Near-Field Cosmology with Dwarf Elliptical Galaxies
Proceedings IAU Colloquium No. 198, 2005
H. Jerjen and B. Binggeli, eds.

doi:10.1017/S1743921305003522

On the origin of dwarf spheroidal galaxies. Clues from cosmological simulations

Massimo Ricotti[1] and Nicholay Y. Gnedin[2]

[1]Dept. of Astronomy, University of Maryland, College Park, MD 20742-2421, USA
email: ricotti@astro.umd.edu

[2]Dept. of Astronomy, University of Colorado, Boulder, CO 80309, USA
email: gnedin@casa.colorado.edu

Abstract. We compare the properties of dwarf galaxies in the Local Group with the simulated galaxies formed before reionization in a cosmological simulation of unprecedented spatial and mass resolution including radiative feedback effects. We find that a subset of the Local Group dwarfs, the dwarf Spheroidals, are remarkably similar to the simulated dwarf galaxies in all their properties already before reionization. Simulated and observed dwarf Spheroidal galaxies not only have similar properties but also follow the same scaling relations. Based on this similarity and on the observed ages of their dominant stellar populations we propose the hypothesis that Local Group dwarfs form in two different ways: (i) most dwarf Spheroidals are pristine fossils of the pre-reionization era and (ii) dwarf irregulars are more massive galaxies that formed most of their stars later, after reionization. There is also a group of "polluted fossils" with properties that are intermediate between these two main groups. We predict the existence of many more dwarf Spheroidals, fainter and with lower surface brightness than the observed population.

Keywords. early universe, Local Group, galaxies: dwarf, formation, high-redshift, individual (UMi, Draco, Antlia, Sculptor, Phoenix, Sextans, Cetus, Tucana, KKR25 AndI-III, AndV-VI)

---

1. Introduction

The punchline in this talk is to provide evidences in support of the primordial origin of dwarf Spheroidals (dSphs). I will present a comparison between the abundant observational data on Local Group dwarfs and the results of detailed cosmological simulation of formation of dwarf galaxies in the pre-reionization era.

Almost all Local Group dwarf Spheroidals exhibit a prominent old population and a fraction show a decline of their star formation rates about 10 Gyr ago. In the standard Λ-CDM theory stellar reionization took place 12.5 Gyr ago but current observational techniques for measuring absolute stellar ages are not able to differentiate between 10 and 12.5 Gyr (*e.g.*, Krauss & Chaboyer 2003). Although the observed drop of star formation rate is consistent with reionization at redshift $z \sim 6$, as noted by Grebel & Gallagher 2004, the metallicity spreads observed in the old populations may imply a star formation history protracted over about 2 Gyr, to redshift $z \sim 3$. In this talk I critically discuss this important issue. I will show that our simulations reproduce the observed metallicity spreads without a protracted period of star formation. The metallicity spreads observed in our simulated dwarfs can be understood in terms of hierarchical accretion of sub-haloes containing stars with different metallicities.

The key difference between our proposal for the origin of dSphs and the tidal hypotheses (Stoehr *et al.* 2002, Kravtsov *et al.* 2004) is whether most of the stars in a given dwarf galaxy formed in *halos of mass* $\lesssim 10^8\ M_\odot$ before reionization ($z > 6$, 12.5–13 Gyr ago) or in *more massive halos* after reionization, during the epoch of formation of the Milky Way and Andromeda ($z \sim 2$–3, 10–11 Gyr ago). We find that most dSphs are fossils of galaxies with mass $M_{\rm dm} < 10^8$ M$_\odot$ that formed before reionization, while dIrr formed later in more massive halos. The original contribution of our study is that for the first time we have been able to simulate the first population of galaxies including the relevant feedback processes that are known to self-limit their formation. Before our work (Ricotti, Gnedin, & Shull 2002a, 2002b) negative feedback effects (namely the rapid photo-dissociation of H_2) were thought to suppress the formation of all galaxies with mass smaller than 10^8 M$_\odot$. We instead found that these galaxies do form and, at the epoch of their formation, they closely resemble dSph galaxies. This second result is the one I would like to emphasize in the present talk. Our simulations also show that reionization feedback is not the dominant mechanism that suppresses star formation in most small mass halos. Negative feedbacks such as photo-heating by the stars inside each galaxy and inefficient cooling produce the observed properties of dSphs well before reionization of the IGM is complete. Reionization does not affect substantially their properties because they have already lost most of their gas due to internal ionizing sources. After reionization we expect that the formation of small mass galaxies will stop and their stellar populations will evolve only passively. Only the few most massive dwarfs in our simulation retained some of their gas and may continue to form stars after reionization.

