Astronomy 660: Galaxies and Cosmology
San Diego State University
Spring 2013

Lecture times and locations: T/Th 3:30 – 4:45 PM, Rm. PA 215 (Physics-Astronomy building)
Instructor: Douglas Leonard
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Office Hours: Fridays, 1:00 – 3:00 PM, and by appointment
Website: http://sciences.sdsu.edu/∼leonard/astro660
Required Course Material: *An Introduction to Modern Astrophysics*, **second edition**, by Bradley Carroll & Dale Ostlie.
Astronomy 660 Course Reader: Available at the campus bookstore. Contains selected Powerpoint slides used throughout the course.
Recommended Course Material: *Introduction to Cosmology* (first edition), by Barbara Ryden.
Galaxies in the Universe (second edition), by Sparke & Gallagher.

Course Description

Astronomy 660. Galaxies and Cosmology

Here we consider the universe on the grandest of scales, focusing on cosmology (extragalactic distance scale, Hubble expansion, Newtonian and relativistic cosmology, early universe and cosmic microwave background) and galaxies (morphology, contents, photometric properties). A particular emphasis will be placed on how (very) recent observations are being used to constrain cosmological models.

Student Learning Objectives

Upon completing this course, you should be able to:

- Construct an argument based on astronomical evidence that the universe has evolved from a hot, dense state;
- Present the currently favored scientific theory for what the ultimate fate of our universe will be, and outline the astronomical observations upon which it is based;
- Discuss the major morphological and kinematic similarities and differences among spiral, elliptical, and irregular galaxies;
- Describe the astronomical observations that compel astronomers to believe in the existence of dark matter and dark energy;
- Describe at least three major areas in extragalactic astrophysics in which our astronomical knowledge is known to be incomplete.

Course Schedule[1]

Topics will be covered in the order given below; important course dates are noted.

Galaxies

- Edwin Hubble's discovery
- Course introduction
- Assumed background knowledge — the Astronomy 660 Toolkit: Newton's laws, using Newton's formulation of Kepler's Third Law to measure mass, virial theorem, trigonometric parallax, magnitudes, flux and luminosity, distance modulus, light: wave nature, blackbody radiation (Planck's function, radiation pressure and density), introduction to spectroscopy, UBV filters and color index, relativistic Doppler shift (redshift and blueshift), $E = mc^2$, spectral lines and Kirchoff's laws, photons, Bohr atomic model and hydrogen's spectral lines
- Measuring distances in astronomy: parallax, Cepheids, and Malmquist bias
- Background material for study of galaxies: H-R diagram, stellar mass-luminosity relation, metallicity, interstellar dust and extinction
- H II regions
- Metallicity (Z) and Population I, II, and III stars
- Globular clusters
- The Hubble sequence
- Brief overview of Milky Way contents and morphology: age-metallicity relation, mass-to-light ratio, Galactic bulge, disk, and stellar halo, globular clusters, rotation curve and evidence for dark matter, the Galactic center, evidence for a supermassive black hole
- $r^{1/4}$ law
- Spiral galaxies: morphology, rotation curves, Tully-Fisher relation, mass-to-light ratios, metallicity gradients, supermassive black holes and their relation to other observables
- Globular clusters, introduction to density-wave theory, X-ray luminosity, abundance of dust, K-correction
- Elliptical galaxies: morphological classes, dust and gas content, metallicity, surface brightness profiles, kinematics of stellar population (Faber-Jackson relation), Fundamental plane, rotation parameter)
- Elliptical galaxies: morphology-density relation, correlations with diskiness/boxiness
- Galaxy luminosity function
- Galaxy evolution

[1] All dates (as well as topic ordering) subject to changes announced in class. Please consult each week's *Weekly Handout* for the specific topics to be covered along with the textbook and *Course Reader* readings assigned each week.

