DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

Chair
- Joshua A. Frieman

Professors
- Jacob L. Bean
- John E. Carlstrom
- Fausto Cattaneo
- Hsiao-Wen Chen
- Daniel Fabrycky
- Wendy L. Freedman
- Joshua A. Frieman
- Michael D. Gladders
- Nickolay Y. Gnedin
- Daniel E. Holtz
- Dan Hooper
- Wayne Hu
- Edward W. Kolb
- Andrey V. Kravtsov
- Jeffrey McMahon
- Angela V. Olinto
- Paolo Privitera
- Robert Rosner
- Abigail G. Vieregg

Associate Professors
- Bradford A. Benson
- Damiano Caprioli
- Clarence L. Chang
- Alex Drlica-Wagner

Assistant Professors
- Chihway Chang
- Alex Ji
- Austin Joyce
- Harley Katz
- Gordan Krnjaic
- Jamie Law-Smith
- Diana Powell
- Leslie Rogers
- Irina Zhuravleva

Emeritus Faculty
- Kyle M. Cudworth
- Doyal A. Harper, Jr.
- Lewis M. Hobbs
- Edward J. Kibblewhite
- Arieh Königl
- Richard G. Kron
- Donald Q. Lamb, Jr.
- Stephan S. Meyer
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 scheduled for construction in Chile 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 graduate courses
- Full-time scholastic residence of at least 300 units of coursework per quarter, including summer
- Completion of pre-candidacy research projects
- Successful completion of a two-part Candidacy Exam, taken at the beginning and end of the second year
- 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.

PRE-CANDIDACY REQUIREMENTS

During the first and second years, students complete the following Core Courses:

- ASTR 30100 Stars
- ASTR 31000 Cosmology I
- ASTR 30400 Galaxies
- ASTR 30300 Interstellar Matter
• ASTR 31100 High Energy Astrophysics
• ASTR 30600 Detection of Radiation

Other required courses are:
• ASTR 35000 Order-of-Magnitude Astrophysics
• ASTR 34000 Statistical Methods in Astrophysics
• ASTR 49900 Graduate Research Seminar
• ASTR 49910 Graduate Seminar: Colloquium
• ASTR 49920 Graduate Seminar: Fellowship and Proposal Writing
• ASTR 49930 Graduate Seminar: Candidacy Preparation

Additionally, ASTR 37100 Precandidacy Research is taken every quarter. In this course, students arrange with a faculty 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 two-part Candidacy Exam taken in the Autumn and Spring Quarters of the second year.

**PLAN OF STUDY**

<table>
<thead>
<tr>
<th>First Year</th>
<th>Autumn Quarter</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
<th>Summer Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTR 30100</td>
<td>ASTR 31000</td>
<td>ASTR 30400</td>
<td>ASTR 37100</td>
<td></td>
</tr>
<tr>
<td>ASTR 35000</td>
<td>ASTR 49910</td>
<td>ASTR 49920</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTR 37100</td>
<td>ASTR 37100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Year</th>
<th>Autumn Quarter</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
<th>Summer Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTR 30300</td>
<td>ASTR 31100</td>
<td>ASTR 30600</td>
<td>ASTR 37100</td>
<td></td>
</tr>
<tr>
<td>ASTR 37100</td>
<td>ASTR 34000</td>
<td>ASTR 49930</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTR 49900</td>
<td>ASTR 37100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Advancement to candidacy is made when a student has successfully passed the two-part Candidacy Exam, and established a Thesis Committee by the end of the Autumn Quarter of the third year. After candidacy is established, students enroll in ASTR 49400 Post-Candidacy Research and may also take electives of advanced coursework. Ph.D. candidates are expected to meet with their committees at least twice per year to review progress on the thesis project.

**FINANCIAL SUPPORT**

All students admitted to the Ph.D. program are offered full financial support. Generally this takes the form of a teaching assistantship that provides a full tuition scholarship and pays a competitive monthly stipend. Teaching assistants are typically assigned to one of the undergraduate laboratory courses in the general education program. The department requires a minimum of two quarters of teaching, after which students may continue to be supported through teaching assistantships, research assistantships, or fellowship funding. Students are urged to compete for the many national and other fellowships available. Incoming students who hold a fellowship may defer the teaching assignment requirement.

**GRADING POLICY**

All 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. 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.

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.

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.

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.

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.

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.

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.
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. Equivalent Course(s): CMSC 21400, PHYS 21400, PSMS 31400, ASTR 21400, CHEM 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.
Equivalent Course(s): ASTR 22060, GEOS 32060, GEOS 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.

