

ASTRONOMY & ASTROPHYSICS

Astronomy and astrophysics apply physical principles to understand the properties of objects in space. The range of scales of phenomena to be investigated is vast—from neutron stars the size of cities, to galaxies containing billions of stars, or even the entire Universe as a single system. The Haverford astronomy and astrophysics curricula are based on the study of these systems and of their evolution. Any study of astronomy and astrophysics is enriched by a firm understanding of the physics underlying these phenomena, and as such astronomy and astrophysics majors share many similarities with physics. Our curriculum is shaped to provide a solid foundation in the basic principles of both astronomy and physics, an understanding of the most recent developments in astronomy and cosmology, and the inspiration to pursue further learning in the sciences.

Entry to either the astronomy or astrophysics major comprises foundational courses in physics and mathematics during the first two years as well as ASTR H106/ASTR H204 (typically taken in the sophomore year), which surveys all major areas of modern astrophysics. We also offer a number of more focused, upper level courses on specific topics in astronomy and astrophysics, including one on modern observational techniques. These courses usually reflect the research interests of our faculty.

Student research is a vital part of both majors. Our faculty work at the cutting edge of modern astronomy and cosmology, creating exceptional research opportunities for majors. Some of those opportunities are based on campus, within the College's William J. Strawbridge Observatory, equipped with telescopes and powerful computational facilities. Other opportunities lie off-campus, and we also encourage students to apply for summer research experience in other departments (as well as our own).

Learning Goals

The courses offered in the astronomy and astrophysics program address a variety of learning goals:

- Knowledge of the contents of the extraterrestrial universe, including planets, stars, galaxies, and the large-scale structure of the universe itself, and understanding the formation and evolution of all of these.
- Problem-solving skills: like physics, astronomy emphasizes the understanding of the physical world in terms of physical laws, an endeavor that is validated by applying these mathematical laws to a variety of astrophysical phenomena and then solving the resulting mathematical problem in order to verify the subsequent predictions with observations.
- Constructing models: the construction of models to describe natural phenomena and astronomy represents the most creative aspect of any science.
- Developing physical intuition: the ability to look at a complicated system and know what's important.
- Computer programming: a cornerstone of modern astronomy, from data analysis to modeling.
- Observing skills in using a variety of astronomical instruments and techniques.
- Research experience, which involves:
 - confronting the unknown and tolerating its ambiguity.
 - generating new science with which to understand new observations.
 - analyzing data.
 - the art of scientific collaboration.
 - oral and written communication of new results.
 - designing new experiments/observations, and networking with other scientists to possibly generate new collaborative efforts.

Haverford's Institutional Learning Goals are available on the President's website, at <http://hav.to/learninggoals> (<http://hav.to/learninggoals/>).

Curriculum

Introductory Courses

The department regularly offers courses that require no prerequisites or prior experience in astronomy. These are intended primarily for non-science students.

Major Programs

Students can choose to major in either astronomy or astrophysics. Both majors provide substantial training in quantitative reasoning and independent thinking through work in and out of the classroom.

The department also offers a minor in astronomy.

- The astrophysics major is the same as a physics major, but with an astronomical emphasis. This major is appropriate for students who wish to pursue the study of astronomy with attention to the physical principles that underlie the observed phenomena. The depth of the physics training required for a degree in astrophysics will prepare students who wish to pursue graduate study in astronomy or astrophysics, or to make use of their physics training for a wide range of other careers.
- The astronomy major is appropriate for students who desire an in-depth education in astronomy that can be applied to a wide-range of career trajectories, but who do not necessarily intend to pursue graduate study in astronomy.

Although a variety of pathways can lead to a major in the department, we advise prospective astronomy or astrophysics majors to:

- study physics (PHYS H105 or PHYS H115 and PHYS H106, or PHYS H101 and PHYS H102, or Bryn Mawr equivalents), beginning in their first year.
- enroll in ASTR204 and PHYS H213/PHYS H214 in their sophomore year.

For students with little or no prior computer programming experience, and who do not intend to take CMSC105, we advise (but do not require) taking ASTR 104 / PHYS 104 in the first or second year. (Students who do well in this course can, if desired, go on to take CMSC107.)

Students may major in astronomy or astrophysics, but not both. Astrophysics majors may not double major in either physics or astronomy, nor can they minor in either physics or astronomy. Astronomy majors may pursue a double major or a minor in physics, however we encourage students considering that option to look more closely at being an astrophysics major.

For either major, students may count courses taken outside the Quaker Consortium toward the major with advanced permission; typically two to

three courses may be granted credit in this way. Students interested in this option should discuss this point with their major/pre-major advisor in advance.

Concentrations and Interdisciplinary Minors

Astronomy and astrophysics majors can pursue concentrations in scientific computing and education, while astrophysics majors with interdisciplinary interests in biophysics may also qualify for the biophysics concentration.

