

# ASTRONOMY

**Director of undergraduate studies:** Greg Laughlin, 46 HLH 208, 436-9405, astro.dus@yale.edu (greg.laughlin@yale.edu); astronomy.yale.edu

Astronomy is a quantitative physical science that applies physics, mathematics, and statistical analysis to observing, describing, and modeling the universe. The undergraduate courses and degree programs offered by the Department of Astronomy train students in research techniques and quantitative reasoning and develop creative problem solvers. Students who complete the major continue on to top-tier graduate programs in astrophysics or related science fields, and they are sought after by employers in a range of fields from health care management to the banking and investment industry. The department offers a B.A. degree in Astronomy and a B.S. degree in Astrophysics.

## INTRODUCTORY COURSES

**Introductory courses with no prerequisites** The department offers a variety of courses without prerequisites that provide an introduction to astronomy with particular attention to recent discoveries and theories. Courses numbered below 150 are intended for students who desire a broad, nontechnical introduction to astronomy. These courses fulfill the science distributional requirement, and some also fulfill the quantitative reasoning distributional requirement.

Courses with numbers between 150 and 199 are topical rather than survey courses. Most of these offerings fulfill both the science and the quantitative reasoning requirements. ASTR 155 is a laboratory course that provides a hands-on introduction to astronomical observing. ASTR 160 and 160 provide an introduction to frontier topics in modern astrophysics and cosmology.

**Introductory courses with high school calculus and physics prerequisites** Students who have taken calculus and physics in high school may enroll in quantitative introductory courses. ASTR 210 and ASTR 220 focus on fundamental measurements and tools used in astronomy and include an in-depth study of stellar astrophysics (ASTR 210) or galaxies and cosmology (ASTR 220). These courses overlap in content, so students should take either ASTR 210 or 220 but not both. ASTR 255 provides training in data analysis and research techniques, including computer programming and numerical and statistical analysis.

## PREREQUISITES

**B.A. degree program** The prerequisites for the B.A. degree are PHYS 170 and 171, or 180 and 181, or 200 and 201, and MATH 112 and 115.

**B.S. degree program** Prerequisites for the B.S. degree include an introductory physics sequence (PHYS 180 and 181, or 200 and 201, or 260 and 261); a physics laboratory sequence (PHYS 165L and 166L, or 205L and 206L); and the mathematics sequence MATH 112, 115, and either MATH 120 or ENAS 151. ASTR 155 may be substituted for one term of the physics laboratory sequence. All prerequisites should be completed by the end of the sophomore year.

**Prerequisites for advanced electives** Courses numbered 300 and above are more specialized and intensive. The prerequisites for these courses include ASTR 210 or 220, multivariable calculus, and two terms of introductory college physics.

## REQUIREMENTS OF THE MAJOR

**B.A. degree program** The B.A. degree program in Astronomy is designed for students who do not plan to continue in a graduate program in astronomy, but who are interested in the subject as a basis for a liberal arts education or as a physical science background to careers such as medicine, teaching, journalism, business, law, or government. It allows greater flexibility in course selection than the B.S. program because the emphasis is on breadth of knowledge rather than on specialization.

Ten courses are required beyond these prerequisites, including either ASTR 210 or 220, ASTR 255, 310, one additional Astronomy elective numbered 150 or above, and the senior requirement (ASTR 492). Two of the ten courses must be advanced courses in mathematics, such as MATH 120 or ENAS 151, or courses in mathematical methods, including statistics or computer science, such as CPSC 112, MATH 200 or above, or ASTR 356. Three electives can be drawn from any of the natural, applied, or mathematical sciences (including additional astronomy courses); at least two of these must be advanced enough to have college-level prerequisites.

**B.S. degree program** The B.S. degree program in Astrophysics is designed to provide a strong foundation in astrophysics for students interested in graduate study or a career in astronomy, physics, or a related science.

