AS 413 – Extragalactic Astrophysics & Cosmology (Fall 2010)
TR 11:00 am – 12:15 pm (lecture; recorded in Zoom; in-person and remote)
W 1:25pm – 2:15pm (discussion; not recorded; **remote only**)

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Office Hours: Mon. 8:30am–10:30am and by appointment **(remote only)**

Course Description

This course serves as an introduction to advanced topics in extragalactic astrophysics (astrophysics outside the Milky Way) and cosmology (the study of the universe as a whole). Galaxies are the fundamental building blocks of the universe; i.e., they are the basic "bricks" out of which the structure of the universe is assembled. Therefore, it's natural to combine studies of the present-day properties of galaxies, as well as theories of their formation and evolution, with studies of cosmology in order to gain an understanding of how the universe came to be as we currently observe it. Particular emphasis will be placed on the use of modern extragalactic observations to constrain theories of the origin and nature of the universe. In addition to topics that are well understood, we will also discuss a number of current unanswered questions in modern cosmology and how the answers to these questions may ultimately shape our theories of the origin and evolution of the universe.

Learn *from* Anywhere

AS413 will be adopting the L*f*A model for the semester. When possible, lectures will be live "in person" in room CAS502, with synchronous remote participation available through Zoom. Lectures will take place on Tuesdays and Thursdays. Discussion sections will take place on Wednesdays. All discussion sections and office hours will be held as live remote Zoom sessions. All lectures will be recorded via Zoom and will be posted on learn.bu.edu for those students wishing to engage in remote, asynchronous learning. **Discussion sections and office hours will not be recorded.** Note: all Zoom recordings will be processed through Kaltura Media so that they cannot be downloaded. Only Professor Brainerd and students who are registered for AS413 will have access to the recordings. Information on Zoom meeting IDs and passwords will be posted on learn.bu.edu. **Do not share the Zoom meeting IDs or passwords with anyone who is not registered as a student in AS413.** Students who do not wish to have their images and/or voices recorded may opt out in various ways. Students attending in person who wish to opt out of video recording should sit out of view of the room camera when it is in use. Students attending in person who wish to ask a question, but who also wish to opt out of having their voices recorded, should email their question to Professor Brainerd, who will respond to the question after class. Students attending remotely who wish to opt out of video recording should keep their cameras off, and they may also choose to use an alternative, non-identifying Zoom name that has been shared privately with Professor Brainerd in advance of the Zoom session. Students attending remotely who wish to ask a question, but who also wish to opt out of having their voices recorded, should email their question to Professor Brainerd, who will respond to the question after class. Students who are attending remotely can also call in to the Zoom session with caller ID disabled. **Students should not use the "chat" function in Zoom to send questions to Professor Brainerd during class because it is impossible for her to monitor the chat while also sharing her computer screen.**

SARS-CoV-2/COVID-19 Safety Protocols

All students must adhere to BU's strict guidance on preventing the transmission of SARS-CoV-2, the novel coronavirus that causes the disease known as COVID-19. Students must wear a face covering that covers their mouths and noses at all times, must maintain physical distancing of at least 6 feet at all times, and are responsible for sanitizing their chairs and desks both prior to the start of class and after class has ended. BU will be providing sanitizing wipes for this purpose. **Eating and drinking in CAS502 and in the hallway outside CAS502 is absolutely prohibited.** All assignments and examinations must be submitted through learn.bu.edu. Students who fail to adhere to BU's strict guidance on COVID-19 safety protocols will be reported to the office of the Dean of Students. For guidance on BU's COVID-19 safety protocols, students should refer to https://www.bu.edu/back2bu/ .

BU Hub Learning Outcomes

AS413 satisfies the requirements for the BU Hub learning outcomes for Historical Consciousness (HCO) and Research and Information Literacy (RIL). The HCO and RIL outcomes will be satisfied and evaluated as discussed below.

