Simulations of dwarf galaxy formation in the $\Lambda$CDM model: from star formation to dark matter core formation and implications for environmental effects

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Outline

I. Cosmological simulations of field dwarfs: status overview

II. Dark matter core formation via baryonic outflows

III. Near-field cosmology with star formation histories and stellar population of dwarfs

IV. Implications of core formation on the origin of dSphs: from tidal stirring to the “too-big-to-fail” problem
Cosmological simulations of (dwarf) galaxy formation have become sensible only in the last few years. **Before overcooling and angular momentum problem**

Increased numerical resolution (to avoid artifacts) + improvements of sub-grid models of star formation and feedback have been key

Before 2010: resolution $\sim 10^5$ $M_\odot$, first sub-grid models of supernovae feedback capable of maintaining a hot gas phase and slow down SF (eg Stinson et al. 2006)

Without feedback only “red and dead” dwarfs at $z=0$ (purple curve on the left)

...But ubiquitous dense central stellar bulge while field dwarfs bulgeless!

SPH simulation (LCDM model)
Galaxy with $M^* \sim 5 \times 10^9$ $M_\odot$

Governato, Willman, Mayer + 2007
Mayer, Governato & Kaufmann 2008
THE STAR FORMATION DENSITY THRESHOLD

STARS FORM IN MOLECULAR CLOUDS, i.e. in gas at densities in range 10-100 cm$^{-2}$ (depends on metallicity, ambient UV flux)

TILL 2010 IN COSMOLOGICAL SIMULATIONS OF GALAXY FORMATION STARS FORMED BASED ON A SCHMIDT LAW, $d\rho_{\text{star}}/dt \sim \varepsilon \rho_{\text{gas}}^{1.5}$ ($\varepsilon = 0.05-0.1$)

AT GAS DENSITIES $> 0.1$ cm$^{-3}$ (typical density of Warm Neutral Medium in Milky Way!)

(eg Abadi et al. 2003; Governato, Mayer+, 2004; Governato et al. 2007, Mayer+ 2008; Piontek & Steinmetz 2010; Scannapieco et al. 2010; Agertz et al. 2011; Naab et al. 2007)

TO CAPTURE COLD DENSE MOLECULAR PHASE:

FIRST STEP IS TO RESOLVE REGIONS OF CORRESPONDING DENSITY IN SPH $\gtrsim 2$ SPH kernels per Jeans mass $\sim 10^6$ Mo, eg Bate & Burkert 1997

required mass resolution $10^4$ Mo ---+ hi-res zoom-in cosmo sim

REVISIT FORMATION OF GAS-RICH DWARFS ($10^8$-$10^{10}$ Mo)

WITH HIGH SF THRESHOLD PLUS “BLASTWAVE” SUPERNOVAE FEEDBACK (Stinson et al. 2006)


“BLASTWAVE FEEDBACK”: COOLING SHUT-OFF FOR 10-30 Myr NEAR SITES OF SN II EXPLOSIONS (MIMICS ADIABATIC SEDOV-TAYLOR PLUS SNOWPLAUGH PHASE)

with SPH code GASOLINE (Wadsley et al. 2004)

and now with its successor code ChaNGa
“Clustered” Star Formation powers-up supernovae feedback

The K-S relation of each particle:

$$\frac{d\rho_*}{dt} = \frac{\epsilon_{\text{SF}} \rho_{\text{gas}}}{t_{\text{dyn}}} \propto \rho_{\text{gas}}^{1.5} \quad \rho > \rho_{\text{thres}}$$

SN feedback (blast-wave model):

$$E_{\text{SN}} = \epsilon_{SN} \times 10^{51} \text{ erg s}^{-1}$$

$$\frac{N_{\text{new}*}}{m_{\text{gas}}} \propto \sqrt{n_{\text{SF}}}$$

Radius of blastwave $R_e$ set by local density/temperature/energy injection, ~ 30-50 pc in typical conditions

I - Higher supernovae rate per gas mass “unit” as SF density threshold rises, so enhanced effect of feedback where stars can form

II. Stronger local SN feedback further amplified by the fact that ISM becomes more inhomogeneous and clumpy with high SF threshold
Hi-res dwarf galaxy formation: blowing the wind

