ASTR 660: GALAXIES AND COSMOLOGY
SPRING 2017
SCHEDULE #20319

COURSE INFORMATION

Class Days: Tuesday and Thursday
Class Times: 3:30 PM – 4:45 PM
Class Location: SSW-2650

Professor: Douglas C. Leonard
Contact Information:
Office Hours Days: Friday
Office Hours Times: 10:00 AM – 11:30 AM
Office Hours Location: Physics 238
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Course Overview

Official Course Catalog Description: Morphology, photometric, and spectroscopic properties, dynamics, and evolution of normal galaxies. Current interpretations of peculiar galaxies and QSO's. The extragalactic distance scale. Observational cosmology.

Purpose and Course Content: 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, observed properties). A particular emphasis will be placed on how recent observations are being used to constrain cosmological models.

Student Learning Outcomes: 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;
- Describe the astronomical observations that compel astronomers to believe in the existence of dark matter and dark energy;
- Discuss the major morphological and kinematic similarities and differences among spiral, elliptical, and irregular galaxies;
- Describe at least three major areas in extragalactic astrophysics in which our astronomical knowledge is known to be incomplete.

Enrollment Information

Prerequisites: Astronomy 450. *Highly* recommended: Astronomy 680.

Adding/Dropping Procedures: The general add/drop/waitlist procedure for this course is specified by the rules set forth by San Diego State University at the website: http://arweb.sdsu.edu/es/waitlist/index.html

Statement for Students with Disabilities: If you are a student with a disability and believe you will need accommodations for this class, it is your responsibility to contact Student Disability Services at (619) 594-6473. To avoid any delay in the receipt of your accommodations, you should contact Student Disability Services as soon as possible. Please note that accommodations are not retroactive, and that I cannot provide accommodations based upon disability until I have received an accommodation letter from Student Disability Services. Your cooperation is appreciated.

Course Materials

Required Course Material:

Text: *An Introduction to Modern Astrophysics*, **second edition**, by Bradley Carroll & Dale Ostlie.

Recommended Course Material:

Text: *Introduction to Cosmology* (first edition), by Barbara Ryden.

Text: *Galaxies in the Universe* (second edition), by Sparke & Gallagher.

Options for Accessing Course Materials: All material is available for purchase at the campus bookstore, and may be purchased elsewhere as well (used/rental copies are fine). Note that there is one copy of *An Introduction to Modern Astrophysics* available for student use in the Astronomy Department Reading Room (PA-215A). All course handouts and Powerpoint slides shown in lecture will be posted to the course's Blackboard website (http://blackboard.sdsu.edu) shortly before (or, after) each class.

Course Structure and Conduct

Style of the Course: This course will be a traditional lecture course, with active student participation and questions encouraged.

Course Schedule[1]

Topics will be (roughly, and subject to change) covered in the order given below; important course dates are noted.

Introduction

- Course overview
- Assumed course 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; interstellar extinction
- Edwin Hubble's first discovery: Galaxies
  - Basic types of distances in astronomy defined: Proper distance, coordinate distance, luminosity distance, angular diameter distance, emission distance, observation distance, light-travel distance, and comoving distance
  - Measuring distances in astronomy: Parallax and Cepheid variable stars
  - Extinction and Malmquist bias
- Introduction to supernovae and their use as distance indicators
- Introduction to galaxy classification (the Hubble sequence)
- Very brief introduction to galaxy morphology and globular clusters
- Spiral galaxy rotation curves and the (re)discovery of dark matter

Cosmology

The Expanding Universe

- Edwin Hubble's second discovery: The Hubble Law and the expanding universe
- The cosmological principle
- General theory of relativity and the curvature of spacetime
  - Proper time
  - Spacetime interval
  - Metric for flat spacetime
  - Curved spacetime *outside* of a mass concentration: The Schwarzschild metric

[1] All dates subject to changes announced in class. Please consult each week's Weekly Handout for exact dates. Note that each "week" will begin on a Tuesday, with the sole exception of the first "week" which starts on the first day of class, which is on a Thursday.

