Galaxy formation - Summary

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This summary is based on the book Chapter 26 from Carroll, Bradley W., and Dale A. Ostlie. An Introduction to Modern Astrophysics

1 Galaxy formation

A successful model of galaxy formation needs to explain all the different structures in galaxies that we can observe. E.g. how to form elliptical, spiral and irregular galaxies.

1.1 The stellar birthrate function

Models must explain the rate of formation of stars of various masses, as well as the chemical evolution of the interstellar medium.

The **stellar birthrate function**, is a combination of the star formation rate (SFR) and the initial mass function (IMF). It represents the number of stars per unit volume with masses between M and M + dM that are formed out of the ISM during the time interval between t and t + dt.

The star formation rate (SFR) describes the rate per unit volume at which mass in the ISM is being converted into stars. → The SFR may be highly variable in both space and time.

The **initial mass function (IMF)** represents the relative numbers of stars that form in each mass interval. The IMF is often modelled as a power-law fit. → the production of massive stars drops off very rapidly with increasing mass. **Very difficult to determine through observational studies.**

1.2 The G-dwarf problem

If the first generation of stars was born without any metals and the chemical evolution of the ISM occurs within a closed box, then the **calculations predict too many stars of low metallicity when compared with observations**. This is known as the **G-dwarf problem**.

Possible solutions:

- if heavy-element enrichment of the ISM resulted from rapidly evolving massive stars before the gas and dust settled into the disk.
- the disk accumulated mass over a significant period of time (not a closed box model) → substantial infall of metal-poor material onto the Galactic disk → lower initial mass density would imply fewer stars formed during the early history of the disk, fewer metal-poor stars would be observed today. Evidence: Milky Way is getting gas from the metal poor Magellanic Clouds.
- the IMF could have been different in the early history of the Galaxy, and a larger fraction of more massive stars were formed with correspondingly fewer low-mass stars
- Early-type galaxies → ellipticals (only spheroid shape)
- Late-type galaxies → spirals (have a disk)

2 ELS collapse model

- based on observed correlations between the metallicity of stars in the solar neighborhood, and their orbital eccentricities and orbital angular momenta.
- most metal-poor stars tend to have the highest eccentricities, and the lowest angular momenta about the rotation axis of the Galaxy.
- metal-rich stars tend to exist in nearly circular orbits and are confined to regions near the plane of the Galaxy.
- **Milky Way Galaxy formed from the rapid collapse of a large proto-Galactic nebula. The oldest halo stars formed early in the collapse process.** → halo stars are naturally very metal-poor (Population II)
- the ISM evolved chemically over time

- the rapid collapse slowed when collisions between gas and dust particles became more frequent and the kinetic energy of infall was dissipated
- angular momentum → development of a disk of chemically enriched gas from which Population I stars continue to form today.
- inner portions of the Galaxy would collapse more rapidly → very old stellar population within the bulge

2.1 Problems with the ELS model

- model: all halo stars and globular clusters should be moving in the same general direction ⇔ **approximately one-half of all outer-halo stars are in retrograde orbits**
- the net rotational velocity of the outer halo is roughly 0 km s^{-1}, the inner halo has a small net rotational velocity → this suggests that the early environment of the Galaxy was fairly turbulent and clumpy
- **age spread among the globular clusters and halo stars** → 2-billion-year variation in ages → collapse must have taken roughly an order of magnitude longer to complete than proposed by the model
- existence of a multicomponent disk having differing ages
- compositional variation found between globular clusters → clusters located nearest the Galactic center are generally the most metal-rich and oldest, clusters in the outer halo exhibit a wider variation in metallicity and tend to be younger
- the large variety of galaxies suggests → ongoing dynamical evolution via mutual interactions and mergers

3 Dissipative collapse model

- free-fall collapse versus a slow, dissipative one
- dissipative collapse can be described in terms of the time necessary for the nebula to cool significantly
- If the cooling timescale, is much less than the free-fall timescale, then the cloud will not be pressure-supported and the collapse will be rapid (i.e., essentially in free-fall).
- If the cooling time exceeds the free-fall timescale, the gas cannot radiate its energy away fast enough to allow for a rapid collapse, and the gravitational potential energy that is released during the collapse will heat the nebula adiabatically. This situation is another example of the virial theorem.
- the cooling depends on the cooling function
- Processes involved in the cooling of the gas:
  - recombination of hydrogen and helium
  - thermal bremsstrahlung and Compton scattering.
  - interactions between pairs of particles in the gas, collisions excite ions, atoms, or molecules, which then radiate the energy away in the form of photons, cooling the gas.
- The galaxies that are observed today would be expected to have masses in the range from $10^8 M_\odot$ to $10^{12} M_\odot$. → this corresponds approximately to the lowest mass galaxies and the large elliptical galaxies. However, galaxies can also grow more massive trough mergers.
- first stars → supernova shock waves → gas was reheated to temperatures of a few million kelvins, slowing the rate of collapse

