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NUMERICAL SIMULATIONS OF THE METALLICITY DISTRIBUTION IN DWARF SPHEROIDAL GALAXIES

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Abstract. Recent observations show that the number of stars with very low metallicities in the dwarf spheroidal satellites of the Milky Way is low, despite the low average metallicities of stars in these systems. We undertake numerical simulations of star formation and metal enrichment of dwarf galaxies in order to verify whether this result can be reproduced with "standard" assumptions. The answer is likely to be negative, unless some selection bias against very low metallicity stars is present in the observations.

1 Introduction

The study of the formation and evolution of galaxies is one of the most important issues of present-day astronomy. The currently favoured models suggest that large galaxies such as the Milky Way formed through the hierarchical accretion of a number of smaller objects.

One possible way to test this scenario is to focus on dwarf galaxies: in fact, it is reasonable to expect that their assembly was considerably less complicated than that of the Milky Way, and easier to understand.

The nine dwarf spheroidal (dSph) satellites of the Milky Way are ideal targets in this respect: theoretically, they might be the "fossil" remnants of the "building blocks" which ended up inside the Milky Way; observationally, they can be studied in much greater detail than more distant objects.

For example, it has been possible to study their stellar populations, extracting informations about their star formation (SF) and chemical evolution histories (see e.g. the review by Mateo 1998), which turned out to be quite varied. However, all of them contain a population of very old stars, and all of them exhibit low mean metallicities (Grebel & Gallagher 2004).

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Large observational programs (such as DART, i.e. Dwarf Abundances and Radial-velocities Team) are measuring, for the first time, the stellar metallicity distribution in dSph galaxies (Tolstoy *et al.* 2004; Koch *et al.* 2006; Battaglia *et al.* 2006). Despite the low average metallicities (consistent with previous estimates), out of about 2000 stars which were observed in four different galaxies (Carina, Fornax, Sculptor, and Sextans), none of them turned out to have a metallicity lower than [Fe/H]=-3, which is quite surprising (Helmi *et al.* 2006).

Here, we use numerical simulations of chemical enrichment of dwarf galaxies in order to investigate whether this dearth of very metal poor stars (VMPSs, i.e. stars with [Fe/H] ≤ -3) is consistent with the simple hypothesis that the gas in the dwarf galaxies was completely self-enriched in metals (i.e. that the gas metallicity when SF started in these galaxies was essentially 0), and that the IMF of these galaxies was always given by a Salpeter power law extending from 0.1 to 100 $M_{\odot}$.

2 The Simulations

2.1 The Method

We modified the public SPH code Gadget (Springel *et al.* 2001; Springel 2005) in order to include the treatment of gas cooling, SF, supernova (SN) and stellar wind feedback, and metal enrichment of the inter-stellar medium. A complete description will be given in Ripamonti *et al.* 2006. Here it is sufficient to say that the gas cooling rate was taken from Sutherland & Dopita (1993) (if $T \geq 10^4$ K; otherwise it was assumed to be 0), the SF recipe assumes a Schmidt law (see e.g. Thacker & Couchman 2000), the stellar lifetimes are taken from the Geneva evolutionary tracks (e.g. Schaller *et al.* 1992), and that SN energies and yields are from Woosley & Weaver (1995).

2.2 Sculptor

Our simulations were aimed at reproducing the chemical properties of the Sculptor dSph (hereafter, Scl), rather than those of the full sample of Helmi *et al.* (2006). The reason for this choice is that the low metallicity tail of Scl extends to slightly lower metallicities than those of the other three dSphs (a fact which will strengthen our conclusions). Furthermore, the SF history of Scl appears to have lasted only a few Gyr, and after this initial period it appears to have stopped, as no stellar population younger than about 10 Gyr has been detected: such a simple history should be relatively easy to reproduce.

The total mass of Scl was quoted to amount to a few $\times 10^7\, M_{\odot}$ (Queloz *et al.* 1995), but more recent estimates (Battaglia *et al.* 2006) have put it at a much higher value ($\sim 5\times10^8\, M_{\odot}$). Here we report the results of simulations where its total mass was assumed to be $M_{halo} = 10^8\, M_{\odot}$: such a value is low when compared to recent measurements, but this should have only a small effect on the metallicity distribution of the stars in the galaxy.