- Comparing proper and coordinate distances
- Curved spacetime *inside* a dust-filled, expanding universe: The Robertson-Walker metric
- Cosmological time dilation and cosmological redshift
- Cosmic scale factor (R) and its relationship to cosmological redshift (z)
- Cosmological time dilation demonstrated with supernovae as cosmic clocks

- Hubble flow and peculiar velocity
- Comparing proper, coordinate, and luminosity distances for static universes (flat or curved)
- Making a Hubble diagram with luminosity distances
- Hubble time
- The gold-standard distance indicator: Type Ia supernovae (SNe Ia)

The Dynamic, Matter-Only 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 and the "age crisis" with globular clusters
- Lookback time
- Return to the Robertson-Walker metric: The path of photons through a dust-filled universe, the particle horizon, and the horizon distance
- "Physics-free" derivation of the deceleration parameter, q_o
- Return to observational astronomy: Measuring q_0 via the redshift-magnitude relation to determine the Universe's fate
- The supernova discovery and the surprise of the century: The accelerating universe
- What could have gone wrong? K-corrections, evolution, extinction?

→ **Quiz (Exact Date TBD, but hopefully ∼March 2)**

The Supernova Discovery: Introducing the Multi-Component Universe

- What is causing the observed acceleration? Could our understanding of gravity be flawed?
- Considering constituents other than pressureless matter: The equation of state parameter, w
- The generalized Friedmann equation
- The fluid equation and the generalized acceleration equation
- Introducing the cosmological constant (Λ)

- How R evolves with time for single-component universes with $w = 1/3$ (radiation/relativistic matter); $w = 0$ (pressureless matter); $w = -1/3$ (fluid with negative pressure); $w < 1/3$ (dark energy); $w = -1$ (cosmological constant); and $w < -1$ (phantom energy)
- The multi-component universe: Incorporating M, Λ, and γ
- q in a multi-component universe, and the conditions for acceleration/deceleration
- The generalized redshift-magnitude relation, and how to constrain Ω_Λ, Ω_M and Ω_γ (or, alternatively, Ω_{rel}) from it
- The supernova result revisited: Statistics review/error analysis
- Testing the cosmological constant with a bold prediction for higher-z: Prediction confirmed, the cosmological constant survives
- Specific results for our "benchmark" universe: Matter-Lambda equality; cosmic "jerk"; age; evolution of R; ultimate fate
- Particle horizon and cosmic event horizon revisited
- Maximum visible age
- The geometry, fate, and dynamical state of the universe in the $\Omega_m - \Omega_\Lambda$ plane
- The very latest SN results in the $\Omega_m - \Omega_\Lambda$ plane

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
- The early universe: 10^{-6} sec $\rightarrow 380,000$ years
- Review of quantum mechanics: Spin states, bosons, fermions, anti-particles, neutrinos
- Key moments in cosmic history, and incorporating the effects of Ω_{rel} on the dynamics of the early universe
- The "concordance cosmology"
- A primer on Big Bang nucleosynthesis
- Review of statistical mechanics: Bose-Einstein statistics, Fermi-Dirac statistics, degrees of freedom, Boltzmann and Saha equations
- Key moments in cosmic history: Matter-anti-matter annihilation; neutrino decoupling; and radiation/matter equality
- Basic statistical mechanics review
- Key moments in cosmic history: Big Bang nucleosynthesis; epoch of recombination/decoupling
- Surface of last scattering
- Large-scale structure of the universe: A brief discussion

- The latest CMB results
- Key moments in cosmic history: Epoch of reionization
- The very early universe 10^{-44} sec $\rightarrow$ 10^{-6} sec : Unification and spontaneous symmetry breaking and decoupling of forces
- The Big Bang on trial: Why we like it
- The Big Bang on trial: The flatness and horizon problems
- The "Sonic Horizon Distance"
- Inflation and the birth of the CMB

