Satellite Accretion in Chemodynamical Simulations of Milky Way-like Galaxies

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with Brad Gibson, Stéphanie Courty, Leo Michel-Dansac, Chris Brook, Greg Stinson, Romain Teyssier, Francesco Calura, Daisuke Kawata, Tomás Ruiz-Lara, Isa Perez, Ivan Minchev, Patricia Sánchez-Blázquez, Estrella Florido.

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The plan...

✧ Introduction to galaxy assembly
✧ Building a galaxy in a (super)computer
✧ Disk profile breaks and the age distribution
✧ Satellite accretion
✧ Chemical evolution: relics of galaxy assembly
Basic galaxy formation - inside out

hierarchical collapse
Basic galaxy formation - inside out

hierarchical collapse

rotation speeds up, continued gas accretion
Basic galaxy formation - inside out

hierarchical collapse

rotation speeds up, continued gas accretion & star formation
Basic galaxy formation - inside out

- Hierarchical collapse
  - Rotation speeds up, continued gas accretion & star formation

- Spiral shape appears due to rotation
  - More gas accretion & star formation
Basic galaxy formation - inside out

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**BUT...**
Cosmological galaxy formation
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Minor mergers are several times more frequent and can contribute to the build of a galaxy’s mass (Lotz et al., 2011; Kaviraj, 2014).
Mergers/accretion

Le Fevre et al. (2000)
Cosmological context...

• Dark matter: gravitational potential

\[ \frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i \]
\[ \frac{d\mathbf{v}_i}{dt} = -\nabla \Phi \]
\[ \nabla^2 \Phi = 4\pi G \rho \]
Cosmological context...

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- **Gas: gravity + hydrodynamics**

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  \frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \mathbf{u}) = 0 \\
  \rho_g \frac{\partial \mathbf{u}}{\partial t} + \rho_g \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p - \rho_g \nabla \Phi \\
  \frac{\partial \epsilon}{\partial t} + \mathbf{u} \cdot \nabla \epsilon + \frac{p}{\rho} \nabla \cdot \mathbf{u} = \frac{\Gamma - \Lambda}{\rho} \\
  p = \rho \varepsilon (\gamma - 1)
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*Ferland et al. (1998)*

*Haardt & Madau (1996)*

*Rosen & Bregman (1995)*

atomic cooling, metal line cooling, UV background
Cosmological context... ...with ‘small’ scale physics

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- Adaptive grid allows large and small scales together

atomic cooling, metal line cooling, UV background
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• Adaptive grid allows large and small scales together
• Sub-grid physics includes star formation, supernovae, chemical enrichment
Cosmological assembly
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$z = 4.8$
A sample of 19 simulated galaxies in either a ‘field’ or ‘loose group’ environment

Loose groups are analogous to the Local Group - not true galaxy groups but looser associations of two-three main halos with masses comparable to MW and Andromeda

Field galaxies have no significant nearby halos

 Few et al. 2012
Galaxies are disk dominated!

“The best disks realised with a conventional energy feedback scheme” - no appeals to radiation pressure, delayed cooling or extreme initial mass functions

Main findings: the difference in properties of loose group galaxies and field galaxies is so subtle that the individual assembly history dominates - no big surprise!

Metallicity gradients fit observed trends (Garnett et al., 1997; Van Zee et al., 1998; Prantzos & Boissier, 2000)

We also see inside-out galaxy formation...

Pilkington, Few et al. 2012

Scannapieco et al. 2012
Inside-out formation in RaDES

Pilkington, Few et al. (2012)
Metallicity Gradients in Disks:
Do galaxies form inside-out?

Yes, they do!

- The steepness in the star formation rate drives the changing metallicity gradient over time
- Inside-out formation is thus well established in the simulations
Surface brightness profiles

Do you see breaks in surface brightness profiles in simulations?

Yes, they do, those things are annoying!

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Bakos et al. (2008)

- SUNRISE (Jonsson, 2006) combines Starburst99 (Leitherer et al. 1999) and ray tracing
- We produce model ‘observations’ of the RaDES galaxies
Disk breaks

The majority of cosmological simulation get exclusively type-II disks, but RaDES has the full range.

**Type-I**
- Luke

**Type-II**
- Oceanus
- Apollo
- Castor
- Artemis
- Tethys

**Type-III**
- Krios
- Eos
- Pollux
Age distribution

• “U-shaped” age distributions are observed features
• Ferguson & Johnson, 2001 (M31); Davidge, 2003 (NGC 2403, M33); Galleti et al., 2004 (M33) all find disk edges that are old and have high metallicities

• Roskar et al. (2008) find U-shaped age distributions in “isolated halo” simulations. Attributed to spiral arm induced radial migration, i.e. An inner disk forms from regular star formation with an outer disk being made of migrated stars.

• Sanchez-Blazquez et al. (2009) find U-shaped age distributions in cosmological simulations finding the same “migrated outer disk” but note some of the outer disk stars form “in-situ”

• It has been suggested that in a CDM universe where inside-out formation prevails, these U-shapes are not expected (Ferguson & Johnson, 2001)
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- The break is the edge of recent star formation
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• The break is the edge of recent star formation
• What about those steps at particular times?
Age distribution

Selene

Sigma-age, $R_{xy}>3.0\text{Kpc}$, $R_{xy}<10.0\text{Kpc}$, $|r_z|<3.0\text{Kpc}$
Merger tree
A better kind of merger analysis
A better kind of merger analysis
Interactions and the age-metallicity relation

![Graph showing interactions and age-metallicity relation]

Sigma-age, $R_{xy} > 3.0 \text{ Kpc}$, $R_{xy} < 10.0 \text{ Kpc}$, $|r| < 3.0 \text{ Kpc}$
• Incorporated chemical evolution model into RAMSES
• Stellar populations now produce SNIa and AGB ejecta in addition to SNII
• Elements produced on differing timescales give rise to observed chemical evolution
• Used to probe uncertainties in the models

Bensby, Feltzing & Oey (2013)
Chemical evolution trends are followed

Alpha-rich, Fe poor regions is older and kinematically hotter

There is substructure in this plot...

Haywood et al. 2013
a, b, c, d are all peaks in star formation (minor mergers) which create abundance 'strata' (increasingly older and hotter)
Feature e. is the satellite. It will one day merge but its chemical abundance signature will remain the same.

\textbf{a, b, c, d} are all peaks in star formation (minor mergers) which create abundance ‘strata’ (increasingly older and hotter).
Decomposing abundance space

Decompose the abundance space into segments and trace those stars back to where they were born
Decomposing abundance space

Many of these weren’t born in the galaxy

Stars born in satellites at later stages

Feature e. stars actual come from two accreted satellites

These are in-situ disk stars formed at different times

Very low mass satellites?
Conclusions

• Galaxies do form inside-out but a short period of extended star formation coupled with migration results in an old disk outside the young star-forming disk
• The edge of the young star forming disk results in a type-II break
• Small mergers can dilute metals (temporarily), increase SFR, excite kinematics and leave chemical imprint of accreted stars
• Star formed prior to mergers have well-mixed AMR in different radial bins, those formed after are more distinct
• The AMR can invert at greater radii: metal enrichments + migration overtakes inside-out formation
• We have a range of break types to look at and only really understand type-II right now
• Ruiz-Lara, Few, Gibson et al. (in prep)
Thank you for your time, questions? comments? statements?

“true collaboration”