Beyond the prerequisites, twelve term courses are required in astronomy, physics, and mathematics. Students complete at least six courses in astronomy, including either ASTR 210 or 220, 255, 310, 320, and a two-term senior project (ASTR 490 and 491). Students also complete three Physics courses numbered 400 or above, normally PHYS 401, 402, and 439. In addition, majors choose either one additional 400-level course in Physics or an Astronomy elective numbered 300 or higher. In mathematics, students complete a course in differential equations selected from MATH 246, PHYS 301, or ENAS 194, and either an additional mathematics course numbered 200 or above or a course in statistics or computing such as CPSC 112, 201, or ASTR 356.

**Credit/D/Fail** Courses taken Credit/D/Fail may not be counted toward the requirements of either degree program.

**SENIOR REQUIREMENT**

**B.A. degree program** The senior requirement consists of a senior essay or independent research project carried out for one term in ASTR 492 under the supervision of a faculty member.

**B.S. degree program** The senior requirement consists of an independent research project in astronomy carried out for two terms in ASTR 490 and 491 under the supervision of a faculty member.

**ADVISING**

Before entering the junior year, students must obtain approval of a course of study from the director of undergraduate studies.

**Graduate work** Graduate courses in astronomy are open to qualified undergraduates who already have a strong preparation in mathematics, physics, and astronomy. Students wishing to take a graduate course must first obtain the permission of the instructor and of the director of graduate studies.

**REQUIREMENTS OF THE MAJOR****ASTRONOMY, B.A.**

**Prerequisites** PHYS 170, 171, or 180, 181, or 200, 201; MATH 112, 115

**Number of courses** 10 courses beyond prereqs, incl senior req

**Specific courses required** ASTR 210 or 220; ASTR 255, 310

**Distribution of courses** 1 astronomy elective numbered 150 or above; 2 advanced math courses; 3 science electives (may include addtl astronomy courses), at least 2 with college-level prereqs

**Senior requirement** Senior essay or senior research project (ASTR 492)

**ASTROPHYSICS, B.S.**

**Prerequisites** PHYS 180, 181, or 200, 201, or 260, 261; PHYS 165L, 166L, or 205L, 206L; MATH 112, 115; MATH 120 or ENAS 151

**Number of courses** 12 courses beyond prereqs, incl senior req

**Specific courses required** ASTR 210 or 220; 255, 310, 320

**Distribution of courses** 3 courses in physics numbered 400 or above; 1 addtl upper-level course in astronomy or physics; 2 courses in math or mathematical methods, as specified

**Substitution permitted** ASTR 155 for 1 term of physics lab prereq

**Senior requirement** Senior independent research project (ASTR 490 and 491)

**FACULTY OF THE DEPARTMENT OF ASTRONOMY**

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

**Associate Professors** Hector Arce, †Daisuke Nagai, †Nikhil Padmanabhan, Frank van den Bosch

**Lecturer** Michael Faison

†A joint appointment with primary affiliation in another department.

**Courses**

**ASTR 105b, The Earth in its Cosmic Context** Gregory Laughlin

Study of the formation, evolution, and history of Earth, its solar system, and its role in a larger cosmic context. Consideration of thousands of other recently discovered planetary systems; the role of life in shaping the Earth and its environment; and the consequences of human activity from a systems perspective. SC

**ASTR 110b, Planets and Stars** Michael Faison

An introduction to stars and planetary systems. Topics include the solar system and extrasolar planets, planet and stellar formation, and the evolution of stars from birth to death. No prerequisite other than a working knowledge of elementary algebra. QR, SC

**ASTR 120a, Galaxies and the Universe** Michael Faison

An introduction to stars and stellar evolution; the structure and evolution of the Milky Way galaxy and other galaxies; quasars, active galactic nuclei, and supermassive black holes; cosmology and the expanding universe. No prerequisite other than a working knowledge of elementary algebra. QR, SC

