DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

Chair
• John E. Carlstrom

Professors
• John E. Carlstrom
• Fausto Cattaneo
• Hsiao-Wen Chen
• Wendy L. Freedman
• Joshua A. Frieman
• Michael D. Gladders
• Nickolay Y. Gnedin
• Doyal A. Harper, Jr.
• Craig J. Hogan
• Dan Hooper
• Wayne Hu
• Daniel E. Holz
• Edward W. Kolb
• Andrey V. Kravtsov
• Angela V. Olinto
• Paolo Privitera
• Robert Rosner

Associate Professors
• Jacob L. Bean
• Bradford A. Benson
• Clarence L. Chang
• Daniel Fabrycky
• Jeffrey McMahon

Assistant Professors
• Damiano Caprioli
• Chihway Chang
• Alex Drlica-Wagner
• Alex Ji
• Austin Joyce
• Leslie Rogers
• Erik Shirokoff
• Irina Zhuravleva

Emeritus Faculty
• Kyle M. Cudworth
• Lewis M. Hobbs
• Edward J. Kibblewhite
• Arieh Königl
• Richard G. Kron
• Donald Q. Lamb, Jr.
• Stephan S. Meyer
• Takeshi Oka
• Patrick E. Palmer
• Eugene N. Parker
Faculty in the Department of Astronomy and Astrophysics work on a wide range of topics at the frontiers of astrophysics: from understanding the beginning of the Universe to the search for habitable extrasolar planets; from the formation and evolution of the earliest galaxies to modeling the most energetic events in the modern Universe; from exploring our own solar system to the largest structures of the Universe. The department participates in major facilities that support the programs of our research groups. Many of these projects take advantage of connections with the neighboring national laboratories, Argonne and Fermilab, for both intellectual and technical resources. Research groups have access to leading telescopes worldwide, including the 6.5-m Magellan Telescopes at Las Campanas, Chile; the Dark Energy Survey at Cerro Tololo Inter-American Observatory in Chile; and the South Pole Telescope, with its ongoing development of powerful new imagers for measuring the Cosmic Microwave Background. Departmental researchers also make use of a number of telescopes (Hubble, Kepler, Chandra, Fermi, and others) and are actively developing new programs for EUSO, POEMMA, JWST, WFIRST, TESS, SOFIA and LSST. Chicago is an active participant in gravitational waves research as a member of LIGO, leading the development of the Holometer at Fermilab, and studying extreme cosmic particles at the Auger Observatory. We are a founding member of the world’s largest optical telescope, the 25-meter Giant Magellan Telescope, which is now under construction in the Chilean Andes with first light expected toward the end of the decade.

**PROGRAM REQUIREMENTS**

The requirements for the Ph.D. degree in Astronomy and Astrophysics are satisfied through the following steps:

- Completion of required core graduate courses
- Full-time scholastic residence of at least 300 units of coursework per quarter, including summer
- Completion of one to three pre-candidacy research projects
- Successful completion of a two-part Candidacy Exam
- Identification of a Thesis Advisor
- Formation of a Thesis Committee
- Thesis research and preparation
- Final Examination

**ADVISING/MENTORING**

Incoming students are assigned a faculty mentor who will advise and guide the student as they navigate the graduate program. Students are invited to seek out potential research supervisors as early as possible. Engagement with research is encouraged and supported by the program structure and through departmental events. Each week there are various talks, seminars, and colloquia highlighting current research by departmental members and visitors that bring together students, faculty, research scientists and post-docs as a vibrant intellectual community. These occasions help facilitate discovery of research areas and projects that may be of interest to incoming students.

**COURSE REQUIREMENTS**

During the first and second years, students complete one core course per academic quarter, and may choose to take elective courses. The core courses are:

- ASTR 30100 Stars
- ASTR 30300 Interstellar Matter
- ASTR 30400 Galaxies
- ASTR 31000 Cosmology I
- ASTR 31100 High Energy Astrophysics
- ASTR 30600 Detection of Radiation
In addition, first- and second-year students enroll in the required courses ASTR 35000 Order-of-Magnitude Astrophysics (for one quarter) and ASTR 49900 Graduate Research Seminar (for up to five quarters).

