Astronomy is the oldest of the natural sciences; since antiquity astronomers have sought to understand the origin and destiny of the universe and its celestial contents. How did the universe evolve from an early, almost uniform, state to the rich structure that we see at the present epoch? Where did the elements of the periodic table come from? How do stars, along with their systems of planets, form and how do they change with time? Do other life-bearing worlds exist? These questions have evolved over millennia, with answers now sought using the mathematical, technological, and computational tools of modern astronomy.

For students interested in examining fundamental questions through scientific study of the universe, the Department of Astronomy and Astrophysics offers several choices to explore. Options include general education courses, the minor program in Astronomy and Astrophysics (aimed at students not majoring in the sciences), and the major program in Astrophysics, with both BA and BS tracks.

General Education Courses

Many options are available for choosing two- or three-quarter sequences that will satisfy the general education requirement in the physical sciences (http://collegecatalog.uchicago.edu/thecollege/physicalsciences/) from among six courses numbered in the 12000s. These courses are designed for students not majoring in the sciences and present a range of foundational topics, from the grand principles governing the universe and understanding its beginning, to the formation and evolution of stars and galaxies, and the search for habitable extrasolar planets. All courses numbered in the 12000s include labs for engaging in astronomical inquiry through classical experiments, opportunities for telescope observing, and data analysis. The Study Abroad program in Paris is another option for completing the general education requirement in the physical sciences.

Students seeking a more in-depth examination of selected astrophysical topics may take a course numbered in the 18000s as a third course in the physical sciences or as a general elective. While the 12000 and 18000 courses are aimed at students not majoring in the sciences, quantitative analysis is an important part of all courses offered by the Department of Astronomy and Astrophysics. Any tools beyond pre-calculus algebra will be taught as needed.

Major in Astrophysics

The major program in Astrophysics reflects Chicago's tradition of interdisciplinary study and emphasis on mastery of the intellectual processes of inquiry and discovery. Students will gain broad knowledge of the universal, physical laws from the nuclear to cosmological; familiarity with computational methods and statistical data analysis; and experience with experimental and observational techniques through participation in research. Graduates of the Astrophysics program will be positioned to pursue advanced degrees in physics, astronomy, or similar fields, or enter government service, science education, or scientific journalism.

There are two tracks for students interested in the major. The program leading to a BA in Astrophysics consists of sixteen courses beyond the general education requirement. The program leading to a BS in Astrophysics consists of eighteen courses beyond the general education requirement. The BS track is recommended for students expecting to apply to graduate school in the physical sciences.

Students interested in a more advanced mathematics track may substitute the MATH 18300-18400-18500-18600 sequence with MATH 20250 and MATH 20300-20400-20500 or MATH 20250 and MATH 18400-18500. Students invited to take the MATH 20700-20800-20900 sequence may also use it as a substitution for MATH 18300-18400-18500-18600.

Please note that courses counted toward the major must be taken for quality grades (no P/F grading).

Summary of Requirements for the BA in Astrophysics

<table>
<thead>
<tr>
<th>General Education</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHYS 13100-13200</strong> Mechanics; Electricity and Magnetism (or higher)</td>
<td>200</td>
</tr>
<tr>
<td>One of the following sequences:</td>
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</tr>
<tr>
<td>MATH 15100-15200 Calculus I-II</td>
<td></td>
</tr>
<tr>
<td>MATH 16100-16200 Honors Calculus I-II</td>
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<td>Total Units</td>
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<tr>
<td><strong>MAJOR</strong></td>
<td></td>
</tr>
<tr>
<td>ASTR 13300 Introduction to Astrophysics</td>
<td>100</td>
</tr>
<tr>
<td>PHYS 13300 Waves, Optics, and Heat (or higher)</td>
<td>100</td>
</tr>
<tr>
<td>MATH 18300-18400-18500-18600 Mathematical Methods in the Physical Sciences I-II-III-IV</td>
<td>400</td>
</tr>
<tr>
<td>Course Code</td>
<td>Course Title</td>
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<td>------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ASTR 20500</td>
<td>Introduction to Python Programming with Applications to Astro Statistics</td>
</tr>
<tr>
<td>ASTR 21100</td>
<td>Computational Techniques in Astrophysics</td>
</tr>
<tr>
<td>ASTR 21200</td>
<td>Observational Techniques in Astrophysics</td>
</tr>
<tr>
<td>One of the following:</td>
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</tr>
<tr>
<td>PHYS 22500</td>
<td>Intermediate Electricity and Magnetism I</td>
</tr>
<tr>
<td>PHYS 23410</td>
<td>Quantum Mechanics I</td>
</tr>
<tr>
<td>ASTR 29800</td>
<td>Undergraduate Research Seminar</td>
</tr>
<tr>
<td>ASTR 25400</td>
<td>Radiation Processes in Astrophysics</td>
</tr>
<tr>
<td>ASTR 24100</td>
<td>The Physics of Stars</td>
</tr>
<tr>
<td>One of the following:</td>
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</tr>
<tr>
<td>ASTR 25800</td>
<td>Astrophysics of Exoplanets</td>
</tr>
<tr>
<td>ASTR 23900</td>
<td>Physics of Galaxies</td>
</tr>
<tr>
<td>ASTR 24300</td>
<td>Cosmological Physics</td>
</tr>
<tr>
<td>Two electives to be selected from list of approved courses</td>
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<tr>
<td>Total Units</td>
<td></td>
</tr>
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</table>