2. Simulation

The simulation we use in this paper has been thoroughly described in Ricotti *et al.* (2002a, 2002b) as run "256L1p3". Here we just remind the reader that the simulation included 256^3 dark matter particles, an equal number of baryonic cells, and more than 700,000 stellar particles. The simulation includes most of the relevant physics, including time-dependent spatially-variable radiative transfer, detailed radiative transfer in Lyman-Werner bands, non-equilibrium ionization balance, etc. In addition, here we also include the effect of reionization, see Ricotti and Gnedin (2005) for details. The limitation of our simulation is that it stops at redshift $z = 8.3$. Clearly, it is a long way to go from $z = 8.3$ to the present day. Therefore, in the rest of this talk, we are assuming that the stellar component of our galaxies does not change after $z = 8.3$ except due to passive stellar evolution. This hypothesis, obviously, does not apply to *all* observed dwarfs, but it may apply to *some* of them. We estimated that about 5-10% of the galaxies present in our simulation at $z = 8.3$ may have survived almost unspoiled until today. In order to compute the luminosities of the simulated galaxies at $z = 0$, we adopt a fiducial ratio of $M_*(z = 8.3)/L_V(z = 0) = 3$. However, our results are not immensely sensitive to that number - changing it to 2 or 10 would not change our conclusions.

3. Results

Clearly, not all dwarfs are true fossils of the pre-reionization era, since many of them had recent episodes of star formation. But is there a subset of Local Group dwarfs that formed before reionization? We can attempt to answer this question by comparing our simulated dwarfs as they would appear at $z = 0$ with the real observed galaxies. Figure 1(left) presents such a comparison for the basic structural parameters: the luminosity L_V, the core radius r_c, and the central luminosity density I_c, defined as $I_c = \Sigma_V/2r_c$, where Σ_V is the surface brightness. From the top panel of that figure it is clear that the simulated galaxies, shown by the gray squares without error-bars, do not exceed about $10^7 L_\odot$. Moreover, it appears that the observed galaxies (shown by squares with error-bars, open circles, and filled circles - the different symbols will be explained later in the text) also fall into two groups - those with luminosities on the order of $10^7 L_\odot$ and below,

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press

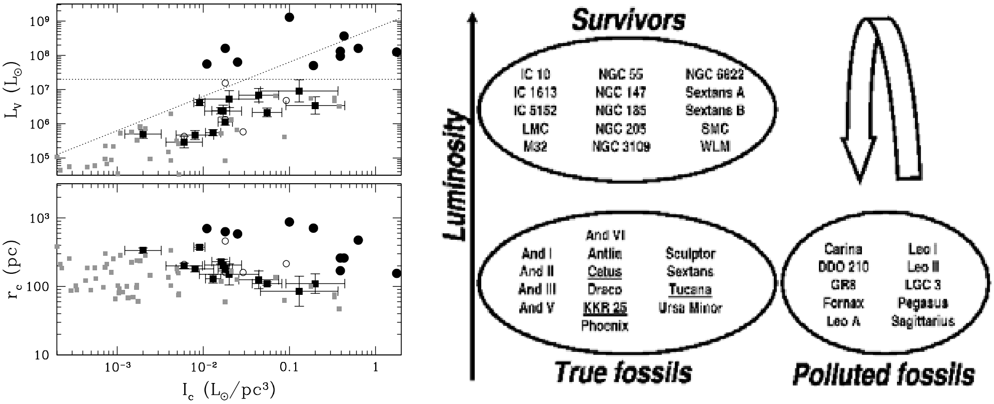

Figure 1. *(Left)* The V-band luminosity (top) and the core radius (bottom) vs the central luminosity density for the Local Group dwarfs (squares with error-bars, open circles, and filled circles - the different symbols are explained in the text) and for the simulated galaxies passively evolved to $z = 0$ (gray squares). Two dotted lines show two possible boundaries between the “fossils” and “survivors”. The data is from Mateo (1998). We have complemented the data using updated distances and photometry from van den Berg (2000) and metallicities and metallicity spreads from Grebel *et al.* (2003). *(Right)* A tentative separation of all Local Group dwarfs into three groups: “survivors”, that formed via the tidal scenario (mostly dIrr), “true fossils”, that formed via the reionization scenario, and “polluted fossils”, that went through both stages. In our tentative classification most dSphs (14) are true fossils: five are M31 satellites, six are Milky Way satellites and three (the underlined names) are isolated from both M31 and the Milky Way.

and those with luminosities in excess of $5 \times 10^7 L_\odot$. In addition, these two groups are also clearly separated in $r_c - I_c$ plane. The low luminosity dwarfs appear to trace the same distribution as the simulated galaxies, having smaller core radii as the central luminosity density increases. This observation can be understood in terms of the less efficient cooling of the gas in dark matter halos of smaller mass.

