ASTRONOMY & ASTROPHYSICS

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Astronomy and Astrophysics are quantitative physical sciences that apply physics, mathematics, and statistical analysis to observing, describing, and modeling the universe. The courses and degree programs offered by the Department of Astronomy train students in research techniques and quantitative reasoning and develop creative problem solvers. The department offers a B.A. degree in Astronomy and a B.S. degree in Astrophysics. The Astronomy degree is intended for students who plan to continue in adjacent fields such as science policy and science journalism. The Astrophysics degree is intended for students who plan to attend graduate school in related fields. Students who complete either major are sought after by employers in a range of fields from healthcare management to the banking and investment industry.

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 1500 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 from 1500 to 1999 are topical rather than survey courses. Most of these offerings fulfill both the science and the quantitative reasoning requirements. ASTR 1550 is a laboratory course that provides a hands-on introduction to astronomical observing. ASTR 1600 and ASTR 1700 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 2100 and ASTR 2200 focus on fundamental measurements and tools used in astronomy and include an in-depth study of stellar astrophysics (ASTR 2100) or galaxies and cosmology (ASTR 2200). These courses overlap in content, so students should take either ASTR 2100 or ASTR 2200, but not both. ASTR 2550 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 1700 and PHYS 1710, or PHYS 1800 and PHYS 1810, or PHYS 2000 and PHYS 2010, and MATH 1120 and 1150.

B.S. degree program Prerequisites for the B.S. degree include an introductory physics sequence (PHYS 1800 and PHYS 1810, or PHYS 2000 and PHYS 2010, or PHYS 2600 and PHYS 2610); a physics laboratory sequence (PHYS 1650L and PHYS 1660L, or PHYS 2050L and PHYS 2060L); and the mathematics sequence MATH 1120, MATH 1150, and either MATH 1200 or ENAS 1510. ASTR 1550 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 3000 and above are specialized and intensive. The prerequisites for these courses include ASTR 2100 or ASTR 2200, 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 the prerequisites, including either ASTR 2100 or 2200; ASTR 2550; ASTR 3100; one additional Astronomy elective numbered 1500 or above; and the senior requirement (ASTR 4920). Two of the ten courses must be advanced courses in mathematics, such as MATH 1200 or ENAS 1510, or courses in mathematical methods, including statistics or computer science, such as CPSC 1001, MATH 2000 or above, or ASTR 3560. 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 courses are required in astronomy, physics, and mathematics. Students complete at least six courses in astronomy, including either ASTR 2100 or 2200; ASTR 2550; ASTR 3100; ASTR 3200; and a two-term senior project (ASTR 4900 and 4910). Students also complete three physics courses numbered 4000 or above, normally PHYS 4010, PHYS 4020, and PHYS 4390. In addition, majors choose either one additional 4000-level course in physics or an astronomy elective numbered 3000 or higher. In mathematics, students complete a course in differential equations selected from MATH 2460, PHYS 4000, or ENAS 1940, and either an additional mathematics course numbered 2000 or above or a course in statistics or computing such as CPSC 1001, CPSC 2010, or ASTR 3560.

Credit/D/Fail No course taken Credit/D/Fail may be applied toward the major requirements of either degree program.

Outside credit Courses taken at another institution or during an approved summer or term-time study abroad program may count toward the major requirements with DUS approval.

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 4920 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 4900 and ASTR 4910 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 (DUS).

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.

SUMMARY OF MAJOR REQUIREMENTS

ASTRONOMY, B.A.

Prerequisites PHYS 1700, PHYS 1710, or PHYS 1800, PHYS 1810, or PHYS 2000, PHYS 2010; MATH 1120, MATH 1150

Number of courses 10 courses beyond prereqs, incl senior req

Specific courses required ASTR 2100 or ASTR 2200; ASTR 2550; ASTR 3100

Distribution of courses 1 astronomy elective numbered 1500 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 4920)

ASTROPHYSICS, B.S.

Prerequisites PHYS 1800, PHYS 1810, or PHYS 2000, PHYS 2010, or PHYS 2600, PHYS 2610; PHYS 1650L, PHYS 1660L, or PHYS 2050L, PHYS 2060L; MATH 1120, MATH 1150; MATH 1200 or ENAS 1510

Number of courses 12 courses beyond prereqs, incl senior req

Specific courses required ASTR 2100 or 2200; ASTR 2550; ASTR 3100; ASTR 3200

Distribution of courses 3 courses in physics numbered 4000 or above; 1 addtl course in astronomy numbered 3000 or above or in physics numbered 4000 or above; 2 courses in math or mathematical methods, as specified

Substitution permitted ASTR 1550 for 1 term of physics lab prereq

Senior requirement Senior independent research project (ASTR 4900 and ASTR 4910)

FACULTY OF THE DEPARTMENT OF ASTRONOMY

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

Associate Professors †Daisuke Nagai, †Nikhil Padmanabhan

Assistant Professors Earl Bellinger, Malena Rice

Lecturer Michael Faison

[†]A joint appointment with primary affiliation in another department.