**ASTR 130a, Origins and the Search for Life in the Universe** Debra Fischer and Lily Zhao

Origins of the universe, stars, and planets; evolution of conditions that were conducive to the emergence of life on Earth; leading theories for the origin of life; the discovery of exoplanets; comparison of Earth's solar system with other systems that have been discovered; the possibility of habitable conditions where life might have arisen on other worlds; methods of searching for life elsewhere. No prerequisite other than a working knowledge of elementary algebra. SC

**ASTR 135b, Archaeoastronomy** Michael Faison

An introduction to how celestial patterns and events were observed and interpreted up to the Copernican revolution. Ancient observatories, calendar systems, records of astronomical events, and the role of astronomical knowledge in culture. Exercises in naked-eye observation of the sky. No prerequisites. SC

**ASTR 155a, Introduction to Astronomical Observing** Michael Faison

A hands-on introduction to the techniques of astronomical observing. Observations of planets, stars, and galaxies using on-campus facilities and remote observing with Yale's research telescopes. Use of electronic detectors and computer-aided data processing. Evening laboratory hours required. One previous college-level science laboratory or astronomy course recommended. SC ½ Course cr

**ASTR 170b, Introduction to Cosmology** Priyamvada Natarajan

An introduction to modern cosmological theories and observations. Topics include aspects of special and general relativity; curved space-time; the Big Bang; inflation; primordial element synthesis; the cosmic microwave background; the formation of galaxies; and large-scale structure. Prerequisite: a strong background in high school mathematics and physics. QR, SC

**ASTR 180b, Introduction to Relativity** Charles Bailyn

Introduction to the theories of special and general relativity, and to relativistic astrophysics. Topics include time dilation and length contraction; mass-energy equivalence; space-time curvature; black holes; wormholes; pulsars; quasars; gravitational waves; Hawking radiation. For students not majoring in the physical sciences; some previous acquaintance with high-school physics and/or calculus may be helpful, but is not required. QR, SC

**\* ASTR 195a / CLCV 213a / HIST 468Ja / HSHM 402a / NELC 353a, Ancient and Medieval Astronomy** Kevin Van Bladel

The history and methods of classical astronomy, one of the seven classical liberal arts, as practiced by ancient and medieval astronomers of Assyria and Babylonia, Greece, Rome, Persia, and by medieval scholars in Latin, Arabic, and Sanskrit, down to the time of Copernicus and Kepler. QR, HU, SC

**ASTR 210b, Stars and Their Evolution** Robert Zinn

Foundations of astrophysics, focusing on an intensive introduction to stars. Nuclear processes and element production, stellar evolution, stellar deaths and supernova explosions, and stellar remnants including white dwarfs, neutron stars, and black holes. A close look at our nearest star, the sun. How extrasolar planets are studied; the results of such studies. Prerequisite: a strong background in high school calculus and physics. May not be taken after ASTR 220. QR, SC

**[ ASTR 220, Galaxies and Cosmology ]****ASTR 255a / PHYS 295a, Research Methods in Astrophysics** Marla Geha

The acquisition and analysis of astrophysical data, including the design and use of ground- and space-based telescopes, computational manipulation of digitized images and spectra, and confrontation of data with theoretical models. Examples taken from current research at Yale and elsewhere. Use of the Python programming language. A background in high school calculus and physics. No previous programming experience required. QR, SC RP

**ASTR 320a, Physical Processes in Astronomy** Franciscus van den Bosch

Introduction to the physics required for understanding current astronomical problems. Topics include basic equations of stellar structure, stellar and cosmic nucleosynthesis, radiative transfer, gas dynamics, and stellar dynamics. Numerical methods for solving these equations. Prerequisites: MATH 120 and PHYS 201 or equivalents, or permission of instructor. Previous experience with computer programming recommended. Taught in alternate years. QR, SC

**ASTR 343b / PHYS 343b, Gravity, Astrophysics, and Cosmology** Laura Newburgh

Introduction to frontier areas of research in astrophysics and cosmology exploring ideas and methods. In--depth discussion of the physics underlying several recent discoveries including extrasolar planets—their discovery, properties, and issues of habitability; black holes—prediction of their properties from GR, observational signatures, and detection; and the accelerating universe—introduction to cosmological models and the discovery of dark energy. Prerequisites: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. QR, SC