Cosmology

The Expanding Universe

- Hubble's second discovery: the Hubble Law
- The cosmological principle
- General theory of relativity and the curvature of spacetime
- Coordinate distance
- Proper time
- Proper distance
- Spacetime interval
- Metric for flat spacetime
- Curved spacetime *outside* of a mass concentration: the Schwarzschild metric
- Curved spacetime *inside* a dust-filled universe: the Robertson-Walker metric
- Comparing proper and coordinate distances
- Cosmic scale factor (R)
- Cosmological time dilation derived
- Cosmological redshift derived
- The expanding universe
- Hubble flow and peculiar velocity
- Making a Hubble diagram with luminosity distances
- Hubble time
- The gold-standard distance indicator: type Ia supernovae (SNe Ia)
- Determining H_0 from the local Hubble diagram with SNe Ia

→ Midterm Exam (Exact Date TBA, but probably ∼ March 19)

The Dynamic, Matter-Only Universe

- The dynamic universe
- Newtonian formulation of a (pressureless) dust-filled universe
- Dynamics of a Newtonian universe: the Friedmann equation
- Critical density and the density parameter (Ω_M)
- How R, H, and Ω_M evolve in a matter-only universe
- Age of universe
- Lookback time
- The basic equations of cosmology: Friedmann, fluid, and acceleration equations, and the equation of state parameter (w)

- Return to the Robertson-Walker metric: comparing distances over time, the path of photons through a dust-filled universe, the partical horizon, and the horizon distance
- Cosmic event horizon
- Return to observational astronomy: measuring the cosmic deceleration to determine universe's fate
- Deceleration parameter (q_o)
- Measuring q_0 via the redshift-magnitude relation

The Supernova Discovery: Introducing the Multi-Component Universe

- The surprise of the century: the accelerating universe
- Considering constituents other than pressureless matter (i.e., $w \neq 0$): the generalized basic equations of cosmology
- Introducing the cosmological constant (Λ)
- How R evolves with time in matter-only, Λ-only, and radiation-only (γ) universes
- The multi-component universe: incorporating M, Λ, and γ
- q in a multi-component universe, and the conditions for acceleration/deceleration
- Deriving Ω_Λ, Ω_M and Ω_γ (or alternatively $\Omega_{\text{relativistic}}$) from the generalized redshift-magnitude relation
- The supernova result with Ω_Λ
- Understanding the supernova result: statistics review/error analysis
- Λ makes a bold prediction for higher-z: prediction confirmed, the cosmological constant upheld
- Fully relativistic cosmology
- The very latest SN results in the $\Omega_m - \Omega_\Lambda$ plane
- Fate of accelerating universe driven by Λ
- Age of universe revisited
- Cosmic jerk
- Evolution of R
- Particle horizon and cosmic event horizon revisited
- Maximum visible age

→ **Course Project Due: April 23**

The Early Universe

- The early universe: a primer — abundances of the elements, steady-state theory, and the prediction and confirmation of the cosmic microwave background (CMB)
- The CMB: dipole anisotropy, Sunyaev-Zel'dovich effect
- Understanding the early universe: key terms, concepts, and particles
- Review of quantum mechanics: spin states, bosons, fermions, anti-particles, neutrinos

- Key moments in cosmic history
- Deriving Ω_{rel}
- The "concordance cosmology"
- Big Bang nucleosynthesis
- Surface of last scattering
- Review of statistical mechanics: Bose-Einstein statistics, Fermi-Dirac statistics, degrees of freedom, Boltzmann and Saha equations
- The very early universe: unification and spontaneous symmetry breaking
- Difficulties with standard Big Bang theory: the flatness and horizon problems
- Inflation and the birth of the CMB

The Concordance Cosmology: SNe + WMAP + BAO

- Angular diameter distance
- Luminosity distance, angular diameter distance, comoving distance, and light travel time distance compared
- Reading the CMB: cosmic harmonics, acoustic oscillations, and implications of angular power spectrum peaks
- WMAP results
- Return to galaxies: large-scale structure, galaxy clustering and baryon acoustic oscillations (BAO)
- The concordance cosmology: SNe + WMAP + BAO
- Are we sure it is the cosmological constant? The latest words on $w(z)$ and w'.