Each of these concentrations is described in its relevant section of the Catalog.

Special Programs

Haverford is part of the KNAC eight-college consortium (<https://astro.swarthmore.edu/KNAC>) that provides research assistantships for a summer student exchange program, grants for student travel to outside observatories, and a yearly symposium at which students present their research.

Study Abroad

Astronomy and astrophysics majors can and do pursue studies abroad. There are a number of programs, mostly in English-speaking countries, that allow astronomy and astrophysics majors to continue and broaden their studies in the field while abroad. Majors may count courses taken abroad toward the major with advanced permission; typically two to three courses may be granted credit in this way. Students interested in studying abroad should discuss this point with their major/pre-major advisor in advance.

Facilities

See the departmental web page for a description of laboratories, equipment and other special facilities for this program.

Astrophysics Major Requirements

- PHYS H105 (<https://catalog.haverford.edu/search/?P=PHYS%20H105>) (or PHYS H115 or PHYS H101 (<https://catalog.haverford.edu/search/?P=PHYS%20H101>)), PHYS H106 (<https://catalog.haverford.edu/search/?P=PHYS%20H106>) (or PHYS H102 (<https://catalog.haverford.edu/search/?P=PHYS%20H102>)), PHYS H213 (<https://catalog.haverford.edu/search/?P=PHYS%20H213>), PHYS H214 (<https://catalog.haverford.edu/search/?P=PHYS%20H214>), PHYS H211 (<https://catalog.haverford.edu/search/?P=PHYS%20H211>) (usually taken concurrently with PHYS H213 (<https://catalog.haverford.edu/search/?P=PHYS%20H213>)).
- Two mathematics courses; MATH H121 (<https://catalog.haverford.edu/search/?P=MATH%20H121>) and all 200-level or higher mathematics courses can be used to satisfy this requirement.
- ASTR H204 (<https://catalog.haverford.edu/search/?P=ASTR%20H204>) and any two credits of 300-level astronomy courses. Majors can substitute 100-level Swarthmore astronomy seminars for 300-level astronomy courses.
- Two of the four core theoretical courses: PHYS H302 (<https://catalog.haverford.edu/search/?P=PHYS%20H302>), PHYS H303 (<https://catalog.haverford.edu/search/?P=PHYS%20H303>), PHYS H308 (<https://catalog.haverford.edu/search/?P=PHYS%20H308>), and PHYS H309 (<https://catalog.haverford.edu/search/?P=PHYS%20H309>) (or their Bryn Mawr equivalents).

P=PHYS%20H308), and PHYS H309 (<https://catalog.haverford.edu/search/?P=PHYS%20H309>) (or their Bryn Mawr equivalents).

- The Senior Seminar, PHYS H399F (<https://catalog.haverford.edu/search/?P=PHYS%20H399F>) and PHYS H399I (<https://catalog.haverford.edu/search/?P=PHYS%20H399I>), including a talk and senior thesis on research conducted by the student. This research can be undertaken in a 400-level research course with any member of the Physics and Astronomy Department or by doing extracurricular research at Haverford or elsewhere, e.g., an approved summer research internship at another institution. The thesis is to be written under the supervision of both the research advisor and a Haverford advisor if the research advisor is not a Haverford faculty member.

Bryn Mawr equivalents may be substituted for the non-astronomy courses.

Astronomy Major Requirements

- PHYS H105 (<https://catalog.haverford.edu/search/?P=PHYS%20H105>) (or PHYS H101 (<https://catalog.haverford.edu/search/?P=PHYS%20H101>) or PHYS H115), PHYS H106 (<https://catalog.haverford.edu/search/?P=PHYS%20H106>) (or PHYS H102 (<https://catalog.haverford.edu/search/?P=PHYS%20H102>)), PHYS H213 (<https://catalog.haverford.edu/search/?P=PHYS%20H213>), PHYS H214 (<https://catalog.haverford.edu/search/?P=PHYS%20H214>).
- Two mathematics courses; MATH H121 (<https://catalog.haverford.edu/search/?P=MATH%20H121>) and all 200-level or higher mathematics courses can be used to satisfy this requirement.
- ASTR H204 (<https://catalog.haverford.edu/search/?P=ASTR%20H204>), four 300-level astronomy credits, one of which may be replaced by an upper-level physics course. Majors can substitute 100-level Swarthmore astronomy seminars for 300-level astronomy courses.
- The Senior Seminar, PHYS H399F (<https://catalog.haverford.edu/search/?P=PHYS%20H399F>) and PHYS H399I (<https://catalog.haverford.edu/search/?P=PHYS%20H399I>), including a talk and senior thesis on research conducted by the student. This research can be undertaken in a 400-level research course with any member of the Physics and Astronomy Department or by doing extracurricular research at Haverford or elsewhere, e.g., an approved summer research internship at another institution. The thesis is to be written under the supervision of both the research advisor and a Haverford advisor if the research advisor is not a Haverford faculty member.

