Galaxy Evolution across the Hubble Time
Proceedings IAU Symposium No. 235, 2006
F. Combes & J. Palouš, eds.

doi:10.1017/S1743921306010234

Formation of dwarf galaxies and small-scale problems of CDM

Oleg Y. Gnedin

University of Michigan, Department of Astronomy, Ann Arbor, MI 48109-1042, USA
ognedin@umich.edu

Abstract. The concordance cosmological model based on cold dark matter makes definitive predictions for the growth of galaxies in the Universe, which are being actively studied using numerical simulations. These predictions appear to contradict the observations of dwarf galaxies. Dwarf dark matter halos are more numerous and have steeper central density profiles than the observed galaxies. The first of these small-scale problems, the "missing satellites problem", can be resolved by accounting for the low efficiency of gas cooling and star formation in dwarf halos. A newly-discovered class of HyperVelocity Stars will soon allow us to test another generic prediction of CDM models, the triaxial shapes of dark matter halos. Measuring the proper motions of HVS will probe the gravitational potential out to 100 kpc and will constrain the axis ratios and the orientation of the Galactic halo.

Keywords. dark matter — Galaxy: halo — galaxies: dwarf — galaxies: formation

1. Is the "missing satellites problem" still a problem?

Hierarchical Cold Dark Matter (CDM) models predict that Milky Way-sized halos contain several hundred dense, low-mass dark matter satellites, an order of magnitude more than the number of observed satellite galaxies in the Local Group. If the CDM paradigm is correct, this prediction implies that the Milky Way and Andromeda are filled with numerous dark halos. This has been termed the "missing satellites problem" (Klypin *et al.* 1999, Moore *et al.* 1999). Despite the recent discoveries of faint companion galaxies by the Sloan Digital Sky Survey that nearly doubled the number of known dwarf spheroidals (Belokurov *et al.* 2006), a large discrepancy between the predicted and observed numbers remains (see Figure 1).

In order to understand why most halos failed to become galaxies, we need to understand their history. In Kravtsov, Gnedin & Klypin (2004), we have analyzed the dynamical evolution of the satellite halos in a high-resolution cosmological simulation of three Milky Way-sized halos. We find that about 10% of the substructure halos with the present masses $\lesssim 10^8 - 10^9$ M$_\odot$ (circular velocities $V_{\rm m} \lesssim 30$ km/s) had considerably larger masses and circular velocities when they formed at redshifts $z \gtrsim 2$. After the initial period of mass accretion while in isolation, these objects experience dramatic mass loss due to tidal stripping. Our analysis shows that strong tidal interaction is often caused by actively merging massive neighboring halos, even before the satellites are accreted by their host halo. These results indicate that some of the systems that have small masses and circular velocities at $z = 0$ could have had masses comparable to those of the SMC and LMC in the past. This can explain how the smallest dwarf spheroidal galaxies observed in the Local Group were able to build up sizable stellar masses in their seemingly shallow potential wells.

We have proposed a new model in which all of the luminous dwarf galaxies in the Local Group are descendants of the relatively massive ($\gtrsim 10^9$ M$_\odot$) high-redshift systems,

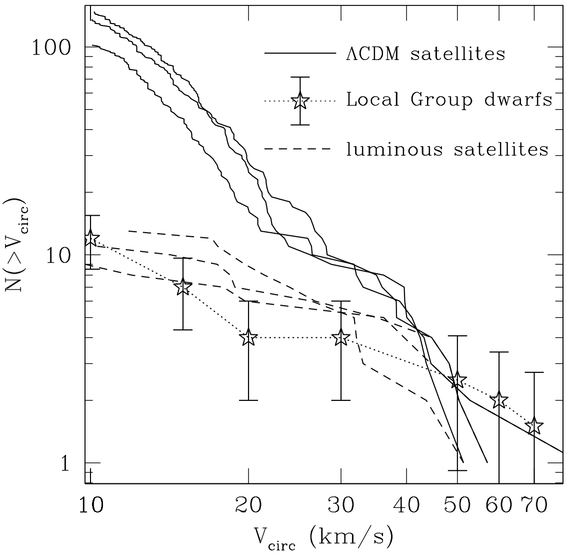

Figure 1. Cumulative velocity function of the dark matter satellites in three galactic halos (*solid lines*) compared to the average cumulative velocity function of dwarf galaxies around the Milky Way and Andromeda galaxies (*stars*). Both observed and simulated objects are selected within the radius of $200h^{-1}$ kpc from the center of their host. The dashed lines show the velocity function for the luminous satellites in our model. The minimum stellar mass of the luminous satellites for the three hosts ranges from $\approx 10^5$ $M_\odot$ to $\approx 10^6$ $M_\odot$. From Kravtsov *et al.* (2004).

in which the gas could cool efficiently by atomic line emission and which were not significantly affected by the extragalactic ultraviolet radiation. We have constructed a semi-analytical galaxy formation model based on the trajectories extracted from the simulation, which accounts for the bursts of star formation after strong tidal shocks and the inefficiency of gas cooling in halos with virial temperatures $T_{\rm vir} \lesssim 10^4$ K. Our model reproduces the abundance, spatial distribution, and morphological segregation of the observed Milky Way satellites, as well as their basic properties such as the stellar masses and densities.

