The range of astronomical phenomena is vast—from the Big Bang origin of the universe, to the death throes of collapsing stars, to the rings of Saturn. The curriculum of the Astronomy Department is based on the study of these systems and of their evolution. Any study of astronomy is enriched by a firm understanding of the physics underlying these phenomena. Our curriculum is shaped to provide both astronomy and astrophysics majors with 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 major is through a pair of courses that survey all major areas of modern astrophysics: ASTR 205 and 206. These are typically taken in the sophomore year, to allow students to build a foundation in physics (our majors require physics courses, as explained below). We also offer a number of more focused, upper level courses on specific topics in astronomy, including one on observational techniques. Some of these 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 computer facilities. Other opportunities lie off-campus through the department’s alliances with national and private observatories, including Kitt Peak in Arizona and the Simons Observatory in Chile.

LEARNING GOALS
The courses offered in the Astronomy Department 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 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.
- 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.

CURRICULUM
Introductory Courses
From time to time, the department offers three courses, ASTR 101A, ASTR 112, and ASTR 114B, which student can take with no prerequisites or prior experience in astronomy. These are intended primarily for non-science students.

The department also offers a half-credit course, ASTR/PHYS 152, for first-year students who are considering a physical science major and wish to study some of the most recent developments in astrophysics.

Major Programs
Our department offers two majors: astronomy and 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 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.  

• The astrophysics major is appropriate for students who wish to pursue the study of astronomy with additional attention to the physical principles that underlie astrophysical phenomena. The depth of the physics training required for a degree in astrophysics will prepare students who wish to pursue a career in astronomy or astrophysics, or to do graduate study in astronomy or astrophysics.  

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

• study physics (PHYS 105 or 115 and 106, or PHYS 101 and 102, or Bryn Mawr equivalents) beginning in their first year.
• enroll in ASTR 205/206 and PHYS 213/214 in their sophomore year.
• take ASTR/PHYS 152 in the second semester of their first year.

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.

MAJOR REQUIREMENTS

Astronomy Major Requirements
The astronomy major is appropriate for students that 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.

• PHYS 105 (or 101 or 115), PHYS 106 (or 102), PHYS 213, PHYS 214.
• Two mathematics courses; MATH 121 and all 200-level or higher mathematics courses can be used to satisfy this requirement.
• ASTR 205, ASTR 206, four 300-level astronomy courses, 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.
• ASTR 404, which may be replaced by approved independent research either at Haverford or elsewhere.
• Written comprehensive examinations.

Bryn Mawr equivalents may be substituted for the non-astronomy courses. ASTR/PHYS 152 is recommended but not required.

Astrophysics Major Requirements
The astrophysics major is appropriate for students who wish to pursue the study of astronomy with additional attention to the physical principles that underlie astrophysical phenomena. The depth of the physics training required for a degree in astrophysics will prepare students who wish to pursue a career in astronomy or astrophysics, or to enter graduate study in astronomy or astrophysics.

• PHYS 105 (or 115 or 101), PHYS 106 (or 102), PHYS 213, PHYS 214, PHYS 211 (usually taken concurrently with PHYS 213).
• Two mathematics courses. MATH 121 and all 200-level or higher mathematics courses can be used to satisfy this requirement.
• ASTR 205, ASTR 206, and any two 300-level astronomy courses. Majors can substitute 100-level Swarthmore astronomy seminars for 300-level astronomy courses.
• PHYS 302, PHYS 303, and PHYS 309.
• The Senior Seminar, PHYS 399, 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 or astronomy departments 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 adviser and a Haverford adviser if the research adviser is not a Haverford faculty member.

Bryn Mawr equivalents may be substituted for the non-astronomy courses. ASTR/PHYS 152 and PHYS 308 are recommended but not required.

MINOR REQUIREMENTS

• PHYS 105 (or 115 or 101); PHYS 106 (or 102).
• ASTR 205; ASTR 206; one 300-level astronomy course. Minors may substitute a 100-level Swarthmore astronomy seminar for the 300-level astronomy course.

We strongly recommend (but do not require) ASTR/PHYS 152.

SENIOR PROJECT
A noted above, we offer two majors: astronomy and
astrophysics. The senior project and requirements differ for the two.

**Astronomy Major**

For many decades, the capstone work for seniors majoring in astronomy (not astrophysics) has been a set of three, three-hour, comprehensive examinations covering all of astronomy. Students are given some choice in which questions to answer. We emphasize that the questions on these written examinations are likely to address topics of current prominence or interest in the field, whether or not they have been covered in our courses. In a year marked by new discoveries about a particular planet, for instance, we might ask for a summary of the scientific findings even though our curriculum barely touches planetary science.

**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 341. 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 in the astrophysics major, students are required to participate in a year-long seminar course, PHYS 399. 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 (typically 25-50 pages, including figures and references), written in the form of a scientific paper. Frequently, this leads to a publication in a peer-reviewed journal.

**Senior Project Learning Goals**

A noted above, we offer two majors: astronomy and astrophysics. While the senior year work differs for the two, the learning goals are closely similar.

**Astronomy Major**

The goal of the comprehensive exams in astronomy is primarily to assess seniors’ grasp of the full extent of their chosen field of study, and secondarily to provide a summary reminder of the field. For students, the comprehensive exams are thus both an evaluative assessment, and to a lesser extent a formative experience. The exams offer the departmental faculty a last chance to lay out the nature of astronomy, both for students planning further study in the field or for those leaving astronomy behind.