Bryn Mawr equivalents may be substituted for the non-astronomy courses.

Senior Project

The senior project and requirements are the same for the Astronomy major and the Astrophysics major.

Coursework prior to the senior year provides students' primary preparation for their thesis work. As outlined in our program's educational goals, this coursework emphasizes: knowledge of the extraterrestrial universe, problem solving skills, constructing models, developing physical intuition, computer programming, observing skills, and research-like inquiry. Students also gain experience with oral and written communication of complex scientific topics in their introductory physics

labs and in upper level coursework, including ASTR H341 Advanced Topics: Observational Astronomy. During group research meetings, students provide weekly oral reports to each other on their thesis progress and receive ongoing support and instruction from faculty.

To pull together the many elements that make up the senior year, students are required to participate in a year-long seminar course, PHYS H399 Senior Seminar. At the approximately biweekly meetings, students and some departmental faculty gather around a table to discuss topics running the gamut from scientific ethics to how to give a scientific talk or write a scientific research paper. Further details on this course are contained in the description of senior year work in physics.

The most important part of the senior seminar remains the senior paper and the senior presentations. We assess students by their performance on a short talk and the draft of the background section of their thesis during the fall semester, a comprehensive talk or poster presentation in the spring semester and a senior thesis written in the form of a scientific paper.

Senior Project Learning Goals

The senior thesis project extends through at least an entire academic year, with many students starting their thesis research during the summer before their senior year. The thesis thus requires students to engage in focused work, towards a single goal, for a substantial time period. We aim for students to develop deep topical expertise in a single subfield of astronomy or astrophysics, and to develop technical expertise in one of the analysis techniques common to that field (often computational data analysis).

Students learn to ask good questions of others and themselves, in pursuit of a deeper understanding of a previously unsolved question about the natural world.

Students are expected to place their senior research work in the context of the scientific literature in their field of study, and to present their results to an audience of professionals (for their thesis) and their peers (for the talk or poster). They are given training in searching and reading the scientific literature by each research supervisor, as well as specific materials through the senior seminar course.

More than is the case in any other undergraduate curricular engagement, students must learn how to be independent and self-motivated to complete their thesis work. This style of scientific inquiry also imbues a realistic sense of professional scientific research in students and increases their grit.

Senior Project Assessment

Each senior's thesis culminates in both a written and an oral component. The written thesis is carefully read and evaluated by two faculty readers. The thesis research itself is evaluated for (i) a demonstrated understanding of the context and content of the research (including a review of the relevant scientific literature), (ii) independent problem solving and synthesis, and (iii) success in understanding the forward looking implications of the research.

The written and oral presentations of the research are evaluated for (i) a clear and appropriate writing style and (ii) well-curated and well-presented visual displays of the research results.

Requirements for Honors

All astronomy and astrophysics majors are regarded as candidates for honors. For both majors, the award of honors will be made in part on

the basis of superior work in the departmental courses and in certain related courses. The award of honors will additionally be based on the senior thesis and talk. High honors carries the additional requirement of demonstrated originality in senior research.

Minor Requirements

- PHYS H105 (<https://catalog.haverford.edu/search/?P=PHYS%20H105>) (or PHYS H115 or PHYS H101 (<https://catalog.haverford.edu/search/?P=PHYS%20H101>)); PHYS H106 (<https://catalog.haverford.edu/search/?P=PHYS%20H106>) (or PHYS H102 (<https://catalog.haverford.edu/search/?P=PHYS%20H102>)).
- ASTR H204 (<https://catalog.haverford.edu/search/?P=ASTR%20H204>); one 300-level astronomy credit. Minors may substitute a 100-level Swarthmore astronomy seminar for the 300-level astronomy course.

ASTR H101 Astronomical Ideas (1 Unit)

Fundamental concepts and observations of modern astronomy, such as the properties of planets, the birth and death of stars, and the properties and evolution of the Universe. Not intended for students majoring in the physical sciences. Enrollment limit: 24

ASTR H204 Introduction to Astrophysics (1 Unit)

General introduction to astronomy including: the structure and evolution of stars; the properties and evolution of the solar system including planetary surfaces and atmospheres; exoplanets; and observational projects using the Strawbridge Observatory telescopes. Prerequisite(s): MATH H118 or equivalent; PHYS H105 or PHYS B121; Co-requisite(s): PHYS H106 or B201 Enrollment Limit: 30 Lottery Preference(s): 1. Physics, astrophysics or astronomy majors 2. Sophomores 3. Physics & astronomy minors 4. First-years

ASTR H304 Computational Physics (1 Unit)