* Credit may be granted by examination.

§ Students who matriculated prior to Autumn 2018 may substitute any 20000-level ASTR course for ASTR 13300.

† Students in the BA in Astrophysics who matriculated prior to Autumn 2020 and who have already completed PHYS 15400 Modern Physics are not required to take PHYS 23410 Quantum Mechanics I.

**SUMMARY OF REQUIREMENTS FOR THE BS IN ASTROPHYSICS (PHYSICS VARIANT)**

**GENERAL EDUCATION**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>PHYS 13100</td>
<td>Mechanics; Electricity and Magnetism (or higher)</td>
<td>100</td>
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<tr>
<td>One of the following sequences:</td>
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<tr>
<td>MATH 15100</td>
<td>Calculus I-II</td>
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<td>MATH 16100</td>
<td>Honors Calculus I-II</td>
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<td>Total Units</td>
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**MAJOR**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>ASTR 13300</td>
<td>Introduction to Astrophysics §</td>
<td>100</td>
</tr>
<tr>
<td>PHYS 13300</td>
<td>Waves, Optics, and Heat (or higher)</td>
<td>100</td>
</tr>
<tr>
<td>MATH 18300-18400-18500-18600</td>
<td>Mathematical Methods in the Physical Sciences I-II-III-IV</td>
<td>400</td>
</tr>
<tr>
<td>ASTR 20500</td>
<td>Introduction to Python Programming with Applications to Astro Statistics</td>
<td>100</td>
</tr>
<tr>
<td>ASTR 21100</td>
<td>Computational Techniques in Astrophysics</td>
<td>100</td>
</tr>
<tr>
<td>ASTR 21200</td>
<td>Observational Techniques in Astrophysics</td>
<td>100</td>
</tr>
<tr>
<td>PHYS 23410 &amp; PHYS 23510</td>
<td>Quantum Mechanics I and Quantum Mechanics II †</td>
<td>200</td>
</tr>
<tr>
<td>ASTR 29800</td>
<td>Undergraduate Research Seminar</td>
<td>100</td>
</tr>
<tr>
<td>ASTR 25400</td>
<td>Radiation Processes in Astrophysics</td>
<td>100</td>
</tr>
<tr>
<td>ASTR 24100</td>
<td>The Physics of Stars</td>
<td>100</td>
</tr>
<tr>
<td>PHYS 27900</td>
<td>Statistical and Thermal Physics</td>
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</tr>
<tr>
<td>One of the following:</td>
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</tr>
<tr>
<td>ASTR 25800</td>
<td>Astrophysics of Exoplanets</td>
<td></td>
</tr>
<tr>
<td>ASTR 23900</td>
<td>Physics of Galaxies</td>
<td></td>
</tr>
<tr>
<td>ASTR 24300</td>
<td>Cosmological Physics</td>
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<tr>
<td>Two electives to be selected from list of approved courses</td>
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<td>Total Units</td>
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<td>1800</td>
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</tbody>
</table>

* Credit may be granted by examination.

