Formation and evolution of the Galaxy in a cosmological context

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Outline

• How do galaxies form in ΛCDM?

• What does the paradigm predict in detail?

• Does the Milky Way fit in this paradigm?

• What is Gaia’s role in unraveling the formation of the Galaxy?
The cosmological framework: $\Lambda$CDM

The paradigm basic ingredients:

• primordial density fluctuations produced during inflation
  - small objects form first

• 74% of the energy budget in a cosmological constant
• 22% in cold dark-matter (CDM)
• 4% in atoms

• fluctuations grow under the action of gravity

The Emergence of the Cosmic Initial Conditions

• Temperature and polarisation power spectra for WMAP and interferometers

• Best $\Lambda$CDM model (1year)
  $\tau_0 = 13.7 \pm 0.2$ Gyr
  $h = 0.71 \pm 0.03$  $\sigma_8 = 0.84 \pm 0.04$
  $\Omega_t = 1.02 \pm 0.02$  $\Omega_m = 0.27 \pm 0.04$
  $\Omega_b = 0.044 \pm 0.004$
  $\tau_e = 0.17 \pm 0.07$

• Parameters in excellent agreement with other astronomical data

White (2004)
Dark-matter N-body simulations of structure formation

- Start from small density fluctuations with CDM power spectrum
- Evolve collisionless DM particles under gravity only
  - Important since dark matter is dominant mass component of galaxies → dictates much of the evolution

Movie at

http://www-theorie.physik.unizh.ch/~moore/movies/bw.mpg
Modelling galaxy formation

Cosmological model
$(\Omega, \Lambda, h)$ dark matter

Primordial fluctuations
$\delta \rho / \rho(M, t)$

Evolution of dark matter halos

Dynamics of cooling gas

Star formation, feedback, evolution of stellar pops

Galaxy mergers

Formation and evolution of galaxies

N-body simulations

Gasdynamic simulations

Semi-analytic modelling

Lacey (2006)
Galaxy formation is complex

- **Gravity**: internal dynamics + tidal field + mergers
  - from Mpc to kpc

- **Gas physics**: cooling + heating + chemical enrichment
  - from 100's kpc to < 1 kpc

- **Star formation**:
  - occurs at level of molecular clouds (< 1 pc);
  - is driven partly by larger-scale environment: spiral arms, mergers (kpc scales)

- **Feedback**:
  - stars return energy + heavy elements to ISM if they explode as SN
  - also through winds
  - black holes also affect their surroundings

Simulations of the formation of a disk galaxy

http://lahmu.phyast.pitt.edu/~gardner/Galaxy/index.html
The formation of a disk galaxy
[from J. Sommer-Larsen]

• Gas cools in halos / filamentary structure is visible also in gas

• At high-z: strong starbursts drive gas out of proto-galactic mini-haloes.

• $z \sim 3$: Initial disk starts to form, mainly grows by cool-out of hot halo gas

• The disk is harassed by discrete accretion events,
  • cold gas from accreted systems is mixed into disk gas
  • accreted stars generally end up in the halo.

• Two fairly large sub-systems are responsible for the formation of the thick disk at $z \sim 1$
  • puffing up the already present thin disk.

• At $z \sim 0.1$ the spinning disk is at the center of a slowly rotating cooling flow, feeding the disk with mass and angular momentum.

Distribution of metals:

• At the center of the galaxy $<[O/Fe]> \sim 0$,
  • most of the star-formation has taken place already, so that there has been time for the SNIa’s to recycle the Iron.

• In the outer disk $<[O/Fe]>$ is larger than zero.
  • the star-formation history is much more flat: star-formation is ongoing and not all the Iron from to come SNIa’s has been recycled
The formation of a disk galaxy

Formation epoch of the various galactic components

• Halo stars are either very old (first generations) or typically originate from tidally stripped/disrupted satellites.

• Bulge stars have $z_{\text{form}} \sim 2-3$

• Disk stars have $z_{\text{form}} \ll 2-3$, the disk forming inside-out in this case.

Overview of our Galaxy

dark halo

stellar halo

thick disk

thin disk

bulge

Freeman 2007
The thin disk is metal-rich and covers a wide age range. The other stellar components are all relatively old (note similarity of [Fe/H] range for thick disk and globular clusters).

![Graph showing [Fe/H] - age relation for components of the Galaxy](Freeman 2007)

The MW and the hierarchical paradigm

Main characteristic of model: mergers

- Can we find the signatures?
  - Substructure and the search for tidal streams

- How did the building blocks look like?
  - What is the link to today's nearby small galaxies (dSph)?
Where to look for substructure?