→ Note: The last class is Tuesday, May 7.

→ **Final Exam:**

Thursday, May 16, 1:00 PM → 3:00 PM, Room PA-215 (normal lecture room).

Assignments and Course Grades

Course grades will be based on the following scale:

Grade	Percentage
A	93.00 – 100%
A-	90.00 – 92.99%
B+	85.00 – 89.99%
B	75.00 – 84.99%
B-	70.00 – 74.99%
C+	65.00 – 69.99%
C	55.00 – 64.99%
C-	50.00 – 54.99%
D+	45.00 – 49.99%
D	35.00 – 44.99%
D-	30.00 – 34.99%
F	$<$ 29.99%

The final course grade will be determined based on your work in the following areas:

- *Homework assignments*: 20%. Homework assignments (consisting of problems and, occasionally, essays) will be collected periodically throughout the semester, roughly every two weeks. They will be graded on a cumulative basis. Late homeworks will not be accepted under any circumstances *except* if you are observing for the prior two nights before the homework due date, in which case it will be due the day following your final observing night. You must contact me ahead of time to make arrangements for this. Otherwise, it is your responsibility to turn in your homework *before* the start of class on the day it is due.
- *Midterm Examination*: 25%. There will be one midterm exam, which will take place in class roughly on March 19 (exact date TBD).
- *Course Project*: 25%. The course project will be a written report, to be turned in no later than the start of class (3:30 PM) on Tuesday, April 23. Details about the nature of the course project will be given several weeks into the term.
- *Final Examination*: 30%. The final examination is a comprehensive exam covering the entire semester's material, with a particular emphasis on the material covered since the midterm exam. It will be given at the following time and place:

  Thursday, May 16, 1:00 PM → 3:00 PM, Room PA-215 (normal lecture room)

  → **Note**: The University's final examination schedule is always posted online well before the start of each semester. San Diego State University policy expressly forbids the administration of final exams other than at the scheduled time (see p. 470 of the current General Catalog). If you are unable to take the final exam at the scheduled time, then you can not take Astronomy 660 this semester. Also, please note that it is your responsibility to create a schedule for yourself that does not result in having many finals on the same day; no special accommodation will be made for students who create a schedule for themselves that results in them having multiple final exams on the same day.

  Please note that no late assignments will be accepted (other than as provided above), or make-up exams given except under extraordinary circumstances. There will be no "extra credit" projects given. Finally, no form of cheating will be tolerated, and will result in automatic failure in the course and additional disciplinary action by the University.

Final Grade Calculator Worksheet

To compute your final grade in the course:

Step 1: Write down your final homework percentage:

Step 2: Take the number obtained in step 2, and multiply it by 0.2. Write that number down here, and put a box around it:

Step 3: Take your midterm exam percentage and multiply it by 0.25. Write the resulting number down here and put a box around it:

Step 4: Take your course project percentage and multiply it by 0.25. Write the resulting number down here and put a box around it:

Step 5: Take your final exam percentage and multiply it by 0.3. Write the resulting number down here and put a box around it:

Step 6: Add the boxed numbers from Steps 2, 3, 4, and 5 together and write it here:

Step 7: Use the grade scale given on the previous page to calculate your final letter grade, and write it down here:

In all likelihood, this is your final grade for the course. In *exceptional* cases, I may *raise* your grade by up to one mark (e.g., C- to C; B+ to A-, etc.) based on such subjective criteria as my sense of your overall *enthusiasm* for the class and course material. This can be demonstrated in many ways, including "class participation" (note that giving the sense that you are an engaged listener is considered to be just as important as actively contributing to the discussion), attendance, coming to office hours, effort and dedication, and so forth. Note that I will never *lower* a grade that you have earned; your enthusiasm can only help you.