RESEARCH

A significant fraction of time in the first two years is devoted to research projects. This work, organized as ASTR 37100 Precandidacy Research, is presented as part of the two-part Candidacy Exam taken in the Autumn and Spring Quarters of the second year. Advancement to candidacy is made when a student has successfully passed the two-part Candidacy Exam and established a Thesis Committee. After candidacy is established, students enroll in ASTR 49400 Post-Candidacy Research and may also take electives of advanced coursework.

GRADING POLICY

Required courses are taken for a quality grade (3.0 on a scale of 4.0). ASTR 37100 Pre-Candidacy Research and ASTR 49400 Post-Candidacy Research are typically taken as P/F, but a letter grade may be requested by the student.

Graduate students are expected to maintain an average grade of B (3.0 on a scale of 4.0) or better in course work at the 300-level. If a student falls below this average, the Deputy Chair for Academic Affairs, in consultation with the student and other faculty, will identify appropriate actions for enhancing academic progress.

ELECTIVES

Elective courses numbered in the 300s and 400s provide more depth in particular research areas, allowing students to explore topics of interest. Students may also take electives during pre-candidacy, or following advancement to candidacy. An instructor may choose to issue a grade of P/F in certain elective courses; however, the student may request a letter grade instead.

DISSERTATION AND FINAL EXAMINATION

The Ph.D. thesis may be a single-author or multiple-author paper that is submitted to a research journal of high quality and judged to be suitable for publication by the student’s full Thesis Committee. This research is presented to the Thesis Committee in a Final Examination to engage in dialogue and debate, and receive constructive criticism. Final examinations are public events attended by the departmental community.

CONTACTS

For general information about application procedures, please contact the Student Affairs Administrator, Laticia Rebeles, lrebeles@astro.uchicago.edu, (773) 702-9808. Additional information regarding the academic program is available on the Department of Astronomy and Astrophysics (https://astrophysics.uchicago.edu/) website.

ASTRONOMY AND ASTROPHYSICS COURSES

ASTR 30100. Stars. 100 Units.
Introduction to stars (physical and observational), hydrodynamics of self-gravitating fluids, statistical mechanics and equations of state, energy transport, astrophysical nuclear reactions, stellar models, advanced topics.
Instructor(s): Alex Ji Terms Offered: Autumn
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

ASTR 30300. Interstellar Matter. 100 Units.
Interstellar medium, collision-less systems, distribution of stars in the solar neighborhood, stellar kinematics/dynamics, observations of galactic large-scale structure, theory of galactic structure and evolution.
Instructor(s): Hsiao-Wen Chen Terms Offered: Autumn
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

ASTR 30400. Galaxies. 100 Units.
The observed universe, the universe at high redshift, early universe microwave background radiation, relativistic homogeneous isotropic cosmologies, evolution of structure in the universe, primordial nucleosynthesis.
Instructor(s): Irina Zhuravleva Terms Offered: Spring
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

ASTR 30600. Detection of Radiation. 100 Units.
Radiation as a random process, optical coherence, and signal analysis in spatial and temporal domains, along with the detection and measurement of radiation with astronomical instruments.
Instructor(s): Jeffrey McMahon Terms Offered: Spring
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

ASTR 31000. Cosmology I. 100 Units.
This course presents an introduction to the principles of cosmology. The first part introduces homogeneous, relativistic cosmologies and covers the Robertson-Walker metric, dynamics in the presence of matter, radiation, and dark energy, the universe as a function of time and redshifts, and techniques for calculating observable quantities. The next part covers the growth and evolution of structure in the universe including the formation of clusters and voids, correlation functions, and the mass spectrum. The next part covers the physics of the early universe, including inflation, primordial nucleosynthesis, and recombination. The final part covers current topics
in cosmology, including analysis of the cosmic microwave background and tests for detecting and measuring dark matter and dark energy.
Instructor(s): Austin Joyce Terms Offered: Winter
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

**ASTR 31100. High Energy Astrophysics. 100 Units.**
This course covers a wide range of phenomena associated with the astrophysics of high energy photons, cosmic rays and neutrinos, including the processes of ionization, bremsstrahlung, synchrotron, pion production, Compton and inverse Compton scattering, as well as cosmic ray acceleration. Specific sources of high energy emission will also be discussed, including active galaxies, pulsars, gamma-ray bursts and supernova remnants.
Instructor(s): Damiano Caprioli Terms Offered: Winter
Prerequisite(s): Open to advanced undergraduates by consent of instructor.

