The Tempest Simulations
Milky Way-type Galaxies, their Environments and Progenitors

John Wise
Brian O'Shea (PI, MSU)
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Background & Motivation

Connection between Local and Distant Galaxies

- Galaxies form hierarchically through mergers
- Most galaxies seen at the edge of the observable universe will merge over \(~13\) billion years to form the present-day galaxy population
- As galaxies grow, their stars chemically enrich the surrounding environment
  - Inside – Interstellar medium (ISM)
  - Around – Circumgalactic medium (CGM)
  - Distant – Intergalactic medium (IGM)
Motivation
Chemical Enrichment – Galactic archaeology

• All stars and gas exhibit some level (1/1000\textsuperscript{th} of solar) of chemical enrichment above lithium (H, He, Li produced in the Big Bang)

• Suggests an early enrichment period from the first generations of stars and galaxies

Can simulations be used to bridge the gap between the most distant galaxies to local ones?

Credit: A. Frebel (MIT)
Motivation
Chemical Enrichment – Galactic archaeology

• All stars and gas exhibit some level (1/1000th of solar) of chemical enrichment above lithium (H, He, Li produced in the Big Bang)

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Launching October 2018
Motivation
The CGM: Dark but rich

- Observations suggest the CGM is more baryon rich than expected

- Half of the gas is contained in this tenuous state

(Tumlinson et al. 2011; Werk et al. 2014; Peeples et al. 2014)

- This medium plays a critical role in regulating star formation and galactic feedback

(Voit et al. 2015)
Motivation
Comparing Observations to Theory

This medium plays a critical role in regulating star formation and galactic feedback (Voit et al. 2015)

Can simulations be used to bridge the gap between observations and theory to better understand the CGM and galaxy formation?
Enzo
An open-source AMR code for astrophysics

• **Physics**
  • MHD, Non-equilibrium chemistry, radiation transport, cosmic ray transport, heat conduction, star/black hole formation & feedback

• **Refinement**
  • DM / Baryon overdensity
  • Local Jeans length
  • Metallicity
  • plus 12 other possible criteria
  • Stable to 41 levels ($10^{14}$ dynamical range)

(The Enzo Collaboration 2014)
Controlled experiment VS Cosmological context

\[ T = 0 \text{ Myr} \]
Controlled experiment VS Cosmological context

$T = 0 \text{ Myr}$
Cosmological galaxy simulations
Cosmological Simulations
Finding the Milky Way-type galaxies

Halo density — 100 Mpc/h box
2048$^3$ particles, $10^7$ halos at $z = 0$

Halo mass function
~8000 halos with $0.5–3 \times 10^{12}$ $M_{\odot}$
Cosmological Simulations
Finding the Milky Way-type galaxies

Halo density — 100 Mpc/h box
2048³ particles, 10⁷ halos at z = 0

Halo mass function
~8000 halos with 0.5–3 x 10¹² M⊙
Cosmological Simulations
Finding the Milky Way-type galaxies

Halo mass function
~8000 halos with $0.5 - 3 \times 10^{12} M_\odot$

Growth histories
~200 halos without major mergers at $z < 2$
Cosmological Simulations
Finding the Milky Way-type galaxies

Growth histories
~200 halos without major mergers at $z < 2$

Environment
30 total halos in mean and $\pm 1\sigma$ env.
Cosmological Simulations
Finding the Milky Way-type galaxies

• Simulate the assembly of these 30 galaxies with “zoom-in” simulations (particle mass = 1.6 x 10^6 M⊙)

• Star formation and feedback prescriptions motivated from the isolated galaxy simulations

• A subset of halos are simulated at higher resolution (down to 5 M⊙), focusing on the first stars and galaxies and reionization.
Solar Superstorms

visualization excerpt
"The Formation of First Stars and Galaxies"

a fulldome production by
NCSA, University of Illinois
Thomas Lucas Productions & Spitz Creative Media

narrated by:
Benedict Cumberbatch
Early stages of reionization from the first stars and galaxies (1\,cMpc$^3$; $z = 25-9$)

Solar Superstorms

visualization excerpt

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Benedict Cumberbatch

Credit: D. Cox+ (AVL)
Cosmological Simulations
First stars and galaxies: Progenitors of the Milky Way (z = 9; 550 Myr)

Actively star forming
($M_{\text{halo}} = 3.2 \times 10^8 \, M_{\odot}$)

Quiescent galaxy
($M_{\text{halo}} = 1.4 \times 10^8 \, M_{\odot}$)

Blue = neutral; red = ionized; green = radiation
Cosmological Simulations
First stars and galaxies: Progenitors of the Milky Way (z = 9; 550 Myr)

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Blue = neutral; red = ionized; green = radiation
Isolated galaxy simulations
Isolated Galaxy Simulations
What can we do with these?

- **We get to choose:**
  - galaxy mass
  - galaxy metallicity
  - halo mass
  - halo temperature/entropy profile
  - star formation prescription
  - stellar feedback model

- **Exploring these quantities:**
  - CGM states vs star formation history
  - Condensation / precipitation (CGM → ISM)
  - Accurate and resolution-independent star formation prescriptions
  - Dependence on galaxy and halo mass

- **We also have a lot of control over resolution!**
Isolated Galaxy Simulations
Star Formation Rates

Quiescent: Gas normal
Isolated Galaxy Simulations

Star Formation Rates

Starburst: Gas rich

Quiescent: Gas normal
Isolated Galaxy Simulations
Differences between Starburst and Quiescent Galaxies – Temperature

400 pc disk resolution; 1600 pc CGM resolution
Isolated Galaxy Simulations
Differences between Starburst and Quiescent Galaxies – Temperature

Starburst

Quiescent

400 pc disk resolution; 1600 pc CGM resolution
Isolated Galaxy Simulations
Differences between Starburst and Quiescent Galaxies – Metallicity

Starburst

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Cosmological Simulations
Resolution Dependence – Forcing CGM refinement

Standard Refinement

Forced Refinement
Cosmological Simulations
Resolution Dependence – Forcing CGM refinement
Cosmological Simulations
Resolution Dependence – Forcing CGM refinement

Standard Refinement

Forced Refinement

\( t = 5.9 \text{ Gyr} \)
\( z = 1.00 \)

10 kpc
Mock Observations
Comparing simulations to observations

Trident http://trident-project.org
Documentation: http://trident.readthedocs.io

Hummels, Smith, & Silvia 2016
Mock Observations
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(for "starburst" simulation)
Mock Observations
Comparing simulations to observations

Composite spectrum, Milky Way foreground, instrument LSF & Noise

Hummels, Smith, & Silvia 2016
Summary

• Suite of isolated galaxy simulations → Mock observations → Compare with observations → Apply subgrid models to cosmological simulations

• Isolated galaxy sims: Realistic entropy CGM profiles are essential to reproduce observations

• Connection between distant and local galaxies → More constraints (direct & indirect) on early galaxy evolution

• Looking forward to Enzo-P! (J. Bordner, SDSC)