We can now see how our separation in these two groups (based only on the luminosity) compare with the available data on the star formation history of observed dwarfs. Hereafter we will adopt the star formation histories compiled by Grebel & Gallagher (2004). In order to schematically separate the observed dwarfs in groups according to their star formation histories, we call those dwarfs that formed few (say, less than 30%) stars after reionization “true fossils”, and those that did form a substantial amount of stars “polluted fossils”. The various symbols in Figure 1(left) and the following ones correspond to these classes: “true fossils” are shown with filled squares with error bars, “polluted fossils” are shown with open circles. Galaxies with dominant younger stellar populations (they mostly are dIrrs) are shown with larger filled circles and we call them “survivors”. All the galaxies in our simulation have almost identical properties to the “true fossils” and most “polluted fossils”. All these galaxies have a prominent old stellar population as expected. Instead all the galaxies with a prominent young population (filled circles) are part of a distinct population that is not present in our simulation. Figure 1(right) presents a tentative separation of the Local Group dwarfs into these three types.

Figure 2(left) compares the surface brightness and the core radii of simulated and observed galaxies as a function of the luminosity. The simulation reproduces very well the structural properties and scaling relations of the galaxies that we classified as “true fossils”. The lines show, for comparison, the scaling relations derived by Kormendy & Freeman (2004) for more luminous late-type galaxies (Sc-Im) with luminosities in the

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press

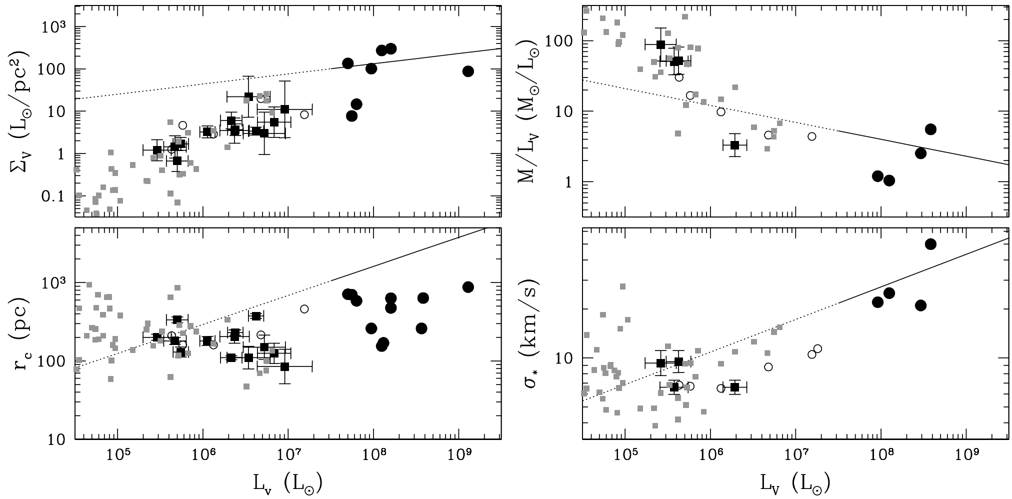

Figure 2. *(Left)* Surface brightness (top) and core radius (bottom) as a function of the V-band luminosity for the simulated and observed dwarfs. *(Right)* Total mass-to-light ratio (top) and stellar velocity dispersion (bottom) for the simulated and observed dwarfs. Symbol markings and the meaning of the lines are the same as in Fig. 1.For comparisons we show (solid lines) the scaling relationships for the more luminous Sc-Im galaxies ($10^8 L_\odot \lesssim L_B \lesssim 10^{11} L_\odot$) derived by Kormendy & Freeman 2004.