**ASTR 31200. Computational Techniques in Astrophysics. 100 Units.**
This course will introduce basic computational techniques most often used in astronomical research, such as interpolation, transforms, smoothing, numerical differentiation and integration, integration of ordinary differential equations, and Monte Carlo methods, and elements of basic computer algorithms, data structures, and parallel programming using Python as the main course programming language with heavy use of NumPy, SciPy, and Matplotlib packages. Practical examples where these numerical techniques are applied will be covered via homework and in class exercises using real-world astronomical problems and results of recent papers with emphasis on implementing the algorithms from scratch. The course will cover the access to astronomical archival data, and how to search it efficiently, focusing specifically on the Sloan Digital Sky Survey, but with introduction to other data sets. Machine learning methods will be introduced to illustrate how large data sets can be mined for interesting information.
Instructor(s): Andrey Kravtsov Terms Offered: Spring
Prerequisite(s): ASTR 20500 or CMSC 12100 or consent of instructor.
Equivalent Course(s): ASTR 21100

**ASTR 31400. Creative Machines and Innovative Instrumentation. 100 Units.**
An understanding of the techniques, tricks, and traps of building creative machines and innovative instrumentation is essential for a range of fields from the physical sciences to the arts. In this hands-on, practical course, you will design and build functional devices as a means to learn the systematic processes of engineering and fundamentals of design and construction. The kinds of things you will learn may include mechanical design and machining, computer-aided design, rapid prototyping, circuitry, electrical measurement methods, and other techniques for resolving real-world design problems. In collaboration with others, you will complete a mini-project and a final project, which will involve the design and fabrication of a functional scientific instrument. The course will be taught at an introductory level; no previous experience is expected. The iterative nature of the design process will require an appreciable amount of time outside of class for completing projects. The course is open to undergraduates in all majors (subject to the pre-requisites), as well as Master's and Ph.D. students.
Instructor(s): Scott Wakely (Autumn), Erik Shirokoff (Winter), Stephan Meyer (Spring) Terms Offered: Autumn Spring Winter
Prerequisite(s): PHYS 12200 or PHYS 13200 or PHYS 14200; or CMSC 12100 or CMSC 12200 or CMSC 12300; or consent of instructor.
Equivalent Course(s): PHYS 21400, ASTR 21400, PSMS 31400, CHEM 21400, CMSC 21400

**ASTR 32060. What Makes a Planet Habitable? 100 Units.**
This course explores the factors that determine how habitable planets form and evolve. We will discuss a range of topics, from the formation of planets around stars and the delivery of water, to the formation of atmospheres, climate dynamics, and the conditions that allow for the development of life and the evolution of complex life. Students will be responsible for periodically preparing presentations based on papers in peer-reviewed journals and leading the discussion.
Instructor(s): Edwin Kite Terms Offered: Winter
Equivalent Course(s): GEOS 22060, GEOS 32060, ASTR 22060

**ASTR 32100. Cosmology II. 100 Units.**
Study of physical cosmology with emphasis on the standard big-bang model and its observational and experimental tests.
Instructor(s): Dan Hooper Terms Offered: Spring
Prerequisite(s): Open to advanced undergraduates who have taken Cosmology I by consent of instructor.

**ASTR 35000. Order-of-Magnitude Astrophysics. 100 Units.**
In physics and astrophysics, an approximate answer is often just as (if not more) useful than an exact answer. Making order-of-magnitude estimates is helpful to develop physical intuition, to verify numerical solutions, and to evaluate whether a research problem is worth pursuing. In this course, students will receive coaching and practice in physics-based reasoning, back-of-the-envelope estimation, and thinking on their feet. Students will be encouraged to take a broad perspective, to think critically, and to have fun using physics to understand the universe around them.
Instructor(s): Leslie Rogers Terms Offered: Autumn
Note(s): Open to 3rd and 4th year undergraduates in the Physical Sciences by instructor consent.
Equivalent Course(s): ASTR 25000

