ASTRONOMY

52 Hillhouse Avenue, 203.432.3000
http://astronomy.yale.edu
M.S., M.Phil., Ph.D.

Chair
Sarbani Basu

Director of Graduate Studies
Jeffrey Kenney (203.432.3013, jeff.kenney@yale.edu)

Professors
Charles Bailyn, Charles Baltay (Physics), Sarbani Basu, Paolo Coppi, Pierre Demarque (Emeritus), Debra Fischer, Marla Geha, Jeffrey Kenney, Richard Larson (Emeritus), Gregory Laughlin, Priyamvada Natarajan, C. Megan Urry (Physics), William van Altena (Emeritus), Pieter van Dokkum, Robert Zinn

Associate Professors
Héctor Arce, Reina Maruyama (Physics), Daisuke Nagai (Physics), Nikhil Padmanabhan (Physics), Frank van den Bosch

Assistant Professor
Jessi Cisewski (Statistics & Data Science), Laura Newburgh (Physics)

FIELDS OF STUDY
Fields include observational and theoretical astronomy, solar and stellar astrophysics, exoplanets, the interstellar medium and star formation, astrometry, galactic astronomy, extragalactic astronomy, radio astronomy, high-energy astrophysics, and cosmology.

SPECIAL ADMISSIONS REQUIREMENTS
Applicants are expected to have a strong undergraduate preparation in physics and mathematics. Although some formal training in astronomy is useful, it is by no means a prerequisite for admission. Applicants are required to take the General GRE as well as the subject test in Physics.

SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE
A typical program of study includes twelve courses taken during the first four terms, and must include the core courses listed below:
The Physics of Astrophysics (ASTR 500), Computational Methods in Astrophysics and Geophysics (ASTR 520), Observational Astronomy (ASTR 555), Interstellar Matter and Star Formation (ASTR 560), either Stellar Populations (ASTR 510) or Stellar Astrophysics (ASTR 550), and either Galaxies (ASTR 530) or The Evolving Universe (ASTR 565). ASTR 620 or PHYS 678 may be substituted for ASTR 520 with the permission of the director of graduate studies (DGS).

Students require the permission of the instructor and the DGS to skip a core class if they think that they have sufficient knowledge of the field. Students will be required to demonstrate their knowledge of the field before they are allowed to skip any core class.

Two of the twelve courses must be research credits, each earned by working in close collaboration with a faculty member. Of the two research credits, one must be earned doing a theoretical research project and one doing an experimental research project. The students need to present the results of the project as a written report and will be given an evaluation of their performance.

The choice of the four remaining courses depends on the candidate's interest and background and must be decided in consultation with the DGS and/or the prospective thesis adviser. Advisers may require students to take particular classes and obtain a specified minimum grade in order for a student to work with them for their thesis. Students must take any additional course that their supervisors require even after their fourth term. In addition, all students, regardless of their term of study, have to attend Professional Seminar (ASTR 710 and ASTR 711) every term. Students must also take Responsible Conduct in Research for Physical Scientists (PHYS 590), which discusses ethics and responsible conduct in scientific research and fulfills the requirement stipulated by the National Science Foundation for all students and for all postdoctoral researchers funded by the NSF. Note that ASTR 710, ASTR 711, and PHYS 590 may not be used to fulfill the twelve-course requirement.

Students are encouraged to take graduate courses in physics or related subjects. On an irregular basis, special topic courses and seminars are offered, which provide the opportunity to study some fields in greater depth than is possible in standard courses. To achieve both breadth and depth in their education, students are encouraged to take a few courses beyond their second year of study.

There is no foreign language requirement. A written comprehensive examination, normally taken at the end of the fourth term of graduate work, tests the student's familiarity with the entire field of astronomy and related branches of physics and mathematics. Particular attention will be paid to the student's performance in the field in which the student plans to do research. An oral examination, held a few weeks after the written examination, is based on the student's chosen field of research. Satisfactory performance in these examinations, an acceptable record in course and research work, and an approved dissertation prospectus are required for admission.
to candidacy for the Ph.D. degree. The dissertation should present the results of an original and thorough investigation, worthy of publication. Most importantly, it should reflect the candidate's capacity for independent research. An oral dissertation defense is required.

Teaching experience is an integral part of graduate education in astronomy. All students are required to serve as teaching fellows for four terms. Both the level of teaching assignments and the scheduling of teaching are variable and largely determined by the needs of the department. Most students will teach in each of their first three terms and complete their fourth teaching assignment sometime after the qualifying exam.

HONORS REQUIREMENT
Students must earn a grade of Honors in at least three classes by the end of the fourth term of full-time study and have a grade average of High Pass or better.