HCO Outcome #1 (*Students will create historical narratives, evaluate interpretations based on historical evidence, and construct historical arguments*): Students will learn to construct historical arguments relating to key questions in extragalactic astrophysics and cosmology: "Why is the night sky dark?" (a.k.a. Olbers' Paradox), "What is our place in the universe?", and "What is the nature of the extragalactic nebulae?" The answers to these questions form the underpinnings of modern, scientific cosmological understanding. In addition, they represent a total intellectual paradigm shift away from the pre- and early-20th century belief that we reside at the center of a finite, non-evolving universe that is in static equilibrium, to our current understanding that we occupy no special place in a universe that is infinite in extent, continuously evolving, and out of equilibrium.

HCO Outcome #2 (*Students will demonstrate an ability to interpret primary source material (textual, visual, or aural) using a range of interpretive skills and situating the material in its historical and cultural context*): Students will read papers on Olbers' Paradox that have been published in the scientific literature, as well as transcriptions of the arguments made by Harlow Shapley and Heber Curtis in the April 26, 1920 National Academy of Sciences' "Great Debate" on The Scale of the Universe. These readings will inform both class discussion and two HCO homework assignments (see HCO Outcome #3 below). Students will also read and discuss an article published recently in Physics Today on the topic of whether or not Albert Einstein truly expressed the opinion that his introduction of "the cosmological term" in the field equations of general relativity was his greatest scientific blunder.

HCO Outcome #3 (*Students will demonstrate knowledge of religious traditions, intellectual paradigms, forms of political organization, or socioeconomic forces, and how these have changed over time*): Students will discuss the underpinnings of the intellectual paradigm shift away from our pre- and early 20th century understanding of the nature of the universe in lectures and discussion sections. Students will also complete two homework assignments related to this material. The assignments will require students to evaluate historical interpretations of observational data and physical theory (involving, e.g., the speed of light). The assignments will require students to construct historical arguments and place those arguments in context with modern observational data and physical theory. The first assignment will involve Olbers' Paradox (understanding the nature of the paradox, and working to resolve the paradox from historical and modern viewpoints). The second assignment will involve the history of establishment of the extragalactic distance scale, which addresses both our place in the universe and the nature of the extragalactic nebulae. Students will be expected demonstrate deep understanding of cosmological paradigm shifts on examinations. In addition to Olbers' Paradox and The Great Debate, students will learn the history behind Einstein's introduction of "the cosmological term" in the field equations of general relativity. Students will be able to discuss the fact that, far from being "Einstein's greatest blunder", the cosmological term allows the widest possible range of theoretical universes to be constructed and is the leading candidate for the source of dark energy in the universe.

RIL Outcome #1 (*Students will be able to search for, select, and use a range of publicly available and discipline-specific information sources ethically and strategically to address research questions*): Discussion section time will be devoted to topics directly related to a research paper that each student will be expected to write. Topics to be covered in discussion section include: strategies for identifying a research paper topic, evaluating the reliability of sources, the importance of correct citation/attribution of sources, citation and bibliographic style used in The Astrophysical Journal, the difference between scientific "acceptance" and scientific "controversy", and constructing an annotated bibliography.

RIL Outcome #2 (*Students will demonstrate understanding of the overall research process and its component parts, and be able to formulate good research questions or hypotheses, gather and analyze information, and critique, interpret, and communicate findings*): Students will complete a research paper on a topic relevant to any of the major topics covered by the course. Prior to writing the paper, students must submit a written proposal for their research topic and an annotated bibliography. The paper must include clear discussion of the historical context of the topic, as well as ways in which previously controversial ideas related to the topic have become accepted by the scientific community or, if appropriate, ways in which the topic currently remains controversial. See the Research Paper section below for additional details.

Evaluation of BU Hub Learning Outcomes: The HCO learning outcomes will be evaluated using the HCO homework assignments, examinations, the research paper, and student participation in discussion sections. The RIL learning outcomes will be evaluated using the annotated bibliography, the research paper, and student participation in discussion sections. See the Grading section below for additional details.