**ASTR 37100. Precandidacy Research. 300.00 Units.**
Students arrange with a faculty research supervisor to conduct a short-term independent research project lasting one or more quarters. Research completed in ASTR 37100 is presented as part of the student's candidacy exams.
Instructor(s): Various Terms Offered: Autumn Spring Summer Winter

**ASTR 40200. Particle Astrophysics. 100 Units.**
This course will provide an introduction to particle physics intended for astrophysicists and cosmologists. In addition to introducing the Standard Model, Feynman diagrams, and other concepts found in particle physics, it will cover a variety of contemporary topics, including dark matter candidates (supersymmetry, axions, etc.), inflation, baryogenesis, neutrino cosmology, and cosmological phase transitions. A background in quantum field theory is not required to participate in this course.
Instructor(s): Dan Hooper Terms Offered: Autumn

**ASTR 40800. The Perturbed Universe. 100 Units.**
This seminar course will cover inflation as the source of structure in the universe and its observational signatures. Topics will include relativistic perturbation theory, canonical and general single field inflationary models, primordial non-Gaussianity, and gravitational waves.
Instructor(s): Wayne Hu Terms Offered: Winter

**ASTR 44700. The Hubble Constant. 100 Units.**
The Hubble constant is the cosmological parameter that sets the absolute scale, size and age of the universe; it is one of the most direct ways we have of quantifying and constraining how the universe evolves. In recent years, a tension has arisen in measurements of the Hubble constant that come from using Cepheid variables to tie into the Hubble expansion based on Type Ia supernovae (~74 km/sec/Mpc), and those inferred from measurements of fluctuations in the cosmic microwave background (~67 km/sec/Mpc). Yet a third method, using red giant branch stars (the Tip of the Red Giant Branch or TRGB) give results that lie between the Cepheids and CMB (~70 km/sec/Mpc). This discrepancy raises the interesting possibility that there is physics missing from our standard (Lambda) Cold Dark Matter cosmological model. In this course we will cover the history of recent measurements of the Hubble constant, delve into how current measurements are made, examine the theoretical ideas for explaining the current tension, and look forward to the future and prospects for either supporting or refuting the case for new physics.
Instructor(s): Wendy Freedman Terms Offered: Spring

**ASTR 49400. Post-Candidacy Research. 300.00 Units.**
Independent research undertaken towards completion of the dissertation.
Instructor(s): Various Terms Offered: Autumn Spring Summer Winter
Prerequisite(s): Completion of all candidacy requirements.

**ASTR 49900. Graduate Research Seminar. 100 Units.**
The instructor chooses a topic for the seminar and assigns papers that develop the topic from the earliest times to the most recent results. Students each present papers during the course, as assigned, and lead a discussion. The purpose is to give students practice in analyzing the literature and presenting to their peers, as well to assure exposure to a breadth in the topics in astronomy and astrophysics.
Instructor(s): Joshua Frieman, Jacob Bean Terms Offered: Spring Winter. Winter Quarter instructor Joshua Frieman; Spring Quarter instructor Jacob Bean.
Prerequisite(s): Intended for doctoral students in the Department of Astronomy and Astrophysics.

**ASTR 50000. Theory and Practice of Science Education. 000 Units.**
In this seminar, students examine their work as teaching assistants through activities that include self-reflection; investigating relevant educational literature; and engaging in in-depth discussions about their own teaching and learning. Readings and discussion topics include questioning techniques, learning theory, cooperative learning, growth mindset, metacognition, developing relationships with students, equity, and differentiation. Students will try out new ideas each week in their learning teams and report their results in class. In many cases, students provide guidance to one another regarding managing issues that typically arise in their learning teams. The seminar is intended for graduate students who are serving as teaching assistants for the first time, and is typically taken in the same quarter in which the student begins teaching.
Instructor(s): Brent Barker Terms Offered: Autumn Spring Winter
Prerequisite(s): Undergraduates serving as course assistants may enroll with instructor consent.
Note(s): Graduate students in Astronomy and Astrophysics and Geophysical Sciences enroll in ASTR 50000 the first quarter in which they will teach.
Equivalent Course(s): GEOS 39500