TWO lcs (DG1 and DG2, different mass assembly history)

V\textsubscript{vir} \sim 50 \text{ km/s}, M\textsubscript{vir} \sim 10^{10} \text{ Mo (LMC-size)}

NSPH \sim 2 \times 10^6 \text{ particles}

Ndm \sim 2 \times 10^6 \text{ particles}

M\textsubscript{sp}h \sim 10^3 \text{ Mo}

gravitational softening = 86 pc

WMAP5 cosmology

- Schmidt-law SF w/high density threshold of 100 atoms/cm\textsuperscript{3}
- Supernovae blastwave feedback model (Stinson et al. 2006)
- Cooling to 300 K owing to metal lines
- Heating/ionization by cosmic UV bg (Haardt & Madau 2006)

Frame = 15 kpc on a side: color-coded gas density of DG1 from z=100 to z=0

Governato, Brook, Mayer et al., Nature, 463, 203, 2010

-- Final baryonic mass fraction within M\textsubscript{vir}
= 0.3 x cosmic baryon fraction

-- Final stellar mass \sim 0.05 cosmic baryon fraction \sim 0.01 M\textsubscript{vir}
(see Oh et al. 2012 for comparison with dwarf galaxies in THINGS survey and other datasets)

-- Final gas/stars ratio in disk \sim 2.5
From unrealistic steep rotation curves at low SF threshold to realistic slowly rising curves at high SF threshold.

Inner dark matter profile flattened to $r^{-0.6}$ by expansion following impulsive supernovae outflows producing potential fluctuations (Pontzen+Governato 2012 - see also Navarro, Frenk & Eke 1996; Read & Gilmore 2005; Maschenko et al. 2008)

$B/D = 0.04 \ h_i = 0.9 \ \mu_e = 21.2 \ \mu_e = 22.9 \ r_e = 0.30 \ n = 0.8$

Sersic fit $n = 1.3$
star formation CLUSTERED rather than DISTRIBUTED, mainly in high density peaks with scales ~ GMCs --> stronger heating produces stronger gas outflows compared to runs with “standard” low SF density threshold (more gas heated at T > T_{vir} at z ~ 1-3, outflows at ~ 100km/s --> final baryonic fraction ~ 1/3 of cosmic)

Outflows correlated with peaks of SFR, often correlated with mergers (hence occur preferentially at z > 1) – see Brook et al. (2010) for details

Outflows mostly from the center of galaxy where star forming density peaks higher --> selective removal of lowest angular momentum material by winds
Confirms earlier prediction of Binney, Gerhard & Silk (2001) --> suppress bulge formation and produce exponential profile
Formation of gas-rich field dwarfs in cosmological hydro simulations across a spectrum of mass scales ($10^8 - 10^{10}$ Mvir)


- Resolution: DM $1.6 \times 10^4$ $M_{\text{sun}}$; Gas $3300$ $M_{\text{sun}}$; Star $1000$ $M_{\text{sun}}$; force resolution 86 pc
- “Field” dwarfs: nearest massive halo $> 3$ Mpc away
- Include metallicity-dependent cooling using CLOUDY, ionization equilibrium (but for H and He rates for non-equilibrium ionization), high SF density threshold of $100$ cm$^{-3}$, blastwave feedback (Stinson et al. 2006), new UV background from stars and QSOs (Haardt & Madau 2013)
- 4 Luminous galaxies with stellar mass ranges from $10^5$ to $10^8$ $M_{\text{sun}}$, and halo mass ranges from $1.8 \times 10^9$ to $3.6 \times 10^{10}$ $M_{\text{sun}}$
- 3 DARK DWARFS where gas accretion and SF are suppressed by the UVB (see also Kuhlen+13)
Stellar Mass of the Group of Seven  (Shen et al. 2013)

- 4 luminous dwarfs, with $M^*$ from $9.6 \times 10^4 M_{\odot}$ to $1.1 \times 10^8 M_{\odot}$
- Bashful & Doc: $M^*/M_h$ on abundance matching curve of Behroozi + (2013)
- Dopey & Grumpy: very small stellar fraction
- Dopey is very H I rich: $M_{\text{HI}} \sim 20 M^*$
Cold Gas Fractions

- Low stellar mass dwarfs in the ALFALFA sample are on average more HI gas rich (however here some gas is stripped due to dwarf-dwarf interactions).

