Astronomy 3785: Cosmology

Course Syllabus

M & W, 12:00-1:15 in 319 Allen Hall

Course Instructor

Professor Andrew Zentner is the instructor for the course. I am a member of the Department of Physics and Astronomy at the University of Pittsburgh. The most effective way to reach me outside of class is through email. My email address is `zentner@pitt.edu`. My office is 401D on the fourth floor of Allen Hall. My campus phone number is 412-624-2752.

Please do not hesitate to contact me with any questions or concerns about this course. I want to work with my students to make this course interesting and fun and allow my students to learn a lot. All too often, students wait until the end of the semester to express concerns, but by that time I cannot change anything. There is **no** question too insignificant and there is no need to wait until it is too late to express a concern. Of course, I have to abide by University and Department rules and I have to work within the Physics & Astronomy curriculum, so I cannot accommodate all requests, but my intention is to make this course as fun and productive as possible.

Office Hours

I will hold regular office hours from 2:45 to 4:15 PM on Mondays and from 1:00 to 2:30 PM on Tuesdays. If you cannot make either of these times, please contact me and we can arrange to meet at another time.

I am happy to use office hours to help in any way I can, including with the preparation of homework. If you come to office hours for help with an assignment, please be prepared to demonstrate that you have put some effort into the problem(s). In particular, be prepared to describe your thought process and the point at which you are stuck. I **will not** help with homework problems if you cannot first describe to me how you tried to solve the problem, and why or how you know that your strategy was incorrect.

Course Description

This course will cover a variety of topics in modern astrophysical cosmology. The focus will be on the major predictions of the well-accepted "big bang" model of cosmology.

Approximately the first two-thirds of the course will cover the homogeneous universe, including the expansion of the universe, cosmological distance measures, the origin of the light elements, the production of relic particles in the early universe, the epoch of cosmological inflation, and the contemporary accelerated cosmological expansion.

The final third of the course will be devoted to the inhomogeneous universe and focus on the theory and contemporary measurments of anisotropy in the cosmic microwave background radiation, the growth of large-scale structure in the universe, and the formation of galaxies.

I intend to set aside the final two to three weeks (depending upon enrollment) for each student to present to the class a paper on a particular topic of their choosing.

My goal is that students will be able to read and understand the primary aspects of well-written, contemporary research papers in cosmology at the end of the course.

Note: I will freely borrow from course materials developed by Wayne Hu, Arthur Kosowsky, Samir Mathur, Gary Steigman, and David Weinberg throughout this course.

Prerequisites

I will assume basic familiarity with special relativity, classical mechanics, quantum mechanics, and thermodynamics at the introductory graduate level or advanced undergraduate level. I will not assume prior familiarity with General Relativity or with Particle Physics. I will try to introduce the basic aspects of General Relativity and Particle Physics Phenomenology as needed throughout the course.

Course Grades, Exams, and Rules

There will be no exams in this course. Most of the graded work in this course will be based on long-form problems. There will be approximately six homework assignments for the course, which will constitute 60% of your final grade. The final 40% of your grade will be based on a term paper and 45 minute, in-class presentation on an advanced topic of your choosing. I give some details about the scope of the project, and suggestions for topics below. You are not bound by my suggestions and may choose any topic. However **I must approve of your topic by Monday, March 1, 2010** in order for you to receive full credit for your term project. It is **your responsibility** to see to it that I approve of your project. I will not make any effort to track you down.

In preparing for class, take note of the following specific warnings and rules.

- I will post new homework assignments on the CourseWeb and I will not hand them out in class. It is your responsibility to check the site and obtain these materials.
- You may discuss homework problems with other students in the course, but you must

hand in a unique solution that is your own.

- Late homeworks will be accepted with a 50% penalty for the point value of the homework up until the time that I post the solutions on the CourseWeb site for the course. No homework will be accepted after this time unless by prior arrangement and no make-up assignments are possible unless by prior arrangement. I may post the solutions any time after the due date without warning.
- Problem solving skills are of utmost importance and you must show all of your work, including all logical and algebraic steps used in deriving your answers in order to earn full credit.
- You **may not** refer to algebraic steps performed by a calculator or by a computer software package (Mathematica, Maple, etc.) for derivations. You must perform and show each step yourself unless I specifically state otherwise.
- Throughout the course, I will give problems where you may need to know information (for example, the lifetime of the neutron) that it is not included in the problem statement. I will assume you can look this up in some reputable source (such as a textbook or paper).

Course Topics in Detail

Here is a rough outline of what will be covered in the course. This plan may be modified according to student interests and questions that may arise during the course and the pace at which we proceed. The pace I have chosen in this outline is ambitious, but I will allow for modifications if the need arises.