An introduction to the methods and problems of computational physics, including matrix methods, ordinary differential equations, integration, eigensystems, Monte Carlo techniques, Fourier analysis, and iterative methods. Course will include a substantial independent project. Crosslisted: Physics, Astronomy, Computer Science Prerequisite(s): PHYS H213, or PHYS B205 and PHYS B207, or instructor consent Enrollment Limit: 18 Lottery preferences as follows: Senior Physics, Astrophysics and astronomy majors Senior Scientific Computing Concentrators Junior majors Junior Scientific Computing Concentrators Other Seniors Sophomores Freshmen

ASTR H325 Advanced Topics in Theoretical Physics (1 Unit)

An introductory course in general relativity with an emphasis on physical principles and geodesics in curved spacetime. Topics include special relativity, the calculus of variations, metrics, tensors, parallel transport, covariant derivatives, geodesics, the equivalence principle, gravitational redshift, the static weak-field metric, the Schwarzschild metric describing spacetime outside of a black holes or star, the precession of planetary orbits and the bending of light by massive objects. Additional topics may include applications to rotating black holes, gravitational waves, cosmology, or Hawking radiation. Prerequisites: Phys H213 or PHYS B205 and B207.

ASTR H341 Advanced Topics: Observational Astronomy (1 Unit)

Observing projects that involve using a CCD camera on a 16-inch Schmidt-Cassegrain telescope. Projects include spectroscopy; variable star photometry; H-alpha imaging; imaging and photometry of galaxies and star clusters; instruction in the use of image processing software and CCD camera operation. Students work in groups of two with minimal faculty supervision. Formal reports are required.

Prerequisite(s): ASTR H204 Enrollment Limit: 18 Lottery Preference(s):

1. Astronomy majors 2. Astrophysics majors 3. Astronomy minors 4. Physics majors 5. Physics minors

ASTR H344 Advanced Topics in Astrophysics: Gravitational Waves (1 Unit)

This course will explore the creation and detection of gravitational waves (GWs) across the spectrum, from the speculative universe-sized GWs that may someday be detected from the epoch of inflation, to the kHz waves that LIGO and nHz waves that NANOGrav has detected! In the course you will investigate theoretical, observational, and computational aspects of GWs across the spectrum, culminating in a final investigative project of your own choosing. Prerequisite(s): ASTR H204

ASTR H352 Topics in Astrophysics: Extragalactic Data Science (0.5 Unit)

A 0.5 credit upper level astronomy/astrophysics elective, which can be taken in series with the other 0.5 credit upper level Astro elective offered the same semester, or as a stand-alone course. This class will cover the basics of modern extragalactic science (a review of our knowledge of the Milky Way and external galaxies) alongside hands on projects involving data science/statistical techniques used to investigate them. Assessment will be highly project based, with regular coding assignments (in python) done during class time, and guided reading of both current, and classic astrophysical literature. Students will leave with an understanding of extragalactic astrophysics as a modern data focused science. Crosslisted: PHYS. Pre-requisite(s): ASTR204

ASTR H353 Topics in Physics: Soft Matter Physics (1 Unit)

This is an upper-level physics elective course which serves as an introduction to the physics of soft condensed matter (squishy stuff!), and will comprise a mixture of seminar-style discussions and chalk talk-like student presentations. Seminar discussions will center around peer-reviewed literature and conference lecture recordings. Students will finish the course having developed general literacy with the core concepts in Soft Matter and an understanding of the major challenges facing professional Soft Matter scientists. During a given semester, the course may follow a narrower theme, like "The Soft Matter Physics of Coffee," or "The Earth as Soft Matter". Crosslisted: ASTR. Pre-requisite(s): Math H121, at least two 200-level courses in physics or another natural science Lottery Preference: Physics majors, astrophysics majors, astro majors and physics/astro minors, seniors, juniors. Enrollment Limit: 15

ASTR H356 Topics in Physics/Astronomy: Introduction to Astroparticle Physics (0.5 Unit)

Astroparticle physics is the study of fundamental particles traveling through space coming from various astrophysical sources. The energies of some of these particles are much higher compared to the ones achievable by the most powerful human-made particle accelerators. In this course, we will learn about cosmic rays, Gamma-rays, neutrinos, neutrino oscillations and masses, dark matter cross-section, freezeout, evidences, candidates, and searches. There will be an emphasis on dark matter and neutrino physics and detection. Crosslisted: ASTR. Pre-requisite(s): ASTR 204 or BMC equiv. PHYS 214 or BMC equiv. (can be taken concurrently) Lottery Preference: Juniors and seniors majoring in physics, astrophysics, and astronomy. Enrollment Limit: 15.00

ASTR H404 Research in Astrophysics (1 Unit)

Intended for those students who choose to complete an independent research project in astrophysics under the supervision of a faculty member. Prerequisite(s): Instructor consent Enrollment Limit: 12