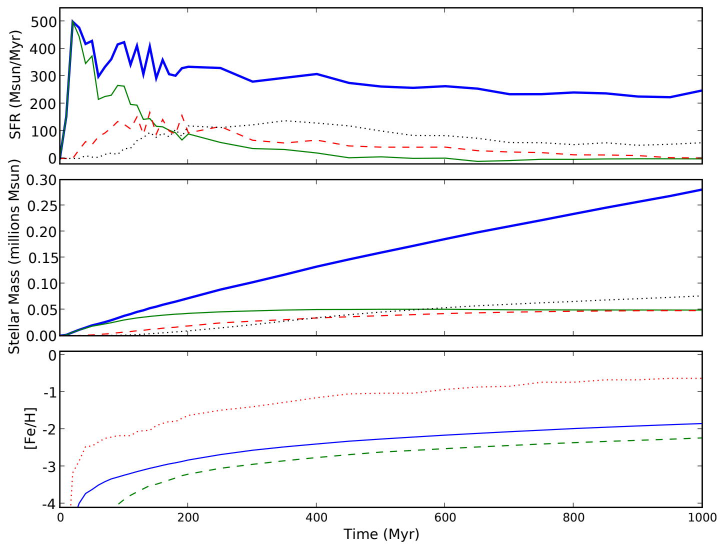

Fig. 1. Evolution of the stellar properties in one of our simulations. Top panel: total SF rate (solid thick), SF rate of stars with [Fe/H] ≤ -3 (thin solid), SF rate of stars with $-3.0 <$ [Fe/H] ≤ -2.5 (dashed), SF rate of stars with $-2.5 <$ [Fe/H] ≤ -2 (dotted). Central panel: total mass of stars, and mass of stars in metallicity ranges (symbols as in the top panel). Bottom panel: maximum (dotted), average (solid), and median (dashed) of stellar metallicities.

2.3 Simulation setup and parameters

At the beginning of our simulations we assume that all the baryons are in gaseous form, and that both the gas and DM follow a NFW profile (Navarro *et al.* 1997) with concentration $c = 10$ and virial radius $R_{200} = 1.5\,\mathrm{kpc}$ (approximately coincident with the present-day tidal radius of Scl). We place 20000 DM particles and 100000 gaseous particles within twice the virial radius. Since we assume that a mass M_{halo} is entirely enclosed within R_{200}, the total mass included in each simulation is about $1.4M_{halo}$, of which a fraction $\Omega_{DM}/(\Omega_{DM}+\Omega_b) \simeq 0.825$ is in the DM component, and a fraction $1-\Omega_{DM}/(\Omega_{DM}+\Omega_b) \simeq 0.175$ is in the baryonic component ($\Omega_{DM} \simeq 0.198$, and $\Omega_b \simeq 0.042$ are the cosmological density parameters of DM and baryons; see Spergel *et al.* 2006).

The initial velocities were assigned according to the recipe for a spherical halo described in Hernquist (1993), and the gas particles were assumed to be cold.

The main parameters of our simulations were related to SF and feedback. They include the typical mass of stellar particles ($50M_\odot$), the SF efficiency C_{sfr} (which was varied in the range $0.001-0.1$; see e.g. Thacker & Couchman 2000), the typical energy of a SN explosion which is transferred to neighbouring gas