§ Students who matriculated prior to Autumn 2018 may substitute any 20000-level ASTR course for ASTR 13300.
† Students in the BS in Astrophysics (Physics Variant) who matriculated prior to Autumn 2020 and who have already completed PHYS 15400 Modern Physics and PHYS 23400 Quantum Mechanics I are not required to take PHYS 23510 Quantum Mechanics II.

**SUMMARY OF REQUIREMENTS FOR THE BS IN ASTROPHYSICS (CHEMISTRY VARIANT)**

**GENERAL EDUCATION**

- CHEM 11100-11200 Comprehensive General Chemistry I-II (or equivalent) ††
- One of the following sequences:
  - MATH 13100-13200 Elementary Functions and Calculus I-II
  - MATH 15100-15200 Calculus I-II
  - MATH 16100-16200 Honors Calculus I-II

Total Units: 400

**MAJOR**

- ASTR 13300 Introduction to Astrophysics
- PHYS 13100-13200-13300 Mechanics; Electricity and Magnetism; Waves, Optics, and Heat (or higher)
- MATH 18300-18400-18500 Mathematical Methods in the Physical Sciences I-II-III
- CHEM 11300 Comprehensive General Chemistry III
- ASTR 20500 Introduction to Python Programming with Applications to Astro Statistics
- ASTR 21100 Computational Techniques in Astrophysics
- ASTR 21200 Observational Techniques in Astrophysics
- ASTR 29800 Undergraduate Research Seminar
- ASTR 25400 Radiation Processes in Astrophysics
- ASTR 24100 The Physics of Stars
- CHEM 26100 Quantum Mechanics
- CHEM 26200 Thermodynamics

One of the following:
- ASTR 25800 Astrophysics of Exoplanets
- ASTR 23900 Physics of Galaxies
- ASTR 24300 Cosmological Physics

One elective to be selected from list of approved courses

Total Units: 1800

† Credit may be granted by examination.

†† CHEM 10100-10200 Introductory General Chemistry I-II and CHEM 12100-12200 Honors General Chemistry I-II also satisfy this requirement. Enrollment into a particular sequence is based on chemistry placement or AP score. Students should consult with the Department of Chemistry regarding Advanced Placement and Accreditation Examinations.

**SAMPLE PROGRAMS**

The sample programs below illustrate different paths for fulfilling requirements for the Astrophysics major. Students starting in mathematics courses other than MATH 15100 and MATH 18300 should consult with the Academic Affairs Administrator in Astronomy and Astrophysics regarding the best path through the major.

**BA in Astrophysics starting with MATH 15100**

<table>
<thead>
<tr>
<th>First Year</th>
<th>Autumn Quarter</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 13100</td>
<td>PHYS 13200</td>
<td>ASTR 13300</td>
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<td>MATH 15200</td>
<td>PHYS 13300</td>
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<tr>
<td></td>
<td></td>
<td>MATH 18300</td>
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</table>

<table>
<thead>
<tr>
<th>Second Year</th>
<th>Autumn Quarter</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTR 20500</td>
<td>ASTR 21200</td>
<td>ASTR 21100</td>
<td></td>
</tr>
<tr>
<td>MATH 18400</td>
<td>MATH 18500</td>
<td>ASTR 29800</td>
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<table>
<thead>
<tr>
<th>Third Year</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 22500</td>
<td>Elective</td>
<td></td>
</tr>
<tr>
<td>Elective</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Astrophysics

#### Fourth Year
- **Autumn Quarter**
  - ASTR 25400
  - ASTR 24100
  - ASTR 25800

#### Winter Quarter

**BA in Astrophysics starting with MATH 18300**

#### First Year
- **Autumn Quarter**
  - PHYS 14100
  - MATH 18300
- **Winter Quarter**
  - PHYS 14200
  - MATH 18400
- **Spring Quarter**
  - PHYS 14300
  - MATH 18500

#### Second Year
- **Autumn Quarter**
  - ASTR 20500
  - MATH 18600
- **Winter Quarter**
  - ASTR 21200
  - PHYS 23410
- **Spring Quarter**
  - ASTR 21100
  - ASTR 29800

#### Third Year
- **Autumn Quarter**
  - ASTR 25400
- **Winter Quarter**
  - ASTR 24100
- **Spring Quarter**
  - Elective