MASTER'S DEGREES
M.Phil. Upon application, the department will recommend for the award of the M.Phil. degree any student who has completed all the requirements of the Ph.D. degree except the oral examination, which is based on the student's chosen field of research, and the Ph.D. dissertation. A written master's thesis containing original astronomical research is also required. Students are not admitted for this degree.

M.S. (en route to the Ph.D.) Upon application, the department will recommend for the award of the M.S. degree any student who has taken at least ten courses (not including ASTR 710 and ASTR 711), including at least one research project (ASTR 580). The student should have a grade average of High Pass in the courses and a grade of High Pass or above in the research project.

Program materials are available upon request to the Director of Graduate Studies, Department of Astronomy, Yale University, PO Box 208101, New Haven CT 06520-8101.

COURSES
ASTR 500a, The Physics of Astrophysics Priyamvada Natarajan
Primarily for incoming students in the Ph.D. program in Astronomy. The basic physics and related mathematics needed to take the advanced graduate courses. Topics in mechanics, thermodynamics and statistical mechanics, fluid mechanics, special relativity, and electrodynamics with applications to astrophysical systems are covered. Open to undergraduates with permission of the instructor.

ASTR 520a / G&G 538a, Computational Methods in Astrophysics and Geophysics Paolo Coppi
The analytic and numerical/computational tools necessary for effective research in astronomy, geophysics, and related disciplines. Topics include numerical solutions to differential equations, spectral methods, and Monte Carlo simulations. Applications are made to common astrophysical and geophysical problems including fluids and N-body simulations.

ASTR 550a, Stellar Astrophysics Sarbani Basu
An introduction to the physics of stellar atmospheres and interiors. The basic equations of stellar structure, nuclear processes, stellar evolution, white dwarfs, and neutron stars.

ASTR 560b, Interstellar Matter and Star Formation Hector Arce
The composition, extent, temperature, and density structure of the interstellar medium (ISM). Excitation and radiative processes; the properties of dust; the cold and hot ISM in the Milky Way and other galaxies. Dynamics and evolution of the ISM, including interactions between stars and interstellar matter. Physics and chemistry of molecular clouds and the process of star formation.

ASTR 565b, The Evolving Universe Pieter Van Dokkum
Overview of cosmic history from the formation of the first star to the present day, focusing on direct observations of the high-redshift universe.

ASTR 580a or b, Research Jeffrey Kenney
By arrangement with faculty.

ASTR 595b, Astrophysical Flows Gregory Laughlin
Fluid dynamics and hydrodynamics from an astrophysical perspective. The course covers the development of the Navier-Stokes equations from first principles, and discusses flows in which viscosity, gravity, radiation, and magnetic fields play dynamical roles (both separately and together). Specific applications to be covered include spherical collapse; the hydrodynamics of disks; and fluid waves, shocks, and fronts in a variety of contexts. We also discuss (and use) a variety of numerical schemes for solving fluid dynamical problems.

ASTR 600b, Cosmology Priyamvada Natarajan
A comprehensive introduction to cosmology at the graduate level. The standard paradigm for the formation, growth, and evolution of structure in the universe is covered in detail. Topics include the inflationary origin of density fluctuations; the thermodynamics of the early universe; assembly of structure at late times and current status of observations. The basics of general relativity required to understand essential topics in cosmology are covered. Advanced undergraduates may register for the course with permission of the instructor.

ASTR 610a, The Theory of Galaxy Formation Francisca van den Bosch
This astronomy course focuses on the physical processes associated with galaxy formation. Topics include Newtonian perturbation theory, the spherical collapse model, formation and structure of dark matter haloes (including Press-Schechter theory), the virial theorem,
gravitational interactions, cooling processes, theory of star formation, feedback processes, and numerical simulations. The course also includes a detailed treatment of statistical tools used to describe the large-scale distribution of galaxies and introduces the student to the concepts of galaxy bias and halo occupation modeling. During the final lectures we discuss a number of outstanding issues in galaxy formation.

**ASTR 666a / AMTH 666a / G&G 666a, Classical Statistical Thermodynamics**  John Wettlaufer
Classical thermodynamics is derived from statistical thermodynamics. Using the multi-particle nature of physical systems, we derive ergodicity, the central limit theorem, and the elemental description of the second law of thermodynamics. We then develop kinetics, transport theory, and reciprocity from the linear thermodynamics of irreversible processes. Topics of focus include Onsager reciprocal relations, the Fokker-Planck equation, stability in the sense of Lyapunov, and time invariance symmetry. We explore phenomena that are of direct relevance to astrophysical and geophysical settings. No quantum mechanics is necessary as a prerequisite.

**ASTR 710a and ASTR 711b, Professional Seminar**  Debra Fischer
A weekly seminar covering science and professional issues in astronomy.