ASTR/PHYS 328/428: 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 modern world model.

ASTR/PHYS 328/428 - Cosmology and the Structure of the Universe

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

Course Work

Assignments will be posted on the course web page.

Course work will consist of

- Problem sets
- Midterm and Final exams
- A class project
- Class participation

The participation component is to encourage engagement in class, in whatever form that may take over the course of the semester.

Students registered for ASTR/PHYS 428 will encounter additional problems on the problem sets and exams.

Grades

Grades will be on a curve. The highest performing students will receive the highest grades, and vice-versa. The absolute scale is irrelavant.

	Problem Sets	Midterm Exams	Final Exam	Project	Participation
Number	5	2	1	1	22
Total weight	23%	20%	20%	15%	22%

I will review the situation at the end of the semester to check whether this weighting scheme remains fair.

Problem Sets

Grading will be on a best-effort basis: you get credit for making a serious effort at each problem posed. The point of these exercises is to develop your intuition as a budding cosmologist and gain an appreciation for the sorts of problems that the field faces. Collaboration with your peers is encouraged provided that the final submitted work is your own.

Exams

Exams will be closed book. You are allowed a [dumb] calculator and a writing instrument. You are also allowed a formula sheet that is whatever you can fit on one side of one 8.5 x 11" piece of paper. These are cumulative through the semester: one page for the first exam; that plus another page for the second exam; one more for the final.

Course Project

The course project is described separately. Grading will include personalized feedback.

Class Participation

Showing up may be 80% of life, but it is 22% of this course grade. This is the number of class meetings that are not exams or reviews or holidays or what not. Asking questions will be rewarded; missing class will be penalized.

Missed Assignments

The first rule of missing assignemnts and exams is **don't**. If you do fall ill or suffer some other tragedy at exam time, let me know ASAP (before the exam happens) that you will be unable to attend, and we'll see what can be arranged. This is to be avoided if at all possible. There will be no make-ups and no **extra credit** outside the regular assignments.

Academic Integrity

Academic inegrity is important. It is essential that you do your own work. Ultimately, that is the only way to learn. If, for example, you rely on friends or AI for answers, you won't know how to tell when it is right and when it is wrong, nor will you be able to perform well on your own (e.g., on the exams).

Course Project

The Values of Cosmic Parameters

H_0 | q_0 | T_0 | Ω_m | Ω_Λ | Ω_b | f_b | σ_8 | n_s | r | A_L

The class project is a joint effort to compile observational constraints on the values of the fundamental cosmological parameters.

Each of you will choose a cosmological parameter on which to report. Which one is up to you, but you must **discuss your choice with the instructor in advance** (by Tuesday 19 November at the latest). Some examples of possible topics are given below. There should be a bottom line, like $H_0 = 70$ or $\Omega_m = 0.25$ (along with error bars, of course). Joint analyses are forbidden: letting Planck tell us all the answers at once defeats the purpose of this exercise, which is to check if all the available data point to the same set of cosmological parameters.

You will make a 5 minute oral presentation to the class. Write a title and abstract (1 paragraph) on the result as if you were the author of the paper who is going to present it at a meeting. The written abstract is intended for the other conference attendees - in this case, your classmates - and are due Tuesday 26 November so that they can be posted in advance of your talks on December 3 and 5. They will be posted as part of a schedule of talks so that your audience can read them in advance like abstracts at a conference.

A complete draft of your presentation file is also due on Tuesday 26 November. Last-minute updates are allowed, but a complete draft needs to be submitted before Thanksgiving. Submitted files will be organized on a single computer to minimize switch-over time between speakers.

Topics to Investigate: Observational Constraints

The goal is to learn about observational constraints on cosmological parameters. E.g.,

- H_0 from direct measurements (e.g., Riess et al. 2022 or Freedman et al. 2024).
- Age constraints [$f(q_0,1/H_0)$] from globular clusters (e.g., Valcin et al. 2020 or Ying et al. 2023).
- Ω_b from the light element abundances (e.g., deuterium, helium, lithium)
- Ω_m from
  - kinematics
  - large scale structure (e.g., 2dF; 6dF);
  - cluster baryon fractions (e.g., Evrard)
  - cluster mass-to-light ratios (e.g., CNOC)
- See the more comprehensive list of topics on the course web page. for more ideas.

Note that observational constraints often boil down to a statement like "$\Omega_b h^2 = 0.019$ +/- 0.001." This is the essence of what you're after, though of course you need to understand the method in order to appreciate how the result is obtained and what might go wrong. But we will need something like this as a bottom-line answer for intercomparison of results in the culminating discussion.

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.
- Desrcibe 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.
- 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.
- Analyse observational datasets to infer cosmological information.
- 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 motivations for non-baryonic cold dark matter and dark energy.