According to this model, all of the luminous satellites formed some stars before the reionization ($z > 6$). Afterwards, some galaxies were massive enough to retain their gas and to keep forming stars episodically, with new stars progressively more concentrated towards the center. These objects become dIrr and some dSph types. The other objects lost all of their gas during the reionization and contain only the oldest stellar population, becoming fossil dSph galaxies identified by Gnedin & Kravtsov (2006).

2. Probing the Galactic halo with HyperVelocity Stars

A generic prediction of CDM models is that dark-matter halos are triaxial, with density axis ratios in the range 0.5–0.8. The only currently known observational probe of the shape of the Galactic halo is provided by tidal streams associated with satellite galaxies, such as the Sagittarius dwarf spheroidal galaxy. However, different analyses of the Sagittarius stream data have produced conflicting results, with claims that the Galactic halo is close to spherical (Johnston *et al.* 2005), while others find that a minor-to-major axis ratio as low as 0.6 cannot be ruled out for a prolate halo (Helmi 2004). Measurements

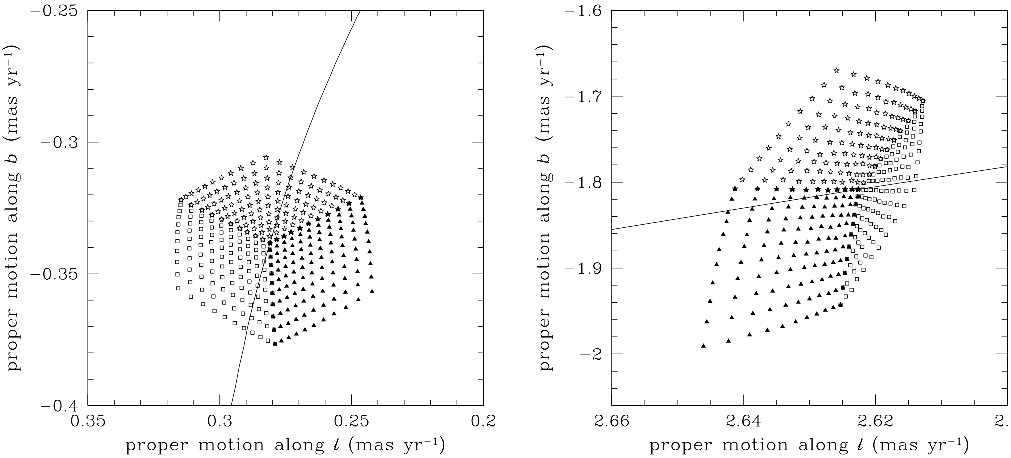

Figure 2. Expected proper motions of HVS1 (left) and HVS2 (right) under a range of different assumptions about the shape and orientation of the Galactic dark-matter halo. The two components of the proper motion are in the directions of Galactic coordinates, l and b, and include the reflex proper motion due to the Sun's motion around the Galactic center. The family of models with the halo major axis along the Galactic X-coordinate is shown by triangles, along the Y-coordinate by open squares, and along the Z-coordinate by open stars. The solid line shows the predicted proper motions for the HVS1 distance from Earth varying from 61 (bottom) to 90 kpc (top), and the HVS2 distance from 18 to 20 kpc, assuming a spherical dark-matter halo. Adapted from Gnedin *et al.* (2005).

of the halo shape close to the Galactic disk are complicated by the dynamical effects of baryons, tending to make even triaxial halos rounder at these radii (Kazantzidis *et al.* 2004). Another, independent measure of the halo shape at larger distances is needed to test the nature of dark matter and to confirm or falsify CDM models.

Such an independent test is now provided by the recently discovered HyperVelocity Stars (Brown *et al.* 2005, 2006a, 2006b; Hirsch *et al.* 2005; Edelmann *et al.* 2005). The first three of these extraordinary stars have heliocentric radial velocities above $+700\,\mathrm{km\,s^{-1}}$ and were found in the course of spectroscopic followups to all-sky surveys that have identified faint blue stars in the Galactic halo. The other four have velocities above +540 km $\mathrm{s^{-1}}$ and were discovered later in a targeted survey. The velocities of all HVSs exceed the plausible limit for a runaway star ejected from a binary in which one component has undergone a supernova explosion. The only known mechanism for a star to obtain such an extreme velocity is ejection from the deep potential of the supermassive black hole at the Galactic center, as a result of scattering with another star or tidal breakup of a binary (Hills 1988).