Pre-requisites and Expectations

AS413 is intended primarily for junior and senior concentrators in Astronomy, Astronomy & Physics, and Geophysics & Planetary Sciences. Students are expected to have completed the astronomy, physics, and mathematics requirements of their respective programs through the sophomore year. The formal pre-requisite classes are AS203, AS312 and PY355. Students are expected to have a good working knowledge of the material in these courses and to be able to apply that knowledge to this class, particularly when it comes to solving problems. In the latter half of the course there will be a significant amount of differential and integral calculus required to solve the problems, and students will be expected to perform these calculations without having been shown examples of the necessary mathematical techniques in an AS413 lecture. **Note that, unless a problem specifically states otherwise, tables of integrals, on-line integrators, and symbolic integrators such as Mathematica may not be used to solve homework problems.** Also, in order to receive full credit for a solution, students must always show ALL of their work, and each line of a solution must follow logically from the line above. Students who have not fulfilled the pre-requisites by completion of AS203, AS312 and PY355 may not enroll in AS413. Students who have earned grades lower than "C" in any of these courses are cautioned that they are likely to find AS413 quite challenging and should expect to devote considerable time outside of class to complete the assignments and to study for examinations.

Instructional Format, Course Pedagogy and Approach to Learning

There will be two lectures and one discussion section every week. Students are expected to attend, and participate in, all lectures and discussion sections unless their absence is excused (for e.g., medical reasons or observance of religious holidays, as outlined in BU's Policy on Religious Observance). Both the lectures and the discussion sections will incorporate the Socratic "question and answer" style of instruction, where students are actively challenged to actively engage with the material. Active student participation (e.g., asking spontaneous questions, responding to questions asked by the professor, and/or engaging the rest of the class in in-depth discussion) will be incorporated into each student's final grade.

Academic Conduct

Students are expected to know and understand the Academic Conduct Code. A copy of the Academic Conduct Code is posted at http://www.bu.edu/academics/resources/academic-conduct-code/ . Cases of suspected academic misconduct (e.g., plagiarism or cheating on examinations) will be referred to the CAS Dean's Office. **Unauthorized downloading, uploading, sharing, and/or duplicating course materials including, but not limited to, assignments, exams, quizzes, slides, videos, and any other material created and/or provided by the instructor without the instructor's express permission is a violation of the Academic Conduct Code.**

Textbook

The textbook recommended for the course is *Extragalactic Astronomy & Cosmology, An Introduction (2nd Edition)* by Peter Schneider. Copies are available at the BU bookstore.

Students can also access a digital version of the textbook through Leganto or by searching the BU library catalog.

Grading

HCO Homework Assignments (total of two, 5% each) – 10%
Homework Problem Sets (approximately eight, lowest 2 scores dropped) – 20%
Video Quizzes – 5%
Midterm Exams (Oct. 8 & Nov. 12, 10% each) – 20%
Annotated Bibliography – 3%
Research Paper – 12%
Class Participation (Synchronous) – 10%
Final Exam – 25%

Homework

Two HCO homework assignments must be completed. These assignments should be handed in by the start of class on the due date, and all solutions must be the student's own original work (see next paragraph). Late HCO assignments will be accepted with a grading penalty. For every day that a HCO assignment is handed in late, 15% of the available points will be deducted.

Approximately eight homework problem sets will be assigned. Solutions to problem sets must be handed in by the start of class on the due date. **Late problem set solutions will not be accepted; instead grades of zero will be assigned if a student is unable to complete a problem set on time.** Although students are encouraged to discuss potential solutions to the homework problems amongst themselves, each student must hand in her or his own original solution (i.e., students who simply copy another's solution will receive a grade of zero for that problem). Illegible solutions will receive a grade of zero. All solutions must be written in (graphite) pencil, blue ink, or black ink. Solutions written in red ink or colored pencil will receive grades of zero. Solutions for each problem must be written on separate pieces of paper, and on only one side of the paper. When a long solution is necessary for a particular problem, multiple one-sided pages must be used. **Handwritten solutions must not use green engineer's paper or blue quadrille paper.** Solutions must be submitted as single files in PDF format with the pages in the correct order.

Video Quizzes

Several Kaltura Media Video Quizzes will be posted on learn.bu.edu. The primary purpose of these videos is to refresh students' memories of topics that were introduced in AS203 or AS312 (e.g., Hubble's Law, the optical morphology of present-day galaxies, the nature of pulsating variable stars, novae and supernovae). Students must complete the video quizzes prior to the lectures in which the review topics will be discussed and expanded upon.