**ASTR 355b, Observational Astronomy** Pieter Van Dokkum

Optics for astronomers. Design and use of optical telescopes, photometers, spectrographs, and detectors for astronomical observations. Introduction to error analysis, concepts of signal-to-noise, and the reduction and analysis of photometric and spectroscopic observations. Prerequisite: one astronomy course numbered above 200, or permission of instructor. Previous experience with computer programming recommended. QR, SC RP

**\* ASTR 356b / PHYS 356b, Astrostatistics and Data Mining** Hector Arce

Introduction to the statistical tools used to analyze and interpret astrophysical data, including common data mining techniques for finding patterns in large data sets and data-based prediction methods. Use of publicly available high-quality astronomical data from large surveys such as SDSS and 2MASS, and from space-based observatories such as Spitzer, Herschel, and WISE. Coding with the Python programming language. Prerequisite: ASTR 255 or equivalent. QR, SC

**[ ASTR 360, Interstellar Matter and Star Formation ]****\* ASTR 375a, Exoplanets** Gregory Laughlin

Planet formation, exoplanet detection techniques, and the modeling of observations of exoplanet atmospheres. Solar system architecture compared with other planetary systems. From an Earth-centric perspective, habitability factors of rocky planets and the implications for life elsewhere. Prerequisites: MATH 120 and PHYS 201 or equivalents, and one astronomy course numbered above 200. QR, SC

**ASTR 380a, Stellar Populations** Robert Zinn

The stellar populations of our galaxy and galaxies of the Local Group. Topics include the properties of stars and star clusters, stellar evolution, and the structure and evolution of our galaxy. Prerequisites: PHYS 201 and MATH 120, and one astronomy course numbered above 200. Taught in alternate years. QR, SC RP

**[ ASTR 385, Introduction to Radio Astronomy ]****ASTR 418b, Stellar Dynamics** Marla Geha

The dynamics and evolution of star clusters; structure and dynamics of our galaxy; theories of spiral structure; dynamical evolution of galaxies. Prerequisites: PHYS 201 and MATH 246 or equivalents; ASTR 310. Taught in alternate years. QR, SC RP

**ASTR 420a, Computational Methods for Astrophysics** Paolo Coppi

The analytic, numerical, and computational tools necessary for effective research in astrophysics and related disciplines. Topics include numerical solutions to differential equations, spectral methods, and Monte Carlo simulations. Applications to common astrophysical problems including fluids and N-body simulations. Prerequisites: ASTR 320, MATH 120, 222 or 225, and 246. QR RP

**ASTR 430b, Galaxies** Jeffrey Kenney

A survey of the contents, structure, kinematics, dynamics, and evolution of galaxies; galaxy interactions and the environments of galaxies; properties of active galactic nuclei. Prerequisites: PHYS 201 and MATH 120, and one astronomy course numbered above 200. Taught in alternate years. QR, SC RP

**[ ASTR 450, Stellar Astrophysics ]****[ ASTR 465, The Evolving Universe ]****\* ASTR 471a and ASTR 472b, Independent Project in Astronomy** Staff

Independent project supervised by a member of the department with whom the student meets regularly. The project must be approved by the instructor and by the director of undergraduate studies; the student is required to submit a complete written report on the project at the end of the term.

**\* ASTR 490a and ASTR 491b, The Two-Term Senior Project** Staff

A two-term independent research project to fulfill the senior requirement for the B.S. degree. The project must be supervised by a member of the department and approved by the director of undergraduate studies.

**\* ASTR 492a or b, The One-Term Senior Project** Staff

A one-term independent research project or essay to fulfill the senior requirement for the B.A. degree. The project must be supervised by a member of the department and approved by the director of undergraduate studies.