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 usually 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 the mathematics sequence MATH 1120, MATH 1150, and either MATH 1200 or ENAS 1510.

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 or higher 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 2000 or higher; and the senior requirement (ASTR 4920). Two of the ten courses must be advanced courses in mathematics, such as courses in mathematical methods, including statistics or computer science, such as MATH 2000 or higher, 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 electives must be numbered 3000 or higher.

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 higher, 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 higher or a course in statistics or computing such as 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, and either MATH 1200 or ENAS 1510

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 2000 or higher; 2 advanced math courses 2000 or higher, one of which can be ASTR 3560; 3 science electives (may include addtl astronomy courses), at least 2 must be 3000 or higher

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 higher; 1 addtl course in astronomy numbered 3000 or higher or in physics numbered 4000 or higher; 1 course selected from MATH 2460, PHYS 4000, or ENAS 1940 and 1 mathematics course numbered 2000 or higher or a statistics or computing course, as specified

Substitution permitted ASTR 1550 for 1 term of physics lab prereq

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

Courses

* **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 1300b, Origins and the Search for Life in the Universe Michael Faison
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 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 Robert Zinn
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 2200. QR, SC 0 Course cr

ASTR 2200b, Galaxies and Cosmology Robert Zinn
An intensive introduction to extragalactic astronomy. The structure and contents of galaxies, evolution of galaxies, observational cosmology, and the history of the universe. Students observe a deep-sky object with campus telescopes. Prerequisite: a strong

background in high school calculus and physics. May not be taken after ASTR 210. QR, SC

ASTR 2550a / PHYS 3950a, Research Methods in Astrophysics Malena Rice
An introduction to research methods in astronomy and astrophysics. 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. 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 1150, PHYS 2010, and ASTR 2100 or 2200, or equivalents, or with permission of instructor. QR, SC

ASTR 3200a, 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 1200 and PHYS 2010 or equivalents, or permission of instructor. Previous experience with computer programming recommended. Taught in alternate years. QR, SC

ASTR 3300b, Scientific Computing in Astrophysics Earl Bellinger
Scientific computer programming in Astrophysics with a focus on the Python Programming language. Algorithms and workflows for reducing and analyzing Astrophysical datasets, both observational and computational. Emphasis is placed on best coding practices, including readability, version control, documentation, and computational efficiency. Weekly lectures, in-depth tutorial/workshops, and invited outside expert guest speakers. Students complete a programming project based on real astrophysical datasets. Prerequisite: ASTR 255 or permission of instructor. Some basic programming experience in Python is strongly recommended.

* **ASTR 3750b, Exoplanets** Malena Rice
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 4180a, Stellar Dynamics Marla Geha
The study of dynamics in astronomy. Stellar dynamics attempts to answer what happens when a large number of particles (stars or galaxies) orbit under the influence of their mutual gravity. This course covers the dynamics of astronomical objects ranging from binary stars to globular clusters to galaxies. Particular emphasis is placed on direct applications to observational data. Taught in alternate years. Prerequisites: PHYS 201 and MATH 246 or equivalents; ASTR 310. 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 3200, MATH 1200, 2220 or 2250, and 2460. QR

ASTR 4500b, Stellar Astrophysics Sarbani Basu
The physics of stellar atmospheres and interiors. Topics include the basic equations of stellar structure, nuclear processes, stellar evolution, white dwarfs, and neutron stars. Prerequisites: PHYS 201 and MATH 120. Taught in alternate years. QR, SC

ASTR 4650a, 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. Prerequisites: MATH 120, PHYS 201, and one astronomy course numbered above 200. Taught in alternate years. QR, SC

* **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.