- SFR at $z=0$ in Bashful and Doc is low (0.01-0.02 $M_\odot/\text{yr}$) despite Bashful and Doc retain significant fraction of baryons $\rightarrow$ feedback regulates SF by allowing only a small fraction of the gas to be in a cold star forming phase.
Mass(Luminosity)-Metallicity Relationship: an important constraint on the feedback model

- Oxygen abundances in the ISM for the 4 dwarfs lie on the mass metallicity relationship and in good agreement with observations of LG dwarfs (Woo+2006), larger samples of nearby dwarf irregulars (Lee+2006), low luminosity galaxies in the local volume (Berg+2012)
- Dopey and Grumpy are extremely metal poor galaxies, but still on the MZR. Similar to a very recently discovered H I-rich dwarf, Leo P (Giovanelli+2013). They simply had too little SF to enrich the ISM significantly
- Stellar metallicity - V band luminosity relation consistent with Milky Way’s dSphs from Kirby+(2011)
Bursty Star formation history

Bursty SF causes strong baryonic mass fluctuations near center

SF burst followed by decrease in $M_b$ and $M_{gas}$

Rapid change of central potential, transfer energy into DM impulsively and generates long lasting-core cores (Pontzen & Governato 2012, Teyssier+ 2013)

SF history of IC1613 as derived in Skillman et al. 2013

Comparison with Bashful, Doc (upper red curves) and Dopey, Grumpy (lower red curves)

Data from LCID project - HST program to obtain hi-res CMD diagrams for nearby dwarfs (see M. Monelli later at this conference).
SF is not very efficient TODAY but DM profiles of Bashful and Doc have cores because SF more efficient early on. Grumpy has a smaller core (radii normalized) despite SF relatively late. Dopey has no core, not surprisingly is the only one with final $M^* < 10^5$ Mo (lowest SF efficiency)
Possible contradiction:

To form cores we need strong bursts of SF. Early on is more efficient since halo mass/potential well to “displace” is lower because progenitor has lower mass.

But isn’t high SF rate early on at odds with the conventional notion that gas-rich dwarfs have “young” stellar populations and are still star forming today?
Not really... Majority of nearby dwarfs appears to have had higher SF efficiency (SFE) in the past than today (exceptions Leo A (Cole et al. 2006) and Aquarius (Cole et al. 2014))

SFE = mean SF history / mean M(t) of halos in corresponding mass range

Implication: cases with very low SFE (eg Leo A) less likely to have cores.

But perhaps most important indicator is mean value of SF rate, hence final M*/Mhalo

Madau, Weisz & Conroy 2014

Consistent with Rapid early stellar mass assembly

--- feedback ---

DM core formation via baryonic outflows
Models now reaching maturity.
Details of sub-grid recipes begin to matter for eg amplitude and duration of SF bursts with implications for:
(a) comparison with observed SF histories, metallicities etc..
(b) predictions for core formation.

....a theorist’s nightmare?

Sensitivity on sub-grid SF parameters (self-shielding, extra feedback mode)

Governato et al. 2014

High frequency burst pattern closer to observed SF history in gas-rich dwarfs?
The next level of analysis
Mock CMD diagrams of simulated dwarfs against observed CMD diagrams for LG dwarfs
We consider also alternative Lambda- Warm Dark Matter (LWDM) cosmology (2 keV particle, mass scale of truncated power spectrum in simulation)

Main points:
- the two CDM dwarfs (differ for sub-grid feedback parameters) are qualitatively consistent with LGS3 (Hidalgo et al. 2011).
- their WDM dwarf analog is deficient of old stars relative to LGS3

Of course need to this for more objects, but remarkable is sensitivity of star formation history to structure formation model

Governato et al. 2014
WDM vs. CDM: once again key diagnostic is the SF efficiency

SF delayed more in WDM model
Here it is equivalent to lower SF efficiency at high z since halo mass is the same in three cases