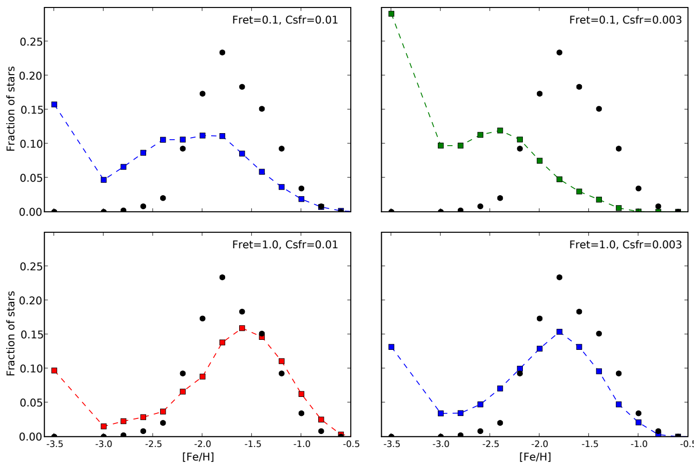

Fig. 2. Metallicity distribution after 1 Gyr for stars in four different simulations (squares connected by dashed lines), differing for the values of F_{ret} and C_{sfr} indicated in each panel. The dots (whose size is comparable to the error bars) show the metallicity distribution of 496 stars in Scl. The leftmost point (at [Fe/H] $= -3.5$) actually groups together all the VMPSs. Values are normalized to the total number of stars.

particles (10^{50} erg)[1], and the fraction F_{ret} of the metals ejected in a SN explosion which is retained by the galaxy (we tested $F_{ret} = 1$ and $F_{ret} = 0.1$; this second value is justified by the results of Mac Low & Ferrara 1999, which found that metals from the SN ejecta can escape from the galaxy far more easily than the rest of the gas).

3 Results

We ran a grid of simulations with different combinations of the above parameters; each one was run for just 1 Gyr, because in all of them we found that the formation of very low metallicity stars had essentially stopped before that time (see Fig. 1). The mass of the stellar component was always much smaller (typically, by a factor 3-10) than the stellar mass in Scl, but SF in the simulated galaxy was still active, even if only for stars with [Fe/H] $\gtrsim -2.3$.

This fact must be kept into account when comparing the observed Scl metallicity distribution with those produced by the simulations, because the average stellar metallicity from the simulations is still growing. In Fig. 2 we show such a comparison in four typical cases.

[1]In experiments conducted with a SN energy of 10^{51} erg, the feedback completely stopped the SF after much less than one Gyr, preventing the formation of more than a few $10^4\ M_\odot$ of stars.

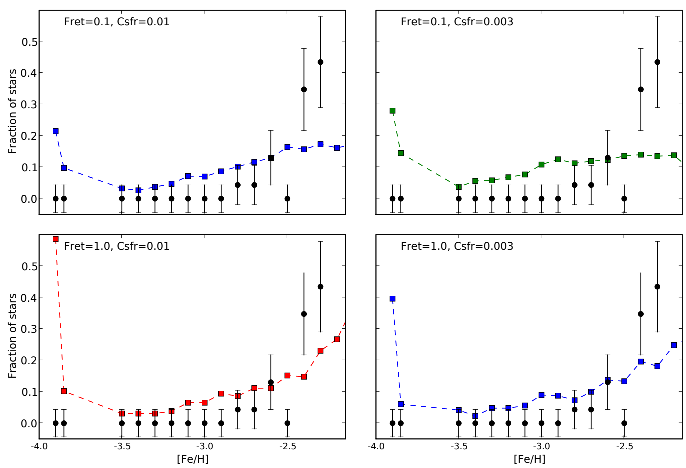

Fig. 3. Metallicity distribution for low metallicity stars after 1 Gyr in four different simulations (squares connected by dashed lines), differing for the values of F_{ret} and C_{sfr} indicated in each panel. Dots with error bars show the metallicity distribution of stars in Scl. The two leftmost bins refer to stars with [Fe/H] ≤ -4, and with $-4 <$ [Fe/H] ≤ -3.5. All the values are normalized to the number of stars with $-3 \leq [Fe]/H \leq -2.3$.

It is apparent that the fraction of VMPSs is always very high; it is higher in models where a low value of F_{ret} and an high value of C_{sfr} are assumed (which is unsurprising because such assumptions correspond to a longer timescale for the metal enrichment of the gas). In all the cases the fraction of VMPSs is difficult to reconcile with the observations, even when a "dilution" by a factor 3-10 (due to the future formation of a large number of stars) is introduced. Furthermore, the models with $F_{ret} = 1$, where this discrepancy is lower, suffer from another problem at the high metallicity end, since they produce an average metallicity which is too high, at least if $C_{sfr} \geq 0.01$.