#### Fourth Year
- **Autumn Quarter**
  - Elective
- **Winter Quarter**
  - ASTR 23900

**BS in Astrophysics (Physics Variant) starting with MATH 15100**

#### First Year
- **Autumn Quarter**
  - PHYS 13100
  - MATH 15100
- **Winter Quarter**
  - PHYS 13200
  - MATH 15200
- **Spring Quarter**
  - PHYS 13300
  - MATH 18500

#### Second Year
- **Autumn Quarter**
  - ASTR 20500
  - MATH 18600
- **Winter Quarter**
  - ASTR 21200
  - PHYS 23410
- **Spring Quarter**
  - ASTR 21100
  - ASTR 29800
  - PHYS 23510

#### Third Year
- **Winter Quarter**
  - PHYS 23410
  - Elective
- **Spring Quarter**
  - PHYS 23510
  - Elective

#### Fourth Year
- **Autumn Quarter**
  - ASTR 25400
  - PHYS 27900
- **Winter Quarter**
  - ASTR 24100

**BS in Astrophysics (Chemistry Variant) starting with MATH 15100**

#### First Year
- **Autumn Quarter**
  - CHEM 11100
  - MATH 15100
- **Winter Quarter**
  - CHEM 11200
  - MATH 15200
- **Spring Quarter**
  - ASTR 13300
  - CHEM 11300
  - MATH 18300
<table>
<thead>
<tr>
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<th>Course 3</th>
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<td>MATH 18400</td>
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<td></td>
<td>Winter</td>
<td>PHYS 13200</td>
<td>MATH 18500</td>
<td>ASTR 21200</td>
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<td>Winter</td>
<td>ASTR 24100</td>
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<td>Spring</td>
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</tr>
<tr>
<td>Fourth</td>
<td>Autumn</td>
<td>CHEM 26100</td>
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</tr>
<tr>
<td></td>
<td>Winter</td>
<td>CHEM 26200</td>
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<tr>
<td></td>
<td>Spring</td>
<td>ASTR 25800</td>
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**BS in Astrophysics (Chemistry Variant) starting with MATH 18300**

<table>
<thead>
<tr>
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<th>Quarter</th>
<th>Course 1</th>
<th>Course 2</th>
<th>Course 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Autumn</td>
<td>CHEM 11100</td>
<td>MATH 18300</td>
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</tr>
<tr>
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<td>Winter</td>
<td>CHEM 11200</td>
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<td></td>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second</td>
<td>Autumn</td>
<td>PHYS 14100</td>
<td>ASTR 20500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>PHYS 14200</td>
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<td>PHYS 14000</td>
<td>ASTR 21100</td>
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<td>Autumn</td>
<td>ASTR 25400</td>
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<td>Winter</td>
<td>ASTR 24100</td>
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<td>Spring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fourth</td>
<td>Autumn</td>
<td>CHEM 26100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>CHEM 26200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring</td>
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</table>

**Electives**

- ASTR 21300: Origin and Evolution of the Solar System 100
- ASTR 21400: Creative Machines and Innovative Instrumentation 100
- ASTR 25000: Order-of-Magnitude Astrophysics 100
- ASTR 28500: Science with Large Astronomical Surveys 100
- ASTR 29001: Field Course in Astronomy and Astrophysics I 200
- ASTR 29002: Field Course in Astronomy and Astrophysics II 200
- ASTR 30100: Stars 100
- ASTR 30300: Interstellar Matter 100
- ASTR 30400: Galaxies 100
- ASTR 30600: Detection of Radiation 100
- ASTR 31000: Cosmology I 100
- ASTR 31100: High Energy Astrophysics 100
- GEOS 22040: Planet Formation in the Galaxy I: From Dust to Planetesimals 100
- GEOS 22050: Planet Formation in the Galaxy II: From Planetesimals to Planets 100
- GEOS 22060: What Makes a Planet Habitable? 100
- PHYS 22600: Electronics 100
- PHYS 23410: Quantum Mechanics I (BA in Astrophysics students who take PHYS 22500 may use PHYS 23410 as an elective.) 100
- PHYS 23510: Quantum Mechanics II (Only BA in Astrophysics students may use PHYS 23510 as an elective.) 100
- PHYS 26000: Fluid Dynamics 100
- PHYS 26400: Spacetime and Black Holes 100
- PHYS 26500: Topics in General Relativity and Cosmology 100

Other courses may be approved as electives by the Deputy Chair for Academic Affairs in the Department of Astronomy and Astrophysics.
Grading
Students in the major or minor programs offered by the Department of Astronomy and Astrophysics must receive a quality grade of at least C in all courses counting toward major/minor requirements. In addition, students who are majoring in Astrophysics must receive a quality grade of at least C- in prerequisite courses offered by other departments.