Strategy

And now, some time-tested tips for success in this class:

- **Pay attention in lecture**! While much of the material covered in class is also covered by the text(s), the ordering, emphasis, and presentation of the topics — especially for cosmology — can be quite different. Also, while lectures are *based* on the text, a conscious effort is made to present the material in a somewhat different manner from that given by the book. Often, in lecture I will concentrate on facilitating your qualitative *understanding of equations rather than their mathematical derivations*, since the text generally does a thorough job on that front (and what it doesn't do can be assigned in the problem sets). Everyone has a different preferred learning style; some find lectures the best way to learn the material, some find a textbook presentation most helpful, but everyone benefits from seeing the material presented more than one time and in multiple ways. By coming to lecture you will also see just what information is being emphasized – this is likely to be the same information that is stressed on your exams.
- **Stay on top of the reading**. The textbook contains much of the material for which you are responsible in this course. Each Tuesday you will be given a "Reading Guide" as part of the weekly handout. Look the reading guides over carefully as you read the week's assignment; they will tell you exactly what parts of the assigned sections are crucial to understand. During certain parts of the course (especially at the beginning, when it is assumed that most of the material is review) the reading assignments will be quite hefty – don't get behind, especially if you have not seen some of the "review" material before! Note that, especially during the cosmology portion of the course, that the reading assignments will not proceed linearly through the text.
- **Get help**. Come to my office hours. Work together with friends in the class. There are lots of opportunities to get assistance on the course material – use them!
- **Study**. Don't wait until the last minute to prepare for the midterm or final. This course presents a large amount of information, and it can really "catch up to you" if you do not stay current with the readings.
- **Visit the course website, http://sciences.sdsu.edu/∼leonard/astro660**. There you will find all of the class handouts and assignments, in case you missed anything. All Powerpoint slides from the lectures are also posted there, usually within a day after the lecture is given.

Other Things

- **Contacting me.** Ordered from the *best* way to get in touch with me to absolute *worst* way to get in touch with me:

  1. **Best way:** *Come to office hours*. This is absolutely the best way to get help from me in a one-on-one (or small group) setting. My office hours are a low-pressure environment, and you don't need to come even with specific questions in mind – if you just want to talk about the material in general or have me review some concepts with you that is fine.
  2. **Good way:** *Send me email*. This is an effective way to contact me directly. I am very responsive to emails, often responding within minutes and almost always within 24 hours.
  3. **OK way:** *Come up immediately after class*. If you have a very quick question (or need to let me know something) that can be dealt with in under a minute or so, coming up immediately after lecture can be effective. If it's more complicated, I may ask you to come back to my office to discuss.
  4. **Poor way:** *Call my office*. This is not such a great way to get hold of me, as I am frequently out of the office, or, if I am meeting with other students at the time, I may not even answer the phone. Send email, and you'll likely get a better response.

5. **TERRIBLE way:** *Come up right before class.* Please do not try to talk with me immediately before class, either at my office or in the lecture room. This is absolutely the worst time to attempt to communicate with me. Before lecture I am likely busy getting the lecture material ready/Powerpoint working/etc. If it's a quick question, or you need to let me know something, speak with me right after class or, even better, during office hours or through email.

- **Class videos.** If you get to class a little early, on most days you will find a video playing, usually having something to do with the material to be presented in that day's lecture. *Getting to class early to watch these videos is completely optional*; they will never contain required material that is not also presented during the formal lecture and/or by the textbook. The official class will never begin before 3:30 PM. That said, many students in the past have found the videos to be a relaxing way to get introduced to the topics being discussed in the course, before class actually begins.
- **Asking questions.** Questions during lecture are encouraged – don't be afraid to put your hand up if something has confused you (and appears unlikely to be covered in the subsequent lecture). In particular, the first ten minutes or so of every Tuesday's class will be specifically set aside to answer any questions that you may have about the course or material.