In Fig. 3 we try to limit the effects of the unknown SF after the first Gyr of evolution by looking just at the metallicity distribution of stars with [Fe/H] ≤ -2.3, because in such metallicity range SF is essentially complete by the time the simulations are stopped. Here the excess of VMPSs appears less dramatic; but this is mostly an artifact of the large error bars due to the low number (23) of observed stars in this metallicity range. Furthermore, the *shape* of the distributions appear to be different: the models fail to reproduce the observed increase in the number of stars at [Fe/H] $\gtrsim -2.5$, and predict a very large number of essentially metal-free stars (when $F_{ret} = 1$ is assumed, most of the VMPSs have [Fe/H] ≤ -4).

4 Discussion and conclusions

The metallicity distribution obtained in our simulations is quite different from the predictions of Lanfranchi & Matteucci (2004), as they predict a quite sharp drop at low metallicity ([Fe/H] $\lesssim -2.5$), in agreement with observations (however, there is significant disagreement at [Fe/H] $\gtrsim -1.5$). This is probably due to their assumptions about the "infall" history of gas inside the galaxy (which implies a very low SF rate at early times, when the VMPSs should form), and about the complete mixing of gas (so that there is no spread in the age-metallicity relation). Instead, we have a large spread (of the order of 1 dex) in the metallicities of stars which form after the very early stages of our simulations; furthermore, we do not need to assume an infall history for the gas, even if it can be argued that our initial conditions are not completely realistic because of the assumption that no star ever formed before the halo density profile reached a NFW shape.

Our simulations indicate that the dearth of observed VMPSs in dSphs is problematic. Apart from the hypothesis that observations are biased in some unidentified way against the detection of VMPSs, possible solutions might involve a pre-enrichment of the gas up to the [Fe/H] ~ -3 level (see e.g. Helmi *et al.* 2006), or a difference between the present and the primordial (metal-free) IMF, such as a suppression of the SF rate of stars below $1\,M_\odot$ in environments of very low metallicity (see e.g. Omukai *et al.* 2005).

References

Battaglia, G., *et al.* 2006, A&A 459, 423

Grebel, E.K., & Gallagher, J.S., 2004 ApJ, 610, L89

Helmi, A., *et al.* 2006, ApJ 651L, 121

Hernquist, L. 1993, ApJS, 86, 389

Koch, A., Grebel, E.K., Wyse, R.F.G., Kleyna, J.T., Wilkinson, M.I., Harbeck, D.R., Gilmore, G.F., & Evans, N.W. 2006, AJ, 131, 895

Lanfranchi, G.A., & Matteucci, F. 2004, MNRAS, 351, 1338

Mac Low, M.-M., & Ferrara, A. 1999, ApJ, 513, 142

Mateo, M.L. 1998, ARA&A, 36, 435

Navarro, J.F., Frenk, C.S., & White, S.D.M. 1997, ApJ, 490, 493

Omukai, K., Tsuribe, T., Schneider, R., & Ferrara, A. 2005, ApJ, 626, 627

Queloz, D., Dubath, P., & Pasquini, L. 1995, A&A, 300, 31

Ripamonti, E., Tolstoy, E., Helmi, A., & Abel, T. 2006, in preparation

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Spergel, D.N., *et al.* 2006, preprint [astro-ph/0603449]

Springel, V., Yoshida, N., & White, S.D.M. 2001, New Astronomy, 6, 51

Springel, V. 2005, MNRAS, 364, 1105

Sutherland, R.S., & Dopita, M.A. 1993, ApJS, 88, 253

Thacker, R.J., & Couchman, H.M.P. 2000, ApJ, 545, 728

Tolstoy, E., *et al.* 2004, ApJ, 617, L119

Woosley, S.E., & Weaver T.A. 1995, ApJS, 101, 181