Given its high-velocity ejection from the Galactic center, $\sim$1000 km $\mathrm{s^{-1}}$, the expected trajectory of a HVS in the Galaxy is nearly a straight line. However, the direction of the HVS present velocity will deviate from being precisely radial due to departures from spherical symmetry of the Galactic potential. A precise measurement of the three-dimensional motions of the HVSs thus probes the shape of the Galactic halo mass distribution in a new way that is entirely independent of any other technique attempted so far.

Figure 2 shows predictions for the proper motions of the first two HVSs, consistent with their positions in the sky and the observed line-of-sight velocities. The orbits are calculated in a generalized triaxial NFW potential, for different assumptions about the density axis ratios. For distant HVSs, the asymmetry of the potential due to the flattened disk causes a smaller deflection than that due to the triaxial halo. The deflection contributed by the disk peaks at $r \approx 10$ kpc but quickly declines at larger distances where the disk density vanishes and the direction of the orbit aligns with the velocity vector. Interactions with the Galactic bar or molecular clouds in the disk are even less important because of the shorter lever arm. On the other hand, the deflection due to the triaxial halo *continues to accumulate along the whole trajectory*. Hence, the proper motions are sensitive to the halo triaxiality and relatively insensitive to any uncertainties in the mass model of the baryons.

We have started an HST program to measure astrometric proper motions for five HVSs. The first-epoch images are taken in Cycle 15 and the second-epoch images will be taken late in Cycle 17. With an almost 3-year baseline, we will easily detect the proper motion of HVS2 and very likely those of the other HVSs.

With an expected measurement accuracy of $\sigma_\mu \approx 0.2\,\mathrm{mas\,yr^{-1}}$ (over 3 years) we can place useful constraints on the orientation of the Galactic halo. In the case of HVS2, for example, if the major axis of the halo is aligned with the direction to the Galactic center ($l = 0°$), the predicted components μ_b all lie below $\mu_b < -1.8\,\mathrm{mas\,yr^{-1}}$. If the major axis is aligned with the disk rotation axis, $\mu_b > -1.8\,\mathrm{mas\,yr^{-1}}$. If the major axis is in the direction of solar rotation, then the predicted μ_l component of the proper motion is well constrained to be $\mu_l = 2.62 \pm 0.01\,\mathrm{mas\,yr^{-1}}$. Note also, that the proper motions are sensitive to the distance to the HVS, and therefore, we will obtain a distance estimate independent from the photometry.

Future astrometric satellites that could reach accuracy of $\sigma_\mu \sim 0.01\,\mathrm{mas\,yr^{-1}}$ will allows us to determine the halo axis ratios. With two or more HVSs we will be able to break the triaxiality-distance degeneracy and to constrain the axis ratios to better than 20%.

Acknowledgements

I acknowledge the support of the American Astronomical Society and the National Science Foundation in the form of an International Travel Grant, and the support of the IAU through grant 11812.

References

Belokurov, V. *et al.* 2006, *ApJ* submitted, astro-ph/0608448

Brown, W. R., Geller, M. J., Kenyon, S. J. & Kurtz, M. J. 2005, *ApJ* 622, L33; 2006a, *ApJ* 640, L35; 2006b, *ApJ* 647, 303

Edelmann, H. *et al.* 2005, *ApJ* 634, L181

Gnedin, N. Y. & Kravtsov, A. V. 2006, *ApJ* 645, 1054

Gnedin, O. Y., Gould, A., Miralda-Escude, J. & Zentner, A. R. 2005, *ApJ* 634, 344

Helmi, A. 2004, *MNRAS* 351, 643

Hills, J. G. 1988, *Nature* 331, 687

Hirsch, H. A., Heber, U., O'Toole, S. J. & Bresolin, F. 2005, *A&A* 444, L61

Johnston, K. V., Law, D. R. & Majewski, S. R. 2005, *ApJ* 619, 800

Kazantzidis, S., Kravtsov, A. V., Zentner, A. R., Allgood, B., Nagai, D. & Moore, B. 2004, *ApJ* 611, L73

Klypin, A., Kravtsov, A. V., Valenzuela, O. & Prada, F. 1999, *ApJ* 522, 82-92

Kravtsov, A. V., Gnedin, O. Y. & Klypin, A. A. 2004, *ApJ* 609, 482

Moore, B. *et al.* 1999, *ApJ* 524, L19