Lower average SF rates explain lower metallicity and dearth of old stars in CMD diagram of WDM dwarf (see previous slide)

Top: Abundance ratios for different versions of the same dwarf simulation
Vertical lines show mean metallicity for nearby dwarfs with similar stellar mass to simulated dwarfs (Kirby et al. 2007)
So far we focused on field dwarfs
Now some implications of dark matter “core” formation on
dwarf galaxy satellites

Via Lactea II: hi-res cosmological simulation of
Milky Way-sized dark matter halo
(Diemand et al. 2007)
Tidal stirring = repeated tidal shocks at pericenters with primary galaxy (Weinberg 1994; Gnedin, Hernquist & Ostriker 1999) turn rotationally supported late-type dwarf ($v/\sigma >> 1$) into faint spheroidals with low $v/\sigma < 0.5$ (Mayer et al. 2001, 2002; 2007; Klimentowski et al. 2008, 2009)

NATURAL SCENARIO FOR FORMATION OF dSPHs/dEs IN HIERARCHICAL UNIVERSE

EXAMPLE below: N-BODY DISK+HALO SATELLITE MODEL PLACED ON 5:1 COSMOLOGICAL ORBIT (apo = 150 kpc, peri = 30 kpc), satellite with initial $M_{\text{vir}} \sim 10^9 M_\odot$

• Tidal heating/stripping of stars + bar/buckling instabilities.

![Diagram of Tidal stirring process](image-url)
Effect of core formation on tidal stirring of dwarf satellites

Models: $V_c \sim 20-60$ km/s, with stellar disk and NFW or “cored” ($\gamma = -0.6$) halo $M^*/M_{\text{halo}}$ satisfy abundance matching constraints for stellar vs. halo mass.

Resolution 30 pc and 300 $M_\odot$

ErisDark zoom-in cosmological simulation of Milky Way-sized halo + hi-res N-body models of dwarfs to replace subhalos at infall (Tomozeiu, Mayer et al., in prep. - technique previously used by Mastropietro et al. 2005 for galaxies in clusters)
Kazantzidis, Lokas & Mayer (2013)
Predecessor work using non-cosmological tidal interaction simulations using dwarf N-Body models orbit inside primary galaxy (live disk+bulge+halo model of the Milky Way)

Initial dwarf models (stellar disk+halo, no gas) with virial mass $10^9$ (Vmax ~ 20 kms) or $2 \times 10^{10}$ Mo (Vmax ~ 50 km/s), DM slope -0.2, -0.6 or -1 (NFW).

Note: Vmax ~ 50 km/s roughly corresponds to massive satellites of MW-halos at infall time giving rise “too big-to fail problem” in the Aquarius simulations at z=0 (Boylan-Kolchin et al. 2012) --> see next slides
"Cores" enhance transformation dIrr—> dSph

Kazantzidis, Lokas & Mayer 2013

Due to lower internal binding energy of stars they respond more impulsively to tidal shocks with a shallow halo profile ($\gamma < 1$) than with a cuspy halo (see also Penarrubia et al. 2010)

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Transformation faster and more effective with shallow DM profiles (significantly lower final vrot/sigma and higher c/a for any initial condition tried), in some cases even complete disruption

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Transformation into dSphs happens even for nearly circular orbits as well as orbits with large pericenters (Leo I easier to accommodate, Cetus/Tucana still predicted to have $v_{\text{rot}}/\sigma \sim 1$ unless orbit nearly radial ($apo/peri \sim 10:1$).

![Graph showing transformation over time with different halo profiles](image)

Time [0-8 Gyr]

black - NFW ($\gamma = -1$)
red ($\gamma = -0.6$)
blue ($\gamma = -0.2$, tidally destroyed)
Effect on the shape: shown is projected isodensity contours for projection that yields the HIGHEST apparent ellipticity.
Impact on “too-big-to-fail problem”: proof-of-concept
Mayer, Kazantzidis, Tomozeiu et al. in prep.