Examinations

All examinations will be open book. The midterm examinations will be held at the regular class meeting time via Zoom sessions, they will be 75 minutes in duration, and they MUST be taken in class on the dates scheduled. If you discover that you are too ill to take a midterm exam with the class, you must notify Prof. Brainerd by telephone or email **prior to** the start of the examination. If you do not do this, you will receive a grade of zero for the examination and will not be given a makeup exam. All makeup midterm exams will be 75 minute **oral** examinations, and they must be completed within 1 week of the missed exam. The final examination will be held at the time scheduled by the university via a Zoom session. **The date and time of the final examination cannot be altered for any reason.**

Research Paper

Students will complete an 8-page research paper (approximately 4,000 words) on a topic of their choosing. The topic should be relevant to any of the major topics covered by the course. Students will first complete a brief, but formal, written proposal for their research topic. After review of the proposal by the professor, the student will either receive permission to go ahead with the desired topic as proposed, or will be asked to revise the proposal (to, e.g., narrow the topic if the original proposal is too broad) prior to going ahead with the research. Students will construct an annotated bibliography for their research paper, which will count towards the final grade in the class. By the beginning of the last week of classes, students will be expected to have written their research paper. The research paper must include explicit discussion of the historical context of the topic (i.e., both why and how the topic became relevant). The research paper must discuss ways in which previously controversial ideas related to the topic have become accepted by the scientific community or, if appropriate, ways in which the topic currently remains controversial. Late research papers will be accepted with a grading penalty. For every day that a research paper is handed in late, 15% of the available points will be deducted.

Lecture and Discussion Section Outline (Fall 2020)

Note: dates below are approximate; topics on a given day are subject to change depending on the actual pace of the class

Sept. 2: Discussion 1

- Course overview, goals and expectations
- Strategies for identifying research paper topics

Sept. 3: Lecture 1

- What cosmology is and is not
- Working definition of the universe and the concept of physical cosmology
- Meaningless questions in cosmology
- The universe as a time machine
- Cosmological Principle

Sept. 8: Lecture 2

- Hubble's Law
- Doppler shifts vs. cosmological redshift
- Velocities of galaxies: observed, Hubble, and peculiar

Sept. 9: Discussion 2

- Darkness at Night: the nature of Olbers' Paradox
- Resolving Olbers' Paradox using pre-20th century physics and (galactic) astrophysics
- Resolving Olbers' Paradox using 20th century physics and extragalactic astrophysics
- Readings: Harrison, E. R., 1977, "The dark night sky paradox", American Journal of Physics, 45, 119 and Pesic, P. 1998, "Brightness at night", American Journal of Physics, 66, 1013

Sept. 10: Lecture 3

- Review of optical morphologies of galaxies
- Surface brightness as a distance-independent quantity
- deVaucouleurs surface brightness law for elliptical galaxies

Sept. 15: Lecture 4

- Exponential disks and Sersic profiles
- Schechter luminosity function
- ***Historical Consciousness Assignment #1 due***

Sept. 16: Discussion 3

- The Great Debate of April 26, 1920 on "The Scale of the Universe"
- Establishment of the extragalactic distance scale and dispelling the notion of 19th and early 20th century "galactocentrism"
- Readings: Shapley, H. 1921, "The Scale of the Universe: Part I", Bull. Nat. Res. Coun., 2, 171 and Curtis, H., 1921, "The Scale of the Universe: Part II", Bull. Nat. Res. Coun., 2, 194

Sept. 17: Lecture 5

- Gravitational potential
- Equation of mass continuity, Poisson's equation
- Virial Theorem
- Computing total potential energy from mass density

Sept. 22: Lecture 6

- Kinematics of elliptical galaxies
- 3-d shapes of elliptical galaxies
- Faber-Jackson relation
- ***Historical Consciousness Assignment #2 due***

Sept. 23: Discussion 4

- Finding source material for research papers **(special guest: Mary Foppiani, BU Libraries)**
- ***Proposal for research paper topic due***

Sept. 24: Lecture 7

- Masses of elliptical and spiral galaxies
- Tully-Fisher relation
- Mass-to-light ratios and dark matter halos

Sept. 29: Lecture 8

- Two-body relaxation
- Collisional timescales in galaxies
- Stellar phase space
- Collisionless Boltzmann equation
- ***Problem set #1 due***