- Week 1: **NO CLASS ON JANUARY 6**
- Week 2: A Basic Overview of Modern Cosmology: This is intended to give the "big picture" of the "big bang" so that there is a sense of where we are going when we delve into each subject in detail. This will not be technical, but qualitative reasoning is important and you will be responsible for the material. I will make my notes available on the CourseWeb.
- Weeks 3, 4, & 5: Basic General Relativity, The Friedmann Equation, the Contemporary Cosmic Expansion, and Cosmological Distance Scales
- Week 6: The Thermal History of the Universe
- Week 7: The Synthesis of the Light Nuclei

- Week 8: Dark Matter and the Production of Thermal Relic Particles
- Week 9: The Horizon & Flatness Problems and Cosmological Inflation
- Week 10: Cosmological Inflation, Dark Energy, Seeding Large-Scale Cosmic Structure
- Week 11: The Growth and Properties of Large-scale Structure in the Universe
- Week 12: Anisotropies in the Cosmic Microwave Background
- Week 13, 14, & 15: FINAL PROJECTS ON ADVANCED TOPICS

Textbook & References

There is no required textbook for this course and contemporary cosmology is a vast subject with parts scattered through many textbooks. The amount of material that can be covered 2.5 hours of lecture each week is limited. The vast majority of my notes will be hand-written on the board in a traditional lecture style. At times, I will use slides and other electronic media to facilitate lectures and I will make all of these materials available on the CourseWeb Blackboard web site for this course at `http://courseweb.pitt.edu`. Please let me know if you have any problems retrieving this material and I will do my best to rectify the problem. You will need to take good notes, but uou will also need to have access to some reference on cosmology in addition to my course notes. My favorite textbooks include.

- *The Early Universe* by Kolb & Turner. This is out of date in terms of observational status, but remains one of the best discussions of important topics like nucleosynthesis. Any serious cosmology student should own this book. The companion volume, *The Early Universe: Reprints* collects many of the classic papers in cosmology into a single volume and is likewise a must-own book. Both books are available used at a pittance.
- *Cosmology* by Steven Weinberg. This book is written at a very advanced level but contains one of the most self-contained and up-to-date treatments of modern cosmology.
- *Structure Formation in the Universe* by T. Padmanabhan. This is a good introduction to the formation of structure in the Universe, but is out of date in its observational detail. There are several known typos in this book.
- *Physical Principles of Cosmology* by P. J. E. Peebles. This book arrives at many of the basic results of modern cosmology without direct recourse to General Relativity. Be forwarned that Peebles is often criticized for approaching problems from a “unique perspective,” but I enjoy it.

- *The Large-scale Structure of the Universe* by P. J. E. Peebles. This is still the standard book for large-scale structure and clustering statistics.
- *Kinetic Theory in the Expanding Universe* by Jeremy Bernstein. This is a favorite of mine. It is beyond the level of this course, but is a lucid and authoritative treatment.

Other useful books are

- *Cosmological Physics* by John Peacock. This book is very far ranging, covering relativity, field theory, and most topics in modern cosmology at some level. This makes it somewhat difficult to manage in a course and of limited pedagogical value. However, it can be a handy "quick-and-dirty" reference guide if you know what you want to look for.
- *Cosmological Inflation and Large-scale Structure* by Liddle and Lyth. This is a good book focusing on the phenomenological aspects of cosmological inflation and the growth of structure. This book is clear and concise and gives a good account of the statistical properties of cosmological density fluctuations. The book has many known typos and corrections are maintained at the books web site `http://astronomy.sussex.ac.uk/ andrewl/infbook/errata.html`.
- *The Primordial Density Perturbation* by Liddle and Lyth. An update of the previous book.
- *Theoretical Astrophysics Volume III* by T. Padmanabhan. A good but ambitous book covering both galaxies and cosmology.
- *Modern Cosmology* by Scott Dodelson. This book contains the most modern perspective on the cosmic microwave background, including its polarization statistics, weak graviational lensing, and data analysis of any of the recommended texts, so it is a valuable addition. This book can be somewhat technical in some places and overly cavalier in others.

Some useful undergraduate texts that treat cosmology in less detail are

- *Principles of Cosmology* by Eric Linder.
- *Introduction to Cosmology* by Barbara Ryden.
- *Introduction to Modern Cosmology* by Andrew Liddle.
- *An Introduction to Modern Astrophysics* by Carroll and Ostlie. This is a general book that contains many simple treatments of topics in galaxy evolution, stellar physics, and cosmology.

- *Astrophysics in a Nutshell* by Dan Maoz. This is likewise a general book on many topics in astrophysics.

Finally, students may wish to learn or review topics in General Relativity or the Standard Model of Particle Physics. Some useful resource may be the following, but feel free to search for your own favorites.

- *A First Course in General Relativity* by Bernard Schutz. This is my favorite introductory book on general relativity.
- *Gravity: An Introduction to Einstein's General Relativity* by James Hartle. A nice undergraduate-level textbook on General Relativity.
- *Gravition* by Misner, Thorne, and Wheeler. This book is a bit hard to wade through, but has some unique perspectives on cosmology.
- *Gravitation and Cosmology* by Steven Weinberg. This is the classic General Relativity book, but is relatively technical if you haven't studied GR before.
- *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions* by Chris Quigg. This is my favorite basic text on the phenomenology of the Standard Model of Particle Physics.
- *Particle Physics* by Abraham Sneiden. This is another nice, basic introduction to the phenomenology of the Standard Model of Particle Physics.
- *Gauge Theory of Elementary Particle Physics* by Cheng and Li. An advanced treatment of the phenomenology of the Standard Model.