4 Hierarchical galaxy formation model

- evidence for mergers play an important role in galactic evolution
- shortly after the Big Bang, density fluctuations existed in the overall distribution of matter → the most common density perturbations occurred on the smallest mass scales → 10^6 to $10^8 M_\odot$ proto-Galactic fragments → began to merge into a growing spheroidal mass
- many of the fragments evolved in virtual isolation, forming stars and globular clusters. They developed their own chemical histories
- inner regions of the growing spheroid was more dense → formed stars faster → old metal poor inner regions + fast chemical evolution
- collisions and tidal interactions between merging fragments disrupted the majority of the fragments → present distribution of the field halo stars, while leaving the remaining globular clusters scattered throughout the spheroid
- rate of collisions greater near the center of the Galaxy → building the bulge more rapidly than the halo. → forming from the inside out.
- Low-mass globular clusters → disrupted comparatively easily

- massive clusters would have spiraled rapidly into the inner regions of the Galaxy where stronger and more frequent interactions disrupted them → **relative uniformity in the masses of globular clusters** observed today (approximately 10^5 to $10^6 M_\odot$).
- isolation in the outher galaxy → fragments in that region would have evolved almost like individual dwarf galaxies → dwarf spherical galaxies still present in the Local Group are assumed to be surviving proto-Galactic fragments.

4.1 The thick disk

- gas began to settle slowly toward the central regions of the Galaxy → angular momentum → collapsing material became rotationally supported and settled into a disk, T $\sim 10^6$ K
- gas was locally more dense, it cooled more rapidly → H I clouds could form and begin producing stars. → reheat the gas between the molecular clouds, maintaining the temperature of the intercloud gas at roughly 10^6 K.
- a few percent of the mass of the gas was converted into stars

4.2 The thin disk

- if the infalling gas was initially much cooler → gas (and dust) was able to settle onto the midplane with a much smaller scale height, similar to today's thin disk. Star formation was then able to proceed
- a significant merger event with a proto-Galactic fragment some 10 Gyr ago, the disk was reheated by the energy of the interaction, causing it to puff up to its present 1-kpc scale height.
- cool molecular gas continued to settle onto the midplane with a scale height of approximately 600 pc
- several billion years, star formation occurred in the thin disk.
- maintaining the scale height was essentially a self-regulating one
- as the gas was depleted in the ISM the SFR decreased
- decrease in the SFR, the thickness of the disk decreased to about 350 pc, the scale height of today's thin disk
- 80% of the available gas was consumed in the form of stars.
- the remaining gas continued to cool, it settled into an inner, metal-rich and gas-rich component of the thin disk with a scale height of less than 100 pc → stars form from this today

Young stars in the bulge: recent mergers with gas-rich satellite galaxies. When those galaxies were disrupted by tidal interactions with the Milky Way, their gas settled into the disk and the center of the Galaxy forming new stars.

the Milky Way's central bar plays a role in the migration of dust and gas into the inner portion of the Galaxy by generating dynamical instabilities as it rotates.

Metallicity gradients: The hierarchical merger scenario predicts that metallicity gradients must exist. However, these would depend on the merger history and past interactions of the galaxies

4.3 The formation of ellpitical galaxies

- many ellipticals may have formed the majority of their stars early in the galaxy-building process, before the gas had a chance to settle into a disk,
- other E's probably formed from the collisions of already-existing spirals
- large number of globular clusters in E's relative to spirals → indicate mergers
- possible that many of the observed globular clusters are captured dwarf spheroidal galaxies
- increased likelihood of interactions in regions where galaxies are more tightly packed, destroying spirals and forming ellipticals
- **Butcher-Oemler effec:** galaxies in the early universe were bluer on average than they are today, indicating an increased level of star formation.
- As observations probe earlier times (more distant galaxy clusters), elliptical, and lenticular galaxies become less abundant relative to spiral galaxies, suggesting an evolution from later Hubble types to earlier types over time.