Cosmology and the Structure of the Universe

This course will explore modern cosmology from both a theoretical and observational perspective. The essential framework of the Friedmann model, the Robertson-Walker metric, and the Newtonian approximation will be given. Important parameters will be introduced and examined: the expansion rate and age of the universe; the density and deceleration parameters and the cosmological constant; nucleosynthesis of the light elements and the cosmic density of baryons; the microwave background and structure formation; and the missing mass problem. Emphasis will be placed on observations which motivate, measure, and test the standard ΛCDM world model.

Outline

1. Introduction
   1. Historical perspective: cosmologies of ancient and medieval peoples
   2. Overview of the genesis of modern cosmology in General Relativity
2. Cosmological Essentials
   1. Simple Newtonian Cosmology
   2. The Robertson-Walker metric and Friedmann models
   3. Empirical Pillars of modern cosmology
   4. Cosmological Parameters: H_0, t, Ω, q, Λ, T(CMBR), Y_p, Ω_b, Ω_{CDM}, σ_8, n
3. The Size scale of the Universe
   1. The Hubble relation
   2. The expansion rate (H_0) and age (t) of the Universe
   3. Calibration: the distance scale ladder
   4. Large Scale Structure: mapping the Universe
4. The Age of the Universe
   1. Globular Cluster ages
   2. White dwarf age limits
   3. Radioactive decay and interstellar grain limits
5. The Density Parameter (Ω)
   1. The role of density parameter (Ω) in specifying world model
   2. Importance of Ω to H_0 and t
   3. Relation of Ω to deceleration parameter (q) and cosmological constant (Λ)
   4. Measures of Ω, q, and Λ
6. Primordial Nucleosynthesis
   1. Photon to baryon ratio (entropy)
   2. Abundances of the light elements: Y_p, D/H, Li/H
   3. Entropy and the density of baryons (Ω_b)
7. Cosmic Microwave Background
   1. Backround Radiation; T(CMBR)
   2. Temperature Anisotropies
   3. Structure formation; growth of fluctuations
   4. The acoustic power spectrum
8. The Mass Discrepancy Problem
   1. Cosmological and dynamical motivations
   2. The need for cold dark matter (CDM)
   3. Alternative possibilities: WDM, SIDM, MACHOs, MOND, etc.
9. The Dark Ages
   1. Recombination and Reionization
   2. The Saha equation in cosmic context
   3. Cosmic Dawn: the first stars
10. The Very Early Universe
    1. Inflation
    2. The Particle Zoo
11. Exoitca
    1. Multiverses
    2. The Far future: a Big Rip?
    - as time permits

Course Work

Assignments will be posted on the course web page and returned electronically.

Course work will consist of

- Problem sets
- Quizes
- A class project

Students registered for ASTR 428 will encounter additional problems on the problem sets and quizes.

Grades

Grades will be on a curve. The highest performing students will receive the highest grades, and vice-versa. The absolute scale is irrelavant: if the best score is 50% that will still warrant an A; if the worst score is 90% it will not.

Aspirationally, quantitative weighting will be **50% problem sets, 40% quizes, 10% project**. Given the likelihood that the COVID-19 pandemic may undermine the best laid plans, an assessment of work completed will be made at the end of the semester to check whether the proposed weighting scheme remains fair.

Missed Assignments

All work is due when it is due. The instructor reserves the right to apply an arbitrary and capricious penalty to work turned in late, typically a 20% reduction *per day*. There will be **no make up** work. You are granted one free pass on one problem set and one quiz: your **lowest score** on one of each will be **dropped**. This provides some flexibility to accommodate periods of illness (of any kind). If you are ill for an extended period that causes you to miss more than that, then we'll cope with that as it happens. I hope to provide everyone with an excellent educational experience with tolerance for the unique circumstances of this semester while also maintaining high academic standards.

One thing we will ***not*** have: on-line exams proctored by Big Brother-ish software. We will either do in-class quizes or take-home exams, as the situation warrants. You are of course expected and required to maintain high standards of academic integrity in any circumstance.

Course Project

Debate: the Values of Cosmic Parameters
H_0 | q_0 | T_0 | Ω_m | Ω_Λ | Ω_b | f_b | σ_8 | n | r

The class project will be a debate of the values of the fundamental cosmic parameters.

Each of you will explore the observational constraints on one of the important cosmological parameters, write a short (< 1 page) report on the current status of the subject, and make an oral presentation about it to the class. The written report, as well as the oral presentation, is intended for your classmates more than me, and will be distributed to everyone. Your written report will be due before your oral presentation so that all may read it ahead of time. The goal is for us all to become well informed prior to a large group debate of how all the pieces fit together.

After all the individual presentations, we will, as a class, discuss and debate the various observations which constrain cosmic parameters. The purpose of the debate is to see if we can arrive at some consensus about the current state of things, and if so, if we agree with the now "standard" Lambda-CDM cosmology. In addition to being an impartial arbiter, each of you will also play the role of advocate for the constraints imposed by the observations you have studied and reported upon. So if someone says "X means Y" you should speak up if Y is excluded by your subject.

All this will happen towards the end of the semester as we can schedule it.

Note that many of the observational constraints often boil down to a statement like "$H_0 = 74 \pm 2$ (stat) ± 2 (sys) km/s/Mpc" or "$\Omega_b h^2 = 0.019 \pm 0.001$." This is the essence of what you're after.

Learning Outcomes

After taking this course, students should be able to

- Quantitatively describe the dynamical evolution of the universe under different cosmological models.
- Distinguish between and employ quantitative metrics for luminosity distance and angular size distance under different cosmological models.
- Desrcibe and distinguish between the various cosmological parameters that define the cosmological model.
- Name the three pillars of the hot big bang cosmology.
- Describe observational evidence for the quantitative values of the various cosmological parameters that define the cosmological model.
- Describe and apply observational cosmological tests.
- Compare and constrast different cosmological distance estimators.
- Critique the quality of and uncertainties in cosmological distance estimators.
- Describe qualitatively the growth of structure under various cosmological models.
- Employ quantitative metrics for measuring structure in the universe.
- Describe physical models for galaxy formation and hierarchical galaxy evolution.
- Describe the observational constraints on models of galaxy evolution over cosmic time.
- Analyse observational datasets to infer cosmological information.
- Quantiatively describe the temperature evolution of the universe.
- Describe big bang nucleosynthesis and how it is constrained by observations of the abundances of the light elements.
- Qualitatively describe the cosmic microwave background and its relation to large scale structure.
- Describe the cosmic dark ages and reionization.
- Describe the motivations for non-baryonic cold dark matter.
- Describe the motivations for dark energy.