**ASTR 33000. Computational Physics and Astrophysics. 100 Units.**
Basic computational methods useful for astrophysics, supplemented by specific examples drawn primarily from
astrophysics. Starting with basics (e.g., precision, errors and error analysis) and basic computational methods
(differentiation, integration/quadrequart, Monte Carlo, numerical linear algebra), and then discussing solution of
problems posed in terms of ordinary and partial differential equations.

**ASTR 33500. Historical Highlights in Astronomy from Hipparcos to Hubble. 100 Units.**
This course will focus on important developments in our understanding of the universe from ancient Greeks
to modern Geeks, taught from the perspective of a scientist. Even more interesting than the advances were
the missteps and false assumptions that impeded progress. The course grade will be based on a 45-minute
presentation about a relevant person or historical discovery.
Equivalent Course(s): CHSS 33501, ASTR 23500

**ASTR 34000. Statistical Methods in Astrophysics. 100 Units.**
An exploration of the variety of statistical methods used in modern astrophysics. We discuss the frequentist
(hypothesis tests, confidence intervals) and Bayesian (explicit priors, model-choosing, parameter estimation)
approaches. Other topics include: Markov Chain Monte Carlo and other computational statistics; multi-
dimensional likelihood space; Fischer information matrices; time series analysis. Assignments draw from
examples in the astronomical literature.

**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.
Equivalent Course(s): ASTR 25000

**ASTR 35900. Physics of Planetary Interiors. 100 Units.**
This course considers the physical processes governing the interior structure and evolution of planets, both
those orbiting the Sun and exoplanets. Topics include an introduction to condensed matter physics relevant to
planet interiors; properties of planetary materials; observational constraints; planet modeling; thermal histories;
differentiation and core formation; connection to planetary atmospheres; and magnetic field generation.

**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.

**ASTR 38400. Gravitational Wave Astrophysics. 100 Units.**
With LIGO's detection of gravitational waves from the merger of two black holes, the era of gravitational-wave
astronomy has arrived. The detection of gravitational waves and photons from the merger of two neutron stars
was similarly revolutionary. This class will explore the basics of gravitational-wave sources and detection. We
will discuss recent results, and explore the future promise of gravitational-wave astrophysics and cosmology.

**ASTR 38700. Cosmic Evolution of Information. 100 Units.**
The course will assemble a concise narrative of how physics and cosmology explain ubiquitous cosmic structure,
complexity, and arrows of time. The cosmic evolution of macroscopic and microscopic information will be
reviewed, including the distinct and unique roles of quantum mechanics and gravity. Readings will be chosen
first to address what is explained by well-established thermodynamics, quantum theory, general relativity,
and inflationary cosmology, and then turn to still-unresolved foundational tensions among theories, such as
the relationship of gravity and causal structure with quantum nonlocality and indeterminacy, and to physical
constraints on future evolution. The course will be conducted as a seminar, with significant student participation
in discussion and presentation. It is designed as a graduate elective, but is open to undergraduates with adequate
preparation in thermodynamics, quantum mechanics, and relativity.
Equivalent Course(s): ASTR 28700

**ASTR 38900. Kepler: Astronomy. 100 Units.**
The course will focus on Johannes Kepler, whose discovery of the three major laws of planetary motion
topped the Copernican model of the universe and established him as a key figure in the 17th century scientific
revolution.
Equivalent Course(s): CHSS 39000, HIPS 28901
ASTR 39000. Counterhistories of Mathematics and Astronomy. 100 Units.
Mathematics and astronomy are often taught as packaged universal truths, independent of time and context. Their history is assumed to be one of revelations and discoveries, beginning with the Greeks and reaching final maturity in modern Europe. This narrative has been roundly critiqued for decades, but the work of rewriting these histories has only just begun. This course is designed to familiarize students with a growing literature on the history of mathematics and astronomy in regions which now make up the global south. It is structured as a loosely chronological patchwork of counterexamples to colonial histories of mathematics and astronomy. Thematic questions include: How were mathematical and astronomical knowledge conjoined? How were they embedded in political contexts, cultural practices, and forms of labor? How did European scientific modernity compose itself out of the knowledges of others? Where necessary, we will engage with older historiographies of mathematics and astronomy, but for the most part we will move beyond them. No mathematics more advanced than high school geometry and algebra will be assumed. However, those with more mathematical preparation may find the course especially useful.
Equivalent Course(s): SALC 39000, HIST 35305, HIPS 27010, ASTR 29000, CHSS 39001, KNOW 39000

ASTR 39900. Reading And Research: Astronomy. 300.00 Units.
Readings and Research for working toward their PhD.