- Stellar halo
  - Most metal-poor and ancient stars in the MW
  - It can form from the superposition of disrupted satellites

- Thick disk
  - Old and metal-weak stars
  - Disks are fragile: easily heated up by minor mergers

Substructures in the (outer) halo

- Shortly after infall ($t/t_{\text{dyn}} \sim 1$)
- Outer Galaxy always in this regime
- Accreted stars are visible as tidal tails
- Tidal tails can be easily found by mapping the positions of halo stars in the sky.
Wide-field surveys

SDSS, 2MASS, ... yielding spectacular results:
- Substructure appears to be common

Substructure in the halo

SDSS, 2MASS, ... yielding spectacular results:
- Substructure appears to be common
- Kinematics needed to understand nature of the overdensities
- Properties seem to suggest large-ish progenitors
Substructure in the halo

Bell et al (2007) quantify the amount of substructure using RMS measure

\[ \sigma \sim \text{Data - Smooth halo}^2 \]

Level of RMS \( \sim 30-40\% \)

Compared to SA models MW stellar halo MW halo is typical

Stellar halos from SA models by Bullock & Johnston (2005)

Overall good agreement
These tidal streams in outer halo are interesting, but the ancient streams from small objects accreted long ago into the halo could be even more interesting.

(most of the mass is in the inner halo; most of the action happened here; the link to the high-z Universe...)

Inner halo streams are too dispersed in configuration space - may see them in phase space, eg $(R_G, V_G)$, or in integral space ie the space of integrals of the motion for stellar orbits, like energy and angular momentum $(E, L_z)$

Inner halo streams:
- spatial coherence is rapidly lost
- kinematic structures become prominent
Kinematics of nearby metal-poor stars: see halo substructure appearing as two streams in $v_z$, detached in velocity space from the rest of the sample - mean metallicity $\sim -1.5$. This cannot be seen in space, only in velocity.

Helmi 99

**Accretion in integral space ($E, L_z$)**

Input - different colors represent different satellites

Output after 12 Gyr - stars within 6 kpc of the sun - convolved with GAIA errors

Helmi & de Zeeuw
Need for GAIA

• 6D phase-space coordinates of the stars in the halo (to construct IoM space)
• large samples of halo stars (to have good statistics)
• accurate velocities (to resolve the individual lumps)

• how many objects?
• when did they merge?
• what were their properties? star and chemical evolution history...

Thick disks

Possible formation scenario is heating by minor merger of pre-existent disk (e.g. Quinn et al 1986)

Villalobos & Helmi (2007)
Revisiting thick disk formation

- What happens to disk and satellite?
- Is it possible to distinguish heated disk from satellite?
- Is this formation scenario correct?

Simulations initial conditions:
- satellites on prograde and retrograde orbits, i = 0, 15, 30, 60 deg
- 10 - 20% of mass of the host; stars + dark matter (all live; disky and E-like)
- orbits consistent with subhalos in LCDM sims (Benson 2005)

Thick disks

- Prograde (red) and retrograde (blue) induce significant tilting and heating
- Disk is flared
- Asymmetric drift
  - consistent with observations
- Higher inclination
  - larger scale-height & $\sigma_z$
- Lower inclination
  - larger scale-length (always increases) & $\sigma_R$
Thick disks

- $\sigma_R/\sigma_z$ strong function of inclination
  - could determine orbital IC

Thick disk: can we find the debris?

- No spatial correlations (after few Gyr)

Volume around the Sun:

- Velocity distribution distinct from disk
- Characteristic “banana” shape
- Well-mixed z-velocities
- Streams in $V_\phi - V_R$
Substructure in phase-space

• Energy and orbits computed for approximate potential
  • Results not sensitive to parameters: substructure is robust

• Easy to disentangle heated disk from accreted satellite:
  • for a given energy, accreted stars are on more eccentric orbits
  • for a given \( L_z \), higher energy

Substructure in phase-space

• Substructure: accreted stars with similar eccentricity

• Streams in velocity space: groups of stars with the same eccentricity
  • at Solar nbhd now (with apocentres at varying radii)

• Variation in eccentricity reflects orbital evolution
  • but not enough to confuse disk and satellite
Summary

• **Galaxies like the Milky Way form via mergers in ΛCDM:**
  - disk results from the accretion of gaseous material and is "young"
  - halo (+bulge? + thick disk?) contains older stars, some fraction of which should have been accreted

• **Concordance model tests:**
  - Lots of substructure (in outer halo): direct evidence of mergers.
    • How many? when?
    • what fraction? what properties?
    • Comparison of stellar populations/chemistry of survivors and field stars show significant differences
  - Evidence of Dark-matter in halo and in satellites

Outlook

• **Many surveys underway and planned for the near future**
  - RAVE: radial velocity survey of 1 million stars near the Sun (1st data release containing 25,000 spectra at [http://www.rave-survey.aip.de](http://www.rave-survey.aip.de))
  - SEGUE (Sloan): radial velocities for ~ 10^5 stars (deeper than RAVE)
  - GAIA: full phase-space info + ages + [Fe/H] and [α/Fe] for 10^9 stars!
  - Wide-field multiplex spectrograph on 8m-class telescope; high-resolution for detailed chemical abundances studies of large numbers of stars