As the capstone experience for senior majors in astronomy, the comprehensives are entirely separate from a student's research experience—unlike the case for majors in astrophysics. Both astronomy and astrophysics majors, however, are required to undertake senior research either on campus or off campus, perhaps in a summer REU experience. For astrophysics majors, this research is central to the senior experience (see below). For astronomy majors, on the other hand, senior research and the comprehensives are decoupled: the former stresses depth; the latter breadth.

**Astrophysics Major**

The Haverford astrophysics 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 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**
A noted above, we offer two majors: astronomy and
astrophysics. Assessment of the senior year work
differs for the two.

**Astronomy Major**
The comprehensives are read and graded by all
astronomy faculty. They are graded on a numerical
1-10 scale for each problem, not the usual
Haverford 4.0 scale. While performance on
astronomy comprehensive exams is not recorded
on a student’s transcript, students must pass the
exams in order to graduate with an astronomy
major.

Comprehensive results are also the primary
determinant of departmental honors for astronomy
majors. High honors are awarded to students who:
• demonstrate clear mastery of the field,
  including both topics central to our curriculum
  and those not.
• are able to situate their responses in a wider
  context of astrophysics or science in general.
• show an understanding of research fields not
  covered in our curriculum.
• display some originality in their responses,
  evidence that they “own” the material.

Regular departmental honors again require mastery
and a sense of context, with less emphasis on
originality.

While the emphasis of comprehensives is on the
first two of the departmental learning goals
(“knowledge of the extraterrestrial universe” and
“problem-solving skills”), we also look for evidence
that other goals have been met, including “scientific
intuition” and written communication skills.

**Astrophysics Major**
As noted, 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. For astronomy
majors, the award of honors will additionally be
based on performance on the comprehensive
examinations, with consideration given for
independent research. For astrophysics majors, the
award of honors will additionally be based on the
senior thesis and talk.

**SCIENTIFIC COMPUTING
CONCENTRATION**
The Concentration in Scientific Computing gives
students an opportunity to develop a basic facility
with the tools and concepts involved in applying
computation to a scientific problem, and to explore
the specific computational aspects of their own
major disciplines.

For more information about the scientific
computing concentration and its requirements,
please see the program’s website
(haverford.edu/scientific-computing) or Catalog
entry.

**SPECIAL PROGRAMS**
In 2010, Haverford became a member of the 0.9m
telescope at Tucson’s Kitt Peak National
Observatory (noao.edu/0.9m) consortium, and in
2013 we became a member of the Northeast
Astronomy Participation Group’s partnership with
the ARC 3.5m telescope at Apache Point Observatory (apo.nmsu.edu) in New Mexico. We offer all Haverford astronomy and astrophysics majors the opportunity to obtain astronomical observations at one of these research facilities in Tucson or Apache Point.

Haverford is also part of the KNAC eight-college consortium (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.

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

FACULTY
Beth Willman (on leave 2016-2017)
Associate Professor of Astronomy

Desika Narayanan
Assistant Professor of Astronomy

Paul Thorman
Visiting Assistant Professor and Laboratory Instructor in Physics

Bruce Partridge
Bettys and Howard Marshall Professor of Natural Sciences and Professor of Astronomy Emeritus

COURSES
ASTRH101 ASTRONOMICAL IDEAS
Bruce Partridge
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. At least 30 spaces will be reserved for freshmen, perhaps more as space dictates. Quantitative (QU); Natural Science (NA)

ASTRH152 FIRST-YEAR SEMINAR IN ASTROPHYSICS
Staff
This half-credit course is intended for prospective physical science majors with an interest in recent developments in astrophysics. Topics in modern astrophysics will be viewed in the context of underlying physical principles. Topics include black holes, quasars, neutron stars, supernovae, dark matter, the Big Bang, and Einstein's relativity theories. Crosslisted: Physics; Prerequisite(s): PHYS 101A, 105A or 115A, and concurrent enrollment in PHYS 102B or 106B (or Bryn Mawr equivalents); Natural Science (NA)

ASTRH205 INTRODUCTION TO ASTROPHYSICS I
Desika Narayanan
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. Natural Science (NA)

ASTRH206 INTRODUCTION TO ASTROPHYSICS II
Staff
Introduction to the study of: the structure and formation of the Milky Way galaxy; the interstellar medium; the properties of galaxies and their nuclei; and cosmology including the Hot Big Bang model. Prerequisite(s): ASTR 205A and MATH 114B or equivalent (or consent); Natural Science (NA)

ASTRH341 ADVANCED TOPICS: OBSERVATIONAL ASTRONOMY
Paul Thorman
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. Natural Science (NA)

ASTRH344 ADVANCED TOPICS: COMPUTATIONAL ASTROPHYSICS
Desika Narayanan
This course will survey general methods utilized in computational physics and astrophysics. The course will focus on coding techniques, numerical recipes, and both abstract and practical concepts in utilizing computers to solve physical problems. No prior coding experience is necessary. Prerequisite(s): PHYS 214. Typically offered in alternate years; Crosslisted: Physics; Natural Science (NA)

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ASTRONOMY

ASTRH343 ADVANCED TOPICS: COSMOLOGY AND EXTRAGALACTIC ASTRONOMY
Desika Narayanan
The study of the origin, evolution and large-scale structure of the Universe (Big Bang Theory). Review of the relevant observational evidence. A study of remote galaxies, radio sources, quasars, and intergalactic space. Prerequisite(s): ASTR H206; Natural Science (NA)

ASTRH404 RESEARCH IN ASTROPHYSICS
Desika Narayanan, Bruce Partridge
Intended for those students who choose to complete an independent research project in astrophysics under the supervision of a faculty member. Natural Science (NA)