Metal poor stars in Dwarf Spheroidal galaxies: numerical simulations

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From protostellar cores to disk galaxies
Zuerich, September 20, 2007
Why are they important:
- Large number (>70% of the Local Group members)
- Building blocks of larger systems (?)
- Detailed observations are possible

Properties:
- $10^6$-$10^7 \, M_\text{sun} < M < 10^9 \, M_\text{sun}$
  often have high $M/L$ ratios
- dIrr – dSpH depending on gas content, SFR, rotation
- Wide range of SFHs
  no Simple Stellar Population
- Small systems have quite low metallicities

Dwarf galaxies are the simplest systems where we can test models of chemical and dynamical evolution
The Sculptor dSph

Very “simple” dSph --> good testbed for models!
- Small mass: $3 \times 10^8 \, M_{\text{sun}}$ (previous estimates: $10^7$-$10^8 \, M_{\text{sun}}$)
- Single SF episode $\sim 10$ Gyr ago (lasting a few Gyrs)
- distance $\sim 80$ kpc (tidal interactions with MW?)
- $R_{\text{tidal}} \sim 1.4$ kpc
- very little gas and rotation

Good observations for $\sim 500$ individual stars available from DART (Dwarf Abundances and Radial velocities Team)

Low average metallicity ($[\text{Fe/H}]\sim-1.8$); but no star below $[\text{Fe/H}]=-3$


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Method

Based on GADGET N-body/SPH code; include simple recipes for:

- Gas cooling
- Star Formation based on KS law \( \text{SFR} = C_\star M_{\text{gas}} t_{\text{ff}}^{-1} \)
- Stellar particles representing either a small cluster or single (massive) stars, each with its own
  - mass function (sampling from a Salpeter IMF)
  - chemical composition (from the properties of the gas which formed the stellar particle)
  - “time of birth”
- Dynamical, ionization and chemical feedback from stellar evolution “events” i.e. OB stars, SN, AGB stellar winds

Advantages: detailed!
Drawbacks: lots of parameters
Key parameters

\[ M_{\text{halo}} = 10^8 \, M_{\text{sun}} \quad M_{\text{gas}} \sim 1.5 \times 10^7 \, M_{\text{sun}} \]

\[ m^* \sim 50 \, M_{\text{sun}} \]

Density: NFW \( (r_{200} \sim 1.5 \, \text{kpc}) \); cored profile for gas
Spherical; low rotation; fixed MW potential

SF efficiency: \( C^* = 0.003 - 0.01 - 0.03 - 0.1 \)

SN mechanical energy output: 10-100% of SN energy \( (\sim 10^{51} \, \text{erg}) \)

Metal retention fraction: 10-100%
Can we reproduce the observed metallicity pattern?

$t=500$ Myr  
$M = 10^8 \, M_{\text{sun}}$

Metal retention 10%

Metal retention 100%
Results – Star Formation History

\[ C_* = 0.01 \]

\[ M = 10^8 \, M_{\odot} \]

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Metal retention 100%
Can we reproduce the observed metallicity pattern?

$t=500$ Myr  
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Metal retention 10%

Metal retention 100%
Results - Metallicity distribution (3)

t=1 Gyr
M=10^8 \, M_{\text{sun}}

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Results - Metallicity distribution – low metallicity tail

t=1 Gyr
M=10^8 M_{\text{sun}}
Results - Metallicity gradient

$t=1$ Gyr
$M=10^8 M_{\text{sun}}$

Metal retention 10%  
$C^*_\text{ret} = 0.01$

Metal retention 10%  
$C^*_\text{ret} = 0.02$

Metal retention 30%  
$C^*_\text{ret} = 0.01$

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Conclusions – future work

- Dearth of stars with [Fe/H]<-3 cannot be explained; need pre-enrichment / IMF truncation / variation in SF efficiency.

- High metallicity side requires incomplete metal retention (i.e metal blow out).

- Models show promising properties (e.g. gradients), but need more work!

- Future improvements include:
  - Milky Way tidal field
  - include more chemical species
Results – Star Formation History
Simulation properties

\[ M_{\text{halo}} = 20, 50, 100, 300 \times 10^6 \, M_{\text{sun}} \]

\[ M_{\text{total}} \sim 1.5 \, M_{\text{halo}} \quad M_{\text{gas}} = M_{\text{total}} \frac{\Omega_b}{\Omega_M} \sim 0.17 \, M_{\text{total}} \]

\[ N_{\text{DM}} = 2-4 \times 10^4 \, (m_{\text{DM}} \sim 1500-3000-15000 \, M_{\text{sun}} \text{ - large softening}) \]
\[ N_{\text{SPH}} = 10^5 \, (m_{\text{SPH}} \sim 40-100-200-1000 \, M_{\text{sun}}) \]
\[ m^* \sim 20-50-200-1000 \, M_{\text{sun}} \]

Density profile: NFW (c=5-10, \( r_{200} \sim 1.5-5 \, \text{kpc} \)); NFW or flat for gas
Spherical; low rotation; fixed MW potential

Most relevant numerical parameters:
SF efficiency: \( C^* = 0.003-0.01-0.03-0.1 \)
SN mechanical energy output: 10-100\% of SN energy (\( \sim 10^{51} \, \text{erg} \))
Metal retention fraction: 10-100\%
and many others (e.g. SF density threshold)

Single Z metallicity value (for the moment)
Dwarf Galaxies - Introduction

Most of the galaxies in the Universe are dwarfs 
(>70% of the Local Group members)

Giant (~L*) galaxies still account for most of the light (and mass), but in hierarchical scenarios of galaxy formation dwarf galaxies are the building blocks of larger systems

Surviving dwarf systems are important for testing galaxy formation/evolution scenarios.