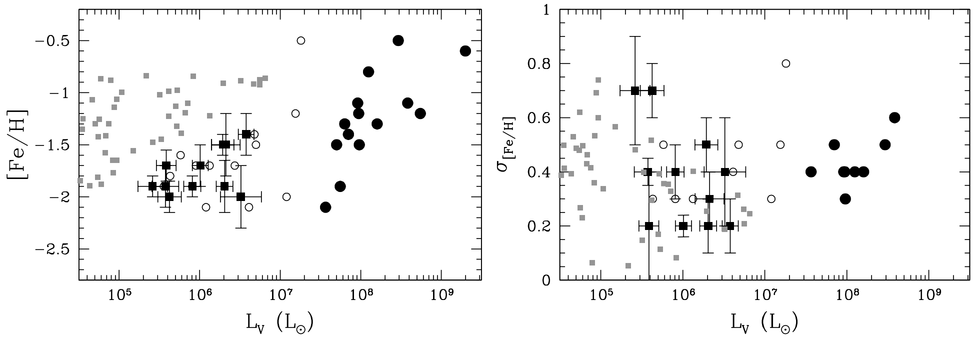

Figure 3. Stellar metallicity (left) and the metallicity spreads (right) as a function of stellar luminosity. We adopt solar abundances and yield y=$\rho_Z/\rho_* = 1$ Z$_\odot$. Symbol markings and the meaning of the lines are the same as in Fig. 1. The spreads $\sigma_{[Fe/H]}$ is defined as the variance of the number weighted metallicity distribution of the "stellar particles" in each dwarf.

range $10^8 L_\odot \lesssim L_B \lesssim 10^{11} L_\odot$. Figure 2(right) compares the dynamical state of these galaxies: the stellar velocity dispersion and the total mass-to-light ratio. The latter quantity for the simulated galaxies is computed in the same way as for the observed ones ($M/L = 136\sigma_*^2 r_c/L$, see Mateo 1998). Within the errors the $\sigma - L_v$ relation seems to be the same power law for all the galaxy types, but "true fossils" obey a steeper relationship between the mass-to-light ratio and luminosity than dIrr and Sc-Im galaxies.

Figure 3 gives yet another comparison between the simulation and the data: the metallicity (left) and the metallicity spreads (right) as a function of stellar luminosity. We find that the typical metallicity variance in each dwarf is about 0.5 dex, in good agreement with observations. The agreement between stellar metallicities in the simulation and the data is somewhat worse. At this point we are not worried by this disagreement as our simulation is not sophisticated enough to predict the stellar metallicities to within a

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press

factor of two. The accretion of stars from the hierarchical distribution of sub-haloes partially explains the large metallicity spread that we find in our simulation. Thus we conclude that the large metallicity spread observed in the old stellar population of dSphs is not a definite signature of star formation extended over 2–4 Gyrs as argued by Grebel & Gallagher (2004). Neither the argument based on the long timescale (*e.g.*, 1–4 Gyr) needed to have a substantial iron production by Type Ia SN is a strong argument in favour of prolonged star formation. The typical time scale for iron enrichment by Type Ia SN is uncertain and very likely is dependent on the mode of star formation. Matteucci & Recchi (2001) estimated that this time scale varies from 40–50 Myr for an instantaneous starburst to 4–5 Gyr for a disk of a spiral galaxy like the Milky Way.

4. Discussion

In this paper we have proposed that dwarf galaxies of the Local Group (and, by implication, all other dwarf galaxies in the universe) formed in three different evolutionary paths: i) *"true fossils"* formed most of their stars in the pre-reionization era, and have had little (say, less than 30%) star formation since then; ii) *"polluted fossils"* started as true fossils, but had substantial episode(s) of subsequent star formation as they continued accreting mass and were tidally shocked during the formation of the parent galaxy halo; iii) finally *"survivors"* started forming stars mostly after reionization. This conclusion is motivated by considering star formation histories of Local Group dwarfs and by comparing their properties with properties of simulated galaxies that formed all their stars before cosmological reionization. The fact that our simulated galaxies are remarkably similar to the subset of the Local Groups dwarfs that we identified as "true fossils" in Figs 1–3 renders support to our conclusions. This subset includes about all known dSphs. It is worth noting that the structural properties of the galaxies that we call "true fossils" are the result of feedback processes in action prior to reionization. The effect of reionization is simply to preserve those properties by suppressing the star formation rate in halos with masses that remain smaller than the filtering mass in the IGM.

To conclude, we would like to emphasize another exciting possibility. From the results of our simulations, we feel quite confident in predicting the existence of fainter and lower surface brightness galaxies than the one currently discovered (see the gray squares at the extreme left corners in Figs. 1–3). Two promising candidates for such a class of dwarf galaxies were recently discovered in M31 and near the Milky Way (Zucker *et al.* 2004, Willman *et al.* 2005).