The Concordance Cosmology: SNe + WMAP + BAO

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

→ Midterm Exam (Exact Date TBD, but hopefully ∼April 11)

Galaxies

- Background material: Stellar mass-luminosity function; metallicity (Z) and opacity; Population I, II, and III stars; role of supernovae in metal enrichment; H II regions
- The Hubble sequence: Basic elliptical and spiral galaxy morphology
- Case study: The Milky Way:
  - Age-metallicity relation
  - Mass-to-light ratio
  - Quantifying surface brightness: The Sersic Profile with exponential and deVaucouleurs special cases
  - Galactic bulge, disk, and stellar halo
  - Galactic center, and evidence for a supermassive black hole
- Spiral galaxies
  - Morphology and brightness profiles

- Rotation curves
- Tully-Fisher relation
- Mass-to-light ratios
- Colors, color gradients, metallicity, and abundance of gas and dust
- X-ray luminosity
- Supermassive black holes, and their evident relations to other observable properties
- Globular clusters
- Introduction to density-wave theory

- Elliptical galaxies
  - Basic properties overview: Light distribution; dust and gas content; rotation; shape (elliptical, twisted, disky, boxy)
  - Properties in detail: Morphological classes; dust and gas content; metallicity; surface brightness profiles
  - Kinematics of stellar population (Faber-Jackson relation, fundamental plane, rotation parameter)
  - Correlations with diskiness/boxiness
- Introduction to galaxy groups and clusters.
- Galaxy luminosity function
- Morphology-density relation
- Galaxy evolution

→ Note: The last class is Thursday, May 4.

→ Final Exam: Thursday, May 11, 1:00 PM → 3:00 PM, Room SSW-2650 (normal lecture room).

Note: The "final exam" in this course will consist of student oral presentations (as part of the final project), and will take place during the time scheduled for the final exam.

→ Final Project written report due by Friday, May 12, 5:00 PM.

Individual and Group Activities Required: There will be weekly reading assignments, along with (nearly) weekly homework assignments (consisting of problems and, occasionally, essays). Homework assignments will be collected throughout the semester (roughly every week). They will be graded on a cumulative basis. Late homeworks will not be accepted under any circumstances (solutions are generally given once the assignment is due) – it is the student's responsibility to turn in homework *at the start of class* on the day it is due. There will be a "final project", consisting of both a written and oral component, assigned midway through the semester and due at the semester's end.

Technology Utilized in the Course: All class Handouts and Powerpoint slides shown in lecture will be posted to the Blackboard website shortly before or shortly after (i.e., usually within a day) each lecture. A scientific calculator is required for this course.

Assignments and Course Grades

Course grades are based on the following scale:

Grade	Percentage
A	93.00 – 100%
A-	87.00 – 92.99%
B+	83.00 – 86.99%
B	77.00 – 82.99%
B-	70.00 – 76.99%
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 will be collected throughout the semester (roughly every week). They will be graded on a cumulative basis. Late homeworks will not be accepted under any circumstances (solutions are generally given once the assignment is due) – it is the student's responsibility to turn in homework *at the start of class* on the day it is due.
- *Quiz*: 15%. There will be one short (∼ 30-minute) in-class quiz given about six weeks into the course – exact date TBD, but hopefully ∼March 2.
- *Midterm Examination*: 35%. There will be one midterm exam, which will take place in class roughly on April 11 (exact date TBD).
- *Final Project*: 30%. The final project will consist of two parts: An oral presentation (to be given during the final examination time for the course: Thursday, May 11, 1:00 PM → 3:00 PM), and a written report, to be turned in no later than 5 PM on Friday, May 12 (you are welcome to turn it in earlier!). Details about the nature of the final project will be given several weeks into the term.

  → **Note**: The University's final examination schedule is always posted online well before the start of each semester, and so all students *must* be available to present their final project during the time-slot indicated by the final exam schedule. Thus, **if you are not able to attend the final exam session at the scheduled time, then you can not take Astronomy 660**.