Honors
Students who have completed the requirements for the BA or BS in Astrophysics are encouraged to prepare an honors thesis based on their work. To be considered for honors, a student must earn a GPA of 3.5 or higher in the required courses for the major and 3.0 overall (or obtain consent from the assistant chair for academic affairs), and have an approved research project that will be supervised by a faculty member.

Eligible students who wish to be considered for honors will first meet with the academic affairs administrator to obtain guidelines and requirements for this option, followed by a meeting with their research mentor resulting in a plan for the supervision of the research. The student enrolls in ASTR 29900 Honors Thesis in any quarter of their graduation year. A goal of the honors track is to mentor students through the process of preparing research and submitting it for publication. Along the way, students present their research to various groups, including Astronomy and Astrophysics faculty, for feedback and discussion.

Minor in Astronomy and Astrophysics
The grand narrative of astronomy holds wide popular appeal and lends itself to interdisciplinary study: there is a deep history and cultural context, the night sky is profoundly inspiring and accessible to everyone, and the spirit of exploration is communicated in daily media reports of new discoveries. The minor in Astronomy and Astrophysics was designed for students not majoring in the sciences to cultivate understanding of science as a human endeavor across multiple social, historical, and cultural contexts, and to develop comprehension of the quantitative reasoning that supports a deep conceptual understanding of science.

Students are allowed flexibility in selecting five courses to compose a rigorous program of study according to individual interest. The selection must include at least two courses numbered in the 12000s and at least one in the 18000s. It is possible for a student pursuing the minor to substitute a course numbered in the 20000s for one of the 18000 courses. Students interested in exploring this option must meet with the academic affairs administrator to discuss course selection. Please note: courses taken to satisfy the general education requirement in the physical sciences may not be counted towards the minor. Students who satisfy their general education requirement in the physical sciences in Astronomy and Astrophysics may pursue the minor through completing the remaining courses numbered in the 12000s and at least one in the 18000s.

There are no Physics or Mathematics prerequisites for the minor. Courses must be taken for quality grades (no P/F grading). Students must meet with the academic affairs administrator before the end of Spring Quarter of their third year to declare their intention to complete the minor and fill out the College’s Consent to Complete a Minor Program (https://humanities-web.s3.us-east-2.amazonaws.com/college-prod/s3fs-public/documents/Consent_Minor_Program.pdf) form.

Study Abroad Program
Every Spring Quarter a three-course Astronomy program is offered in Paris, composed from the courses numbered in the 12000s that are offered on campus. This sequence was designed for students not majoring in the sciences but may also be of interest to science majors who want to supplement their work in physics and chemistry with a quarter devoted to the cosmos. In Spring Quarter 2021, the Paris program will offer ASTR 12600 Matter, Energy, Space, and Time, ASTR 12610 Black Holes, and ASTR 12620 The Big Bang.

The Astronomy program in Paris satisfies the general education requirement in the physical sciences. Students who have already completed their general education requirement in the physical sciences may count the three courses taken in Paris toward the five required to satisfy the minor in Astronomy and Astrophysics. For details, see the Study Abroad (https://study-abroad.uchicago.edu) page for Paris: Astronomy (http://study-abroad.uchicago.edu/programs/paris-astronomy/).