ASTR 40100. Practical Data Analysis. 100 Units.
This course will touch on basic issues related to analyzing and interpreting astronomical data. An emphasis will be placed on understanding the limitations and biases in different types of observations and measurements, and on finding ways of addressing and quantifying them. The course will be project driven so that the students will gain hands-on experience working with different types of data. The projects will cover a range of topics that involve imaging and spectral analysis, and explorations of public data archives.

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.

ASTR 40600. Gravitational Lensing. 100 Units.
Theory of bending of light by gravitational potentials followed by astrophysical and cosmological applications including: microlensing, planetary searches, strong lensing, and weak lensing. In different years, a subsample of these topics may be taught, based on interests of the instructor.

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.

ASTR 40900. Topics in Observational Cosmology: Superconducting Detectors. 100 Units.
This course will cover the physics and application of superconducting detectors and devices for use in astronomical and particle-astrophysics instruments. Technologies include Transition Edge Sensors, SQUID multiplexers, Kinetic Inductance Detectors and other similar implementations of applied superconductivity. The class will focus on applications of these technologies aimed at addressing topics of interest to fundamental physics and astronomy including Dark Matter searches, studies of the Cosmic Microwave Background, and sub-mm astronomy.

ASTR 41000. History of the Telescope. 100 Units.
Consult instructor for course description.

ASTR 41100. Science of the Dark Energy Survey. 100 Units.
Is the accelerated expansion of the Universe due to dark energy or does it require a modification of gravity? This informal seminar course will focus on the use of the Dark Energy Survey (DES), and by extension other surveys, to probe the origin of cosmic acceleration. The course will cover the techniques for probing dark energy in detail, with particular emphasis on weak and strong lensing, clusters, large-scale structure, cross-correlations with the CMB, and supernovae, and explore how DES will realize these techniques. We will familiarize ourselves with the main hardware and software components of the project that underlie the data and science it produces. Students will be given access to proprietary DES data and learn basic techniques for querying the database and looking at the data; and will formulate projects involving analysis of the data, depending on their interests and level of expertise, and report on their findings later in the quarter. By the end of the course, those interested in participating in the DES should have the basic tools to jump into the project (or other projects) and take part in science analysis, and those already involved will hopefully have their skills and knowledge enhanced. The course will start with lectures reviewing cosmic acceleration and the techniques for probing dark energy, continue with more specialized talks and discussions on various aspects of the Dark Energy Survey project and science, including discussion of early DES papers.

ASTR 41600. Intergalactic Medium. 100 Units.
Specialized topics based on forefront topics in the field and on interests of the instructor.
Students will try out new ideas each week in their learning teams and report their results in class. In many cases, learning, growth mindset, metacognition, developing relationships with students, equity, and differentiation. Readings and discussion topics include questioning techniques, learning theory, cooperative learning, growth mindset, metacognition, developing relationships with students, equity, and differentiation.

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.

The first half of the course will be lectures with the goal of establishing a common denominator, and the second half will be research. The course requires a final project to be presented in class.

This course for second-year Ph.D. students in Astronomy and Astrophysics, students will prepare for part two of the candidacy examination through presentations, board work, discussion, and questions.

In this application-based course, students will learn how to prepare strong applications, with the goal of refuting the case for new physics.

The course will explore in considerable detail an area of current faculty research interest in astrophysics. The topic varies, but recent examples include the early universe, high-energy astrophysics, magnetohydrodynamics in astrophysics, and observational cosmology.

This course gives a general introduction to the theory of plasmas with particular emphasis on processes of astrophysical interest. Topics presented will include: Physical description of a plasma and plasma parameters; Debye length, plasma frequency, cyclotron frequency, Larmor radius; single particle motion and adiabatic invariants; kinetic theory and the Vlasov equation; magneto-hydro-dynamics and dynamo theory; plasma waves; waves in a cold and hot plasma/plasmas; Landau damping; collisional processes.

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.

The first half of the course will be lectures with the goal of establishing a common denominator, and the second half will be research. The course requires a final project to be presented in class.

This course for second-year Ph.D. students in Astronomy and Astrophysics, students will prepare for part two of the candidacy examination through presentations, board work, discussion, and questions.

In this application-based course, students will learn how to prepare strong applications, with the goal of refuting the case for new physics.
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.

Equivalent Course(s): GEOS 39500

**ASTR 70000. Advanced Study: Astronomy & Astrophysics. 300.00 Units.**

Advanced Study: Astronomy & Astrophysics