Excused Absence Make-up Policies: A "Makeup exam" for the midterm or quiz will be considered only for the most dire and verifiable circumstances beyond the control of the student.[2]

[2] To request an exam at an alternate time, please read and carefully follow all instructions on the form "Requesting an Exam at an Alternate Time", available at the Blackboard web-site (click on "Class Handouts", and then click on "Requesting an Exam at an Alternate Time"). Note that makeup exams will differ from the exams given in class, and may include (or consist entirely of) a one-on-one oral interview with the professor.

Grade Calculator Worksheet

To compute your final grade in the course:

Step 1: Take your final homework percentage and multiply it by 0.2. Write that number down here, and put a box around it:

Step 2: Take your quiz percentage and multiply it by 0.15. Write the resulting number down here and put a box around it:

Step 3: Take your midterm exam percentage and multiply it by 0.35. Write the resulting number down here and put a box around it:

Step 4: Take your final project percentage and multiply it by 0.30. Write the resulting number down here and put a box around it:

Step 5: Add the boxed numbers from Steps 1, 2, 3, and 4 together and write it here:

Step 6: 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, if your grade falls near a borderline (i.e., within about 1% or so of the next grade) 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, evidence of effort and dedication, and so forth. Note that I will never *lower* a grade that you have earned; your enthusiasm can only help you.

→ A note on grading philosophy: With the possible exception of the small, subjective "grade boost" mentioned above, grades in Astronomy 660 are completely objectively determined based on student performance in the class. Grades in Astronomy 660 are thus earned by the student, based on performance on the exams, homework, and projects in the class; they are not "given" by the professor.

Other Course Policies

- **Late Homework**. No late homework assignments will be accepted for any reason.
- **Extra Credit**. There is no "extra credit" available in this course.
- **Cheating**. Consistent with University policy, cheating is not tolerated in Astronomy 660. If cheating is deemed to have occurred, a "0" will be recorded for the assignment or exam grade and an "Academic Dishonesty Incident Report" will be submitted to the Center for Student Rights and Responsibilities, where the incident will then be investigated by the Student Conduct Administrator who shall determine whether it is appropriate to charge a student with violation of the Student Conduct Code. Details on the judicial process (and the potential results, including "severance from the University") can be found at the Center for Student Rights and Responsibilities web page: http://go.sdsu.edu/student_affairs/srr/Default.aspx .
- **Incompletes**. **No course grades of "Incomplete" (I) will be given.**[3]

[3] Except under only the most extraordinary circumstance — e.g., a severe and documented medical emergency that affects *only* a student's ability to present the final project at semester's end (*all* other coursework must have been completed). See p. 469 of the SDSU General Catalog for official University policy on Incomplete grades.

- **Contacting the professor.** 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 even need to come 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. Office hours are Fridays, from 10:00 AM — 11:30 AM, in the physics building, Rm. 238 (P238), and I strongly encourage you to use them; no appointment is needed.
  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. When sending me email please, if at all possible, send it to me in "plain text" format. It is difficult for my ancient emailer to read "rich-text" or "HTML-formatted" emails. Usually, you can change the format of your outgoing email by changing the "settings".
  3. **OK way:** *Catch me right 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, catching me right after class can be effective.
  4. **Poor ways:** *Call my office, or stop by my office at a time other than office hours.* These are not such great ways to get hold of me, as I am frequently out of the office, or, if I am in the office, may be too busy with other tasks to have a helpful discussion (I may not even answer the phone!). Send an email, and you'll likely get a (much) 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 some 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 the official class start time. 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. In particular, the first ten minutes or so of class each week will be specifically set aside to answer any questions that you may have about the course or material.

- **Classroom safety**. For all information concerning safety in the classroom, please read the information contained at San Diego State University's "Emergency Preparedness" website: http://bfa.sdsu.edu/emergency/ .

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 week 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 in-class exam or quiz. 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 Blackboard website, http://blackboard.sdsu.edu**, when needed. 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.

(Mileva Maric and Albert Einstein, c. 1902.)