Overview of Galaxy Formation Theory

1. Basics

1.1. General Story

Galaxies form through the nonlinear gravitational collapse of dark matter halos. Baryons participate in this collapse with the dark matter, but unlike dark matter are able to radiate energy away and therefore sink deeper into the potential well. They cannot radiate away angular momentum, and they experience gas pressure; this combination leads ultimately to the formation of rotating gas disks. In this process, pockets of the gas cool, becoming neutral or molecular. Inside the molecular regions, individual stars collapse and cool. Through stellar processes, these stars enrich the interstellar medium and return energy to it through feedback. At the centers of the galaxies, black holes form and grow, and also exert feedback on the gas. These feedback effects may help determine the star formation rates of the forming galaxies. As these events occur, galaxies experience further accretion and major mergers. Although there is not an agreed-upon quantitative understanding of this whole process, there is strong evidence that the dark matter halos with masses near $10^{12}\ M_\odot$.

Although this basic story is known, many of its details are unclear and it is not known if the story is complete. The current theories of galaxy formation do a good job reproducing the gross properties of galaxies near $z \sim 0$. It remains to be seen if they consistently predict the differences in the galaxy population at higher redshift, more detailed properties of galaxies such as their mass profiles, stellar kinematics, and internal chemical patterns, and their gaseous environments.

1.2. Halos and Galaxies

An overarching challenge for physical galaxy formation theory can be expressed as the relationship between halo mass and stellar mass of galaxies. Approximately, this relationship expresses how effiently the matter that fell into a halo was converted into star.

This relationship can be observationally constrained through *abundance matching*. Abundance matching assumes that halo mass and stellar mass are at least approximately monotonically related. For any halo mass M_h for which the number density of halos above that mass is predicted to be $\Phi_h(> M_h)$, one can find a corresponding stellar mass M_* for which the real universe is observed to have $\Phi_*(> M_*) = \Phi(> M_h)$, and conclude that halos of mass M_h host galaxies with stellar mass M_*. There are numerous refinements of this technique that account for scatter in the relationship between M_h and M_*, that use subhalos rather than halos, that use circular velocity instead of M_h.

The other basic tool for understanding this relationship is the *halo occupation distribution* model. This model connects N-body predictions of dark matter halo properties to observed galaxy

properties through $P(> M_*|M_h)$, the probability distribution of the number of galaxies above stellar mass M_* within a halo of mass M_h. Many refinements of this model exist, the most important of which is the distinction between *central galaxies* in a halo and *satellite galaxies*. The framework also can be used to study galaxies of different classes or properties, and as a function of different environments around each halo.

Wechsler & Tinker (2018) review the literature of the galaxy-halo connection, including abundance matching and halo occupation distributions. The major conclusion from these studies is that M_*/M_h peaks at $M_h \sim 10^{12}$. This ratio rises linearly or even more steeply between 10^{10} and 10^{12} $M_\odot$ and declines as $\sim M_h^{-1/2}$ at higher masses. These conclusions are validated by using them to predict observations of weak lensing and galaxy correlation functions. They can be further used to study the scatter in the relationship between M_h and M_*, how central and satellite galaxies differ in their star formation histories, and how these properties depend on environment.

These results outline a basic challenge of galaxy formation theories, which is to explain how the efficiency of star formation depends on halo mass.

1.3. Physical Processes

Theoretical models seek to explain galaxy-halo relation and the other properties of galaxies from, most ambitiously, a first-principles approach beginning with pattern of matter fluctuations at the time of recombination. **?** outline the major physical processes at play:

- Gravity, which drives gravitational growth leading to the collapse and clustering of dark matter halos.
- Hydrodynamics, which controls the flow of the baryons and produces shocks.
- Thermal processes, which control the cooling of gas and thus how it will flow into galaxies.
- Star formation, which in the context of galaxy formation models means how cool gas proceeds to fragment and form dense cloud cores that lead to individual stars, and which may affect the subsequent evolution of the galaxy through feedback due to stellar winds and supernovae.
- Black hole formation and growth, which occurs due to gas inflow to the very centers of galaxies, and which may affect the subsequent evolution of the galaxy through AGN feedback.
- Nucleosynthesis, which leads to chemical enrichment of interstellar gas, which affects the thermal processes because of the importance of metal cooling.
- Radiative transfer, which can heat and cool gas, as well as affect the observed nature of the galaxies.

In galaxy formation theories, gas cooling, inflow, and feedback play critical roles, and as noted below can only be modeled through *subgrid* physics—i.e. not from first principles. What simulations can predict from first principles are the effects of gravity on nonlinear collapse, the cooling of gas on large scales, and the flows of gas. However, these first principles calculations are still limited by resolution, which may lead to qualitatively important errors even on large scales.

1.4. Methodology

Simulations of galaxy formation utilize N-body simulations, hydrodynamic simulations, and prescriptions for subgrid physics, or rely on approximations to those simulations known as it semi-analytic models.

As used in the cosmological literature, the term *N-body simulation* refers to a purely gravitational simulation of the collisionless Boltzmann equation, approximated with particle methods. These simulations nominally simulate pure cold dark matter models, with no baryons. Traditional N-body simulations do not solve the collisionless Boltzmann equation fully, but use particles to sample the density field and study the gravitational interactions of the particles. Because the number density of particles in the simulation is far below the number density of expected cold dark matter particles, if the gravitational interactions were solved exactly they would lead to unrealistically short two-body relaxation times in the simulations. Therefore, the gravitational force law needs to be *softened* at some length.

[Semi-analytic]

[Hydro]

[Subgrid physics]

[Feedback]

1.5. Features of Theoretical predictions

[Cooling]

[hot vs cold mode]

2. Commentary

[Successes and challenges]

3. Key References

- *Physical Models of Galaxy Formation in a Cosmological Framework* (**?**)
- *The Connection Between Galaxies and Their Dark Matter Halos* (Wechsler & Tinker 2018)

4. Order-of-magnitude Exercises

1. Estimate the maximum efficiency of converting mass energy into emission for a non-rotating black hole of mass M.

   In order to fall deeper into a potential well, matter has to lose orbital energy and that energy is available for emission. In the case of a black hole, once it reaches the innermost stable circular orbit at $3r_s$, it can simply fall in without any further energy loss.

   Using a Newtonian approximation, the orbital energy is $E = K + U = -U/2$. From infinity to $3r_s$ implies an energy loss per unit mass of $GM/6r_sc^2 = 1/12$, implying a maximum conversion efficiency of ~ 0.08. In a general relativistic calculation, the real energy available is slightly smaller than this (~ 0.06).

   For a spinning black hole, the efficiency can be considerably higher.

2. Estimate efficiency of accretion
3. Estimate hottest gas in continuum
4. What is virial tempereature near disk
5. Doppler velocities to sizes
6. Critical density of CIII] and OIII
7. Estimate filling factor of BLR, NLR
8. Estimate duty cycle

5. Analytic Exercises

1. Eddington luminosity
2. Temperature profile of accretion disk
3. Relationship between energy distribution and synchrotron
4. Superluminal motion
5. Relativistic Beaming
6. Polarization

6. Numerics and Data Exercises

1. Quasar SEDs
2. Quasar variability
3. Densities from line ratios
4. Temperatures from line ratios
5. OIII/Hbeta and ionization parameter
6. resolved spectroscopy of AGN

REFERENCES

Wechsler, R. H., & Tinker, J. L. 2018, ArXiv e-prints, arXiv:1804.03097

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