Tidal evolution of most massive satellites with initial $V_{\text{max}} \sim 50$ km/s
In cosmological simulations satellites with $V_{\text{max}} \sim 50$ km/s \emph{at infall} are too dense and massive to host dSph satellites of the Milky Way, (“massive failures” - eg Boylan-Kolchin et al. 2012)
Infall on different orbits (peri 12-50 kpc, apo 125-250 kpc, consistent with VL2), MW halo with $M \sim 10^{12}$ Mo (see Lokas et al. 2011), 4 representative cases shown here.

Results after $\sim 9$ Gyr
(corresponds to infall at $z \sim 1$, average infall time of $z=0$ satellites in cosmological sims).

Solid lines: $\gamma = - 1$ models dashed lines: $\gamma = - 0.6$ models, data points for MW dSphs (Boylan-Kolchin et al. 2012; Wolf et al. 2010)

Surviving satellites have a lower circular velocity, by a factor of 1.5-2, in shallow vs. cuspy halos ----- with $\gamma = - 0.6$ no “massive failures” expected (Some satellites are completely destroyed)
Conclusions

I. Cosmological simulations of dwarf galaxy formation are finally yielding qualitative sensible results owing to combination of increased resolution in the ISM component and improved models of SN + stellar feedback.  
No more overcooling and angular momentum problem, instead bulgeless exponential disks

II. For some fundamental observables, such as stellar-to-halo mass ratio, gas content, present-day SF rate and mean metallicity models match observations quantitatively

III. An unexpected prediction of the new simulations is the formation of DM cores, which seems unavoidable if powerful baryonic outflows at early times are the reason why dwarfs end up faint, bulgeless and dark matter dominated. Core formation also aids tidal stirring of dIrrs into dSphs and possibly solves “too-big-to-fail” problem.

IV. The SF histories in the models are not yet quantitatively robust and are sensitive to the details of the sub-grid star formation and feedback implementation. However a general robust prediction is that dwarfs with stellar mass > 10^6 M⊙ had much higher SF efficiencies in the past than today, at variance with massive galaxies. This conclusion is supported by HST-derived SF histories of nearby/LG dwarfs

V. Mock CMD diagrams and detailed elemental abundances for gas and stars will take the comparison with observations to new quantitative level, perhaps breaking degeneracies such as those between feedback parametrization and DM model (eg CDM vs. WDM)
Core formation: DM model vs. feedback mode
Suggests degeneracy

Solid lines: CDM and WDM cases with same SF efficiency, dash-dotted line is WDM case with higher SF efficiency
Gas and stellar kinematics of the 4 luminous dwarfs
ERIS: The Basics

☀ Eris is a product of **GASOLINE.**
☀ Follows the formation of a light Milky Way galaxy of mass
  \[ M_{\text{vir}} = 8 \times 10^{11} \, M_{\odot} \]
☀ Selected to have a quiet merger history. No mergers larger than 1:10 after \( z = 3 \).
☀ High mass and spatial resolution: 18.6 million particles within the virial radius. \( \varepsilon_G = 120 \, \text{pc} \)

☀ Physics: metal dependent gas cooling (only for \( T < \sim 10^4 \, \text{K} \),) UVB heating, SN Type Ia and Type II (blastwave) thermal feedback.
☀ High SF gas density threshold: \( n_{\text{SF}} = 5 \, \text{atoms cm}^{-3} \) + control run ErisLT with low SF threshold (\( n_{\text{SF}} = 0.1 \, \text{atoms cm}^{-3} \)) and other runs with lower resolution or lower SF efficiency
☀ Expensive: 9 months per single run at NASA Pleiades and “Rosa” Cray at Swiss National Supercomputing Center using up to 1024 cores.

What is missing: High Temperature metal cooling, \( \text{H}_2 \) cooling, metal and thermal diffusion diffusion, radiative feedback from stars, AGN feedback.....(see Eris2 runs later)
Adiabatic
\[ E_f = E_i \]
Gnedin & Zhao 2002

Sudden, then adiabatic
\[ \frac{\langle E_f \rangle}{E_i} = \frac{1}{2} \left( \frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1} \right) \]

Generalization:
\[ \Delta E = \Delta E(\Phi(t), E_0, j) \]
Pontzen & Governato 2012
Pontzen & Governato 2012