Term Projects

Forty percent of your grade in this course will be based on a term project. This term project must consist of a paper and an in-class presentation during one of the final three weeks of the semester. You may give your presentation prior to handing in your paper. The paper must be approximately eight pages long, single-spaced in a font no larger than 12pt, on an advanced topic in cosmology. The paper may include figures, but these figures must be informative. You may not gratuituously add figures in order to lengthen your paper. In your paper, you must discuss derivations of some important results so that someone else may recreate the derivation, and show examples of calculations that you have performed. Of course, these calculations need not be original. Reproducing the classic Figure 4.1 or Figure 5.1 from *The Early Universe* by Kolb and Turner represent examples of acceptable calculations.

You must present your project results to the rest of the class. The presentations should be approximately 45 minutes in length and you may choose to use PowerPoint or similar software to present your topic. The level of the presentation should be such that it builds off of topics discussed in class and such that the majority of the class can follow the logical arguments. The class will ask questions and critique your presentation. Five percent of your grade will be based on your participation (asking questions etc.) during the presentations of your colleagues. This is part of the learning process.

Topics are open for you to choose, but I must approve of the topic **on or before March 1, 2010** for you to earn full credit. Topics may not be duplicated and I will approve them on a first-come, first-served basis.

A partial list of viable term projects would include the following subjects.

- The Generation of Primodial Density Fluctuations During Cosmological Inflation.
- Light Element Nucleosynthesis Constraints on Particle Physics Beyond the Standard Model.
- Viable Dark Matter Candidates
- Contemporary Constraints on Dark Matter Properties.
- Cosmological Constraints from Cosmic Microwave Background Anisotropies.
- Cosmological Constraints from the Polarization of the Cosmic Microwave Background.
- Constraints on Dark Energy or Decaying Dark Matter from Type Ia Supernovae.
- Monopoles In Cosmology.
- The Generation of the Cosmic Baryon Asymmetry.
- Cosmological Reionization.
- Galaxy Formation in the Standard Cold Dark Matter Cosmology.
- Cosmological Constraints from the Clustering of Galaxies.
- The Late-time Integrated Sachs-Wolfe Effect
- Weak Gravitational Lensing as a Probe of the Properties of the Dark Energy.
- Baryon Acoustic Oscillations as a Probe of the Propeties of Dark Energy.
- Galaxy Clusters as Probes of the Properties of Dark Energy.

Students with Disabilities

If you have a disability, please speak to the as early in the semester as possible. We will make any necessary arrangements to support a successful learning experience, and provide documentation through your disabilities coordinator.

Selected Important Papers in Cosmology

General Relativity

- Einstein, *On the Electrodynamics of Moving Bodies* (1905)
- Einstein, *On the Influence of Gravitation on the Propagation of Light* (1911)
- Einstein, *Does the Inertia of a Body Depend Upon Its Energy Content?* (1905)
- Einstein, *The Foundation of the General Theory of Relativity* (1915)
- Einstein, *Cosmological Considerations on the General Theory of Relativity* (1917)

Big Bang Nucleosynthesis

- Alpher, Bethe & Gamow 1948, Phys Rev 73, pp. 803-804
- Hoyle & Tayler 1964, Nature 203, pp. 1108-1110
- Wagoner, Fowler, & Hoyle 1967, Astrophys. J. 148, 3
- Walker, Steigman, Schramm, Olive, & Kang 1991, ApJ, 376, 51-69

The Cosmic Microwave Background

- Gamow 1946, Phys Rev 70, pp. 572-573
- Gamow 1948, Phys Rev 74, pp. 505-506
- Gamow 1948, Nature 162, 680
- Alpher & Herman 1948, Nature 162, 774
- Dicke et al. 1965, ApJ 142, pp. 414-419
- Penzias & Wilson 1965, ApJ 142, pp. 419-421
- Roll & Wilkinson 1966, Phys Rev Lett 16, pp. 405-407
- Hu 1995, Berkeley PhD Thesis

Inflation

- Guth 1981, Phys Rev D, 23, 347
- Albrech & Steinhardt 1982, Phys Rev Lett 48, 1220
- Linde 1982, Phys Lett. B 108, 389
- Hawking 1982, Phys Lett B, 115, 295

Structure/Galaxy Formation

- White and Rees 1978, MNRAS 183, 341-358
- Davis, Efstathiou, Frenk, & White 1985, Astrophys. J. 292, 371-394
- Cole, Aragon-Salamanca, Frenk, Navarro, and Zepf 1994, MNRAS 271, 781-806