Sept. 30: Discussion 5

- Importance of citation/attribution of sources
- Citation and bibliographic style in astronomy journals
- Scientific “acceptance” vs. scientific “controversy”

Oct. 1: Lecture 9

- Epicyclic approximation for stellar orbits in disk galaxies
- Rotation terminology and notation

Oct. 6: Lecture 10

- The Winding Problem for spiral galaxies
- Evolution of pitch angle in a differentially rotating spiral galaxy
- ***Problem set #2 due***

Oct. 7: Discussion 6

- Review for Midterm Exam #1
- ***Revisions to proposal for research paper topic due (as needed)***

Oct. 8: Midterm Exam #1

Oct. 14: Discussion 7

- Constructing an annotated bibliography
- Resources for research paper

Oct. 15: Lecture 11

- Kinematic Spiral Density Waves
- Orbital resonances

Oct. 20: Lecture 12

- Primary vs. secondary distance indicators for galaxies
- Measuring H_0

Oct. 21: Discussion 8

- Topics TBD based on student questions

Oct. 22: Lecture 13

- Groups and clusters of galaxies
- Dark matter in the Coma cluster
- ***Problem set #3 due***

Oct. 27: Lecture 14

- Superclusters and voids
- Topology of the universe
- Quantifying galaxy clustering

Oct. 28: Discussion 9

- Topics TBD based on student questions
- ***Annotated bibliography due***

Oct. 29: Lecture 15

- Hierarchical clustering
- Hot, warm, and cold dark matter universes
- Simulating galaxy formation on a computer
- ***Problem set #4 due***

Nov. 3: Lecture 16

- Galaxy formation and evolution
- "Nature vs. nurture" in the formation of elliptical vs. spiral galaxies
- Active galaxies

Nov. 4: Discussion 10

- Topics TBD based on student questions

Nov. 5: Lecture 17

- Newtonian cosmology
- Equation of motion for the matter-dominated universe
- ***Problem set #5 due***

Nov. 10: Lecture 18

- Foundations of general relativity

Nov. 11: Discussion 11

- Review for Midterm Exam #2

Nov. 12: Midterm Exam #2

Nov. 17: Lecture 19
- Robertson-Walker metric
- Co-moving coordinates
- Horizons in cosmology

Nov. 18: Discussion 12
- Topics TBD based on student questions

Nov. 19: Lecture 20
- Ages and lookback times
- Kinematics/curvature connection
- Density parameter and useful versions of the Friedmann equation
- ***Problem set #6 due***

Nov. 24: Lecture 21
- Deceleration parameter
- Distances in cosmology

Dec. 1: Lecture 22
- Universes with matter and radiation
- Theoretical expectation of early, radiation-dominated universe
- Cosmic Microwave Background Radiation
- ***Problem set #7 due***

Dec. 2: Discussion 13
- Topics TBD based on student questions

Dec. 3: Lecture 23
- Dark energy in the universe
- Einstein's cosmological constant
- Reading: O'Raifeartaigh, C. 2018, "Investigating the legend of Einstein's 'biggest blunder'", Physics Today (DOI:10.1063/PT.6.3.20181030a)

Monday, Dec. 7: Research paper due

Dec. 8: Lecture 24
- Radiation era and the production of mass from primordial photons
- Baryogenesis problem
- Inflation as a solution to three classic problems: horizon, flatness, and monopole

Dec. 9: Discussion 14
- Review for Final Exam, part 1

Dec. 10: Lecture 25

- Review for Final Exam, part 2
- Course evaluations
- ***Problem set #8 due***

Rubric for Grading of Mathematical Problems

100% - perfect solution

95% - very minor mathematical errors or the solution is slightly incomplete

80% - problem is set up correctly, the right approach to the solution is demonstrated, but the solution has mathematical errors or is somewhat incomplete

65% - solution demonstrates some understanding of the problem and the path to the solution, but with significant limitations or errors (either mathematical or conceptual errors)

50% - solution demonstrates weak understanding of the problem with little demonstration of the path to the solution

35% - solution demonstrates only minimal understanding of the problem and its solution

0% - solution demonstrates no understanding of the problem, or is left blank