already discovered (Tully et al. 2006) but more associations are expected in the $\Lambda$CDM models and might be a challenge for future observations. In particular these association of dwarfs have the properties expected of bound systems with $1-10\times10^{11} \, M_{\odot}$, but they have too little gas and too few stars with a consequent mass-to-light ratio of 100-1000 $M_{\odot}/L_{\odot}$. Such a high mass-to-light ratio breaks the relationship between the $M_{\odot}/L_{\odot}$ and the mass of...
bound systems and leads to a sharp increase of $M_{\odot}/L_{\odot}$ for systems below the mass of $10^{11} M_{\odot}$. A similar break and sharp increase of the $M_{\odot}/L_{\odot}$ at low mass systems has been pointed out from van den Bosch et al. (2003; 2005). The authors found a paucity of light at low mass systems comparing the shallow faint-end of the observed luminosity functions of galaxies with the corresponding halo mass function.

It has not escaped our notice that the scenario we proved explains a lot of properties and peculiarities of the Milky Way substructures. It suggests that dwarf galaxies have been form in a different group environment away from the giant spirals and been accreted already as spheroids. This would naturally explain the mismatch in metallicity between the stellar halo of the Milky Way and the dwarf spheroidals that many have suspected dissolved to build it.

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