As we mentioned above, it is mostly likely that the majority of reionization fossils will merge into larger objects by $z = 0$, and only a small fraction of them will survive. Thus, we can introduce a "survival probability" S (which can be a function of other parameters, in particular the luminosity) of a reionization fossil to remain intact by the present time. Figure 4 shows our predictions for the abundance of these "ultra-dwarfs" in the Local Group. The solid line in Fig. 4 refers to the case in which the survival probability of reionization fossils is kept constant at 3% – in this case the observations may be missing about half of the satellites with luminosities in the range $2 \times 10^5\,\mathrm{L}_\odot \lesssim L_V \lesssim 6 \times 10^5\,\mathrm{L}_\odot$. Alternatively, we can assume that the observations are complete in this luminosity range, in which case the survival probability must be a weak function of luminosity. Fitting the logarithmic dependence (as an example) to the abundance of observed dwarfs in the three lowest luminosity bins ($2 \times 10^5\,\mathrm{L}_\odot \lesssim L_V \lesssim 6 \times 10^6\,\mathrm{L}_\odot$), we find $S(L_v) = 3\%(L_v/2 \times 10^6\,\mathrm{L}_\odot)^{1/3}$. This case is shown with the dashed line in Fig. 4. As one can see, a modest change in the survival probability makes a large change in the predicted numbers of dwarf galaxies in the $L_V \lesssim 10^5\,\mathrm{L}_\odot$ luminosity range. Although, the detection of such

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press

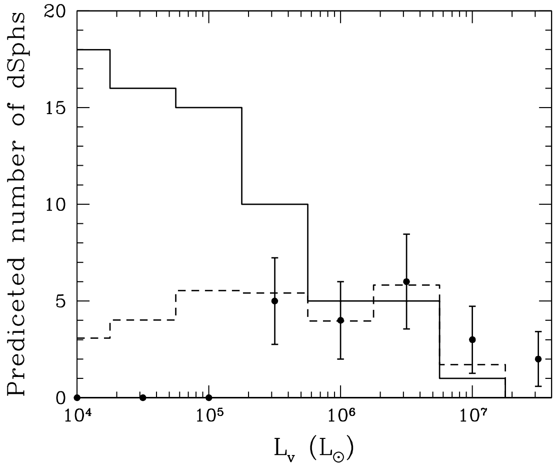

Figure 4. Prediction of the number of faint dSphs per logarithmic luminosity bin in the Local Group (histograms). The points with error bars (Poisson errors) show the number of observed dwarf galaxies in the Local Group. The solid line refers to the case in which the survival probability of reionization fossils is constant as a function of luminosity, while the dashed line shows an example of a case in which the survival probability is mildly luminosity dependent (see text for details).

objects in the Milky Way is very difficult if not impossible using photometric techniques (due to contamination from foreground stars), in the future it might become possible to search for these objects using spectroscopic techniques by measuring the radial velocities of many halo stars.

References

Grebel, E.K., Gallagher, J.S. & Harbeck, D. 2003, *AJ* 125, 1926
Grebel, E.K. & Gallagher, J.S. 2004, *ApJL* 610, L89
Kormendy, J. & Freeman, K.C. 2004, *IAU Symposium* 220, 377
Krauss, L.M. & Chaboyer, B. 2003, *Science* 299, 65
Kravtsov, A.V., Gnedin, O.Y. & Klypin, *A&A* 2004, *ApJ* 609, 482
Mateo, M. 1998, *ARAA* 36, 435
Matteucci, F. & Recchi, S. 2001, *ApJ* 558, 351
Ricotti, M., Gnedin, N.Y. & Shull, J.M. 2002a, *ApJ* 575, 33
Ricotti, M., Gnedin, N.Y. & Shull, J.M. 2002b, *ApJ* 575, 49
Ricotti, M. & Gnedin, N.Y. 2005, *ApJ* 629,
Stoehr, F., White, S.D.M., Tormen, G. & Springel, V. 2002, *MNRAS* 335, L84
van den Bergh, S. 2000, *PASP* 112, 529
Willman, B., *et al.* 2005, *ApJL* submitted (astro-ph/0503552)
Zucker *et al.* 2004, *ApJ* 612, L121

Discussion

Mateo: How do I interpret the number of galaxies at very low luminosities in your plots? That is, can I just scale by the number of known galaxies in the regions of your plots where the data and simulations overlap?

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press

Ricotti: Yes, that is the way to do it. There might be second order corrections due to a possible dependence of the survival rate on the mass (or luminosity) of the primordial dwarfs.

Zaggia: Can you say anything about rotation in dwarfs?

Ricotti: The rotation velocity is negligible with respect to the velocity dispersion of the stars.

Read: What is the origin of the anisotropy (radial) in the outermost point of the stars which is not present in the dark matter?

Ricotti: I do not know. Perhaps it is a signature of accretion of stellar subunits. Remember that most dark matter halos are dark. Stars are formed in a small fraction of DM halos.

Gallagher: Have you modeled abundance ratios of elements that might distinguish the short starburst and extended star formation models, for example the r-process or α-elements relative to iron?

Ricotti: No.

https://doi.org/10.1017/S1743921305003522 Published online by Cambridge University Press