Because of the small size and relatively "unevolved” status dwarfs are believed to be excellent laboratories also for models of chemo-dynamical evolution
Dwarf galaxies - properties

Luminosities: $M_V$ from -18 to -8
luminosity correlates with surface brightness

Masses: $<10^{10} \ M_{\odot}$ (minimum $\sim 10^6\text{-}10^7 \ M_{\odot}$)
high M/L ratios, especially in low mass objects

Morphologies:
Dwarf Irregulars (dIrr) and
Blue Compact Dwarfs (BCD):
- gas rich, star forming, supported by rotation

Dwarf Spheroidals (dSph) and
Dwarf Ellipticals (dE):
- gas poor, no star formation, supported by velocity dispersion
Morphology-Density Relation:

Dwarf galaxies - properties

Star formation histories: complex and varied
no “simple stellar populations”; no two dwarfs have the same SFH

Metallicity-Luminosity Relation:

(Grebel 1999)

(Mateo 1998)
Dwarf galaxies – problems/questions for theory

- "Substructure crisis": number of observed dwarfs is much less than predicted
- Morphology-Density relation (and dSph angular momentum)
- Metallicity-Luminosity relation
- Differences in Star Formation Histories
- Abundance patterns not compatible with MW

(Venn et al. 2004)
Proposed Physical Mechanisms

“External mechanisms”:
- Suppression of star formation by reionization
- Reduction of dwarf masses because of tidal stripping
- Ram pressure stripping
- Galaxy harassment (long range interaction with other dwarfs)
- Tidal effects (tidal stirring, formation of tails)

“Internal” feedback, mainly from SNe:
- blowout/blowaway of the smallest dwarfs
- expulsion of metals, especially from small halos
- regulation of Star Formation activity
  (e.g. in a series of bursts)
- enhancement of M/L ratios
- modifications of abundance patterns as a function of halo mass and cosmic time
New data: DART

DART = Dwarf Abundances and Radial velocities Team

With Multi Object Spectrographs such as VLT/FLAMES the size of spectroscopic samples increases from ~5 to ~300 stars/dwarf

Metallicities

Radial Velocities

Tolstoy et al. 2004
Numerical simulations - objectives

We plan to run numerical simulations with particular care for the chemical evolution.

Our first interest is in simulations of galaxies resembling the DART sample, consisting of dSph galaxies of $10^7$-$10^8 \, M_{\odot}$ (including DM and gas), evolving either in isolation or in the (fixed) potential of a “Milky Way” galaxy.

The aim is to check whether it is possible to reproduce the observed dSph present properties (metallicities, abundance patterns, absence of gas, rotation and star formation) but also to investigate their past history (e.g. checking whether the abundance patterns underwent a significant evolution)
Numerical simulations - methods

We are actively modifying the serial and parallel versions of the GADGET N-body/SPH code in order to adapt it to our purposes.

We introduced simple recipes for the gas cooling, for the star formation rate in the gas component (through a Schmidt/Kennicutt law) and for the “chemo-mechanical” feedback from stars (because of SNI ans SNII events, and of stellar winds from AGB stars)

Given the small mass of the simulated systems, we can achieve a very high mass resolution, especially in the stellar component: we plan to use stellar particles in the mass range 10-100 $M_{\text{sun}}$, and to be able to follow the evolution of single massive stars
Numerical simulations – stellar evolution

Stellar particles will differ from each other, as each of them will be characterized by
- a **mass function** (obtained by sampling a given IMF); this is done by “populating” a certain number of “mass classes”; some stellar particles will represent exactly 1 (massive) star.
- a **chemical composition** (obtained from the properties of the original star-forming gas); at the moment we plan to account for H, He, Fe, C, N, O and the complex of all others alpha-elements
- a “time of birth”

The **evolution** of the stars in each “mass class” will be described in detail by “event tables”, which we take from theoretical models of stellar evolutions (and of SN explosions, when relevant)
Numerical simulations – caveats and extensions

Within our scheme, we should be able to achieve an unprecedented level of detail in the simulations of this kind of objects, as we will follow in detail the evolution of all the stars, especially the most massive (which will be modeled as such)

Important caveats which need to be mentioned:

1) as our models will be very detailed, they will have a (too?) large number of “parameters”: for example, the choice of the theoretical stellar evolution models, of the SN yields, of the IMF
2) we are not including photo-ionization feedback; its inclusion could be a significant extension
3) our treatments of star formation and/or of feedback are simplified and possibly uncertain – in particular we are wondering about SN feedback - SUGGESTIONS WELCOME!!
The Sculptor dSph

Very “simple” dSph:
- Small mass: 107-108 Msun
- Single (but long) SF episode ~10 Gyr ago
- distance ~ 80 kpc

good (simple!) testbed for models

Good observations available from
DART (Dwarf Abundances and Radial velocities Team)

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