Courses

* ASTR 0300b, Search for Extraterrestrial Life Michael Faison

Introduction to the search for extraterrestrial life. Review of current knowledge on the origins and evolution of life on Earth; applications to the search for life elsewhere in the universe. Discussion of what makes a planet habitable, how common these worlds are in the universe, and how we might search for them. Survey of past, current, and future searches for extraterrestrial intelligence. Enrollment limited to first-year students. WR, SC

* ASTR 0400a / PHYS 0400a, Expanding Ideas of Time and Space Meg Urry Discussions on astronomy, and the nature of time and space. Topics include the shape and contents of the universe, special and general relativity, dark and light matter, and dark energy. Observations and ideas fundamental to astronomers' current model of an expanding and accelerating four-dimensional universe. Enrollment limited to first-year students. sc

ASTR 1100a, Planets and Stars Michael Faison

Astronomy 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 1200b, Galaxies and the Universe Hector Arce

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 1550a, Introduction to Astronomical Observing Michael Faison A hands-on introduction to techniques used in astronomy to observe astronomical objects. 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 1700b, Introduction to Cosmology Priyamvada Natarajan An introduction to modern cosmological theories and observational astronomy. 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 1800a, Introduction to Relativity and Black Holes Charles Bailyn Introduction to the theories of special and general relativity, and to relativistic astronomy and 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 2100a, Stars and Their Evolution Hector Arce

Foundations of astronomy and 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 o Course cr

ASTR 2550a / PHYS 3950a, Research Methods in Astrophysics Marla Geha An introduction to research methods in astronomy and astrophysics. The acquisition and analysis of astrophysical data, including the design and use of ground- and spacebased 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. Prerequisite: background in high school calculus and physics. No previous programming experience required. QR, SC RP

ASTR 3100b, Galactic and Extragalactic Astronomy Jeffrey Kenney Structure of the Milky Way galaxy and other galaxies; stellar populations and star clusters in galaxies; gas and star formation in galaxies; the evolution of galaxies; galaxies and their large-scale environment; galaxy mergers and interactions; supermassive black holes and active galactic nuclei. Prerequisites: MATH 115, PHYS 201, and ASTR 210 or 220, or equivalents, or with permission of instructor. QR, SC

ASTR 3200b, Physical Processes in Astronomy Frank 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 3550a, 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. This course should be taken concurrently with ASTR 330, and/or after successfully completing ASTR 255. QR, SC

* ASTR 3560a / ASTR 5560a / PHYS 3560a, Astrostatistics and Data Mining Earl Bellinger

This course is intended to give students majoring in astronomy, physics, or any other physical science the necessary background to be able to conduct research with large and complex datasets. The course provides an introduction to the tools needed for analyzing large volumes of data and gives students more experience in building codes to analyze to them. The course starts with a review of basic probability and statistics. Students then learn the basics of classical statistical inference, regression and model fitting,

Bayesian statistical inference, as well as different data-mining techniques. Coding with the Python programming language. Prerequisite: ASTR 255 or equivalent. QR, SC

ASTR 3800b, 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

ASTR 4000b / MENG 4343 / MENG TBD-4, Orbital Mechanics and Mission Design

Marla Geha

Introduction to spacecraft orbital mechanics, astrodynamics, and the design and implementation of spaceflight maneuvers for Earth-orbiting satellites and interplanetary probes. The class first addresses how to describe and predict the motion of a spacecraft in orbit around the Earth, how to change orbits, lunar and interplanetary trajectories, and how satellites are launched into orbit from Earth. The class then focuses on the space environment and considerations for spacecraft design. Prerequisites: PHYS 170/171, or 180/181, or 200/201, or 260/261. Concurrently with MATH 246, PHYS 301 or other advanced mathematics course. ASTR 255, PHYS 378 or other experience with python coding is recommended. QR, SC

ASTR 4200a, 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

* **ASTR 4710a and ASTR 4720b, Independent Project in Astronomy** Marla Geha 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 4900a and ASTR 4910b, The Two-Term Senior Project** Marla Geha 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 4920a or b, The One-Term Senior Project** Marla Geha 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.