Astronomy and Astrophysics Courses
ASTR 11901. Physics of Stars: An Introduction. 100 Units.
Understanding how stars work - what makes them shine - is one of the great accomplishments of 20th-century science. The theory of stellar structure allows us to investigate the interiors of stars, even though what we observe is radiation from their outer atmospheres. This theory also helps us determine how old stars are, how they create heavier nuclei from lighter nuclei in their centers, and how they evolve from birth to death, ending as a white dwarf, a neutron star, or a black hole. This course introduces you to the concepts behind and applications of this crucial breakthrough. We will review the physical principles - gravity, pressure, radiation, and how radiation interacts with matter - and apply these principles to further our understanding of stellar structure. We will collect our own measurements of stellar properties, such as the temperatures and luminosities of stars, using robotic telescopes controlled via the internet. Using these and other data, we will test the theory of stellar structure and explore what it can tell us about the universe. While it is not required, students who have taken this course in the past have found it beneficial to bring their own laptops to class if they have them.
Terms Offered: Summer
Prerequisite(s): Open to high school students only.

ASTR 12600. Matter, Energy, Space, and Time. 100 Units.
A comprehensive survey of how the physical world works, and how matter, energy, space, and time evolved from the beginning to the present. A brief survey of the historical development of mathematics, physics, and astronomy leads to a conceptual survey of the modern theory of the physical universe: space and time in relativity; the quantum theory of matter and energy; and the evolution of cosmic structure and composition.
The major theme of this course is the understanding of all nature, from the prosaic to the exotic, using powerful quantitative theory grounded in precise experiments. Although quantitative analysis will be an important part of the course, students will not be expected to employ mathematics beyond algebra. (L)
Instructor(s): Paolo Privitera Terms Offered: Autumn
Equivalent Course(s): PHSC 12600

ASTR 12610. Black Holes. 100 Units.
Black Holes are the most exotic, extreme and paradoxical systems in the universe. They are the densest concentrations of energy, yet they convert all matter that falls in to pure space-time curvature; they radiate more power than anything else, even though most of their radiation is not even made of light; they are mathematically the most perfectly understood of any physical structure, but their enigmatic behavior is still the subject of a violent disagreement among experts that highlights our ignorance of how quantum physics relates to gravity.
This course will survey the physics of space and time, the nature of black holes, their effects on surrounding matter and light, the astrophysical contexts in which they are observed, frontier areas of research as quantum gravity and gravitational waves, and the importance of space-time physics to everyday needs such as navigation and energy. The modern theory of space and time, as well as black holes, will be placed in historical context, with special attention to the work of Albert Einstein. Experimental exercises will include direct measurement of the speed of light and gravitational mass, and experience with interferometry. Quantitative analysis will be an important part of the course, but mathematics beyond algebra will not be required. (L)
Instructor(s): Fausto Cattaneo (Summer Quarter); Craig Hogan (Winter Quarter) Terms Offered: Summer Winter.
Summer Quarter instructor is Fausto Cattaneo.
Prerequisite(s): PHSC 12600 or PHSC 12700
Equivalent Course(s): PHSC 12610

ASTR 12620. The Big Bang. 100 Units.
The Big Bang model describes the Universe on the largest scales and its evolution from the earliest observationally accessible times through the formation of the complex world we live in today. This powerful framework allows us to interpret a wide range of observations and to make detailed and precise predictions for new experiments. The key motivating observations include the expansion of the Universe and how it has changed with time; the existence of radiation indicating a hot and dense early phase; the abundance of the light elements; and how matter is organized over a wide range of physical scales. The model naturally incorporates dark matter and dark energy, two surprising and poorly understood components that govern the growth of structure over time. The course will explore the history of scientific cosmology and the evidence for the Big Bang model, its consequences for the earliest moments after the Big Bang, and its predictions for the eventual fate of the Universe. Labs will include a hands-on measurement of the relic cosmic microwave background radiation from the early universe and the use of astronomical data to verify key discoveries in the history of Big Bang cosmology. Quantitative analysis will be an important part of the course, but prior experience with mathematics beyond algebra will not be required. (L)
Instructor(s): Erik Shirokoff Terms Offered: Spring
Prerequisite(s): PHSC 12600
Equivalent Course(s): PHSC 12620

ASTR 12700. Stars. 100 Units.
Elements such as carbon and oxygen are created in fusion reactions at high temperatures and pressures in the deep interiors of stars, conditions that naturally arise in stars like the Sun. This course will outline the physical principles at work and the history of the development of the key ideas: how nuclear physics and the theory of stellar interiors account for how stars shine, why they live for such long times, and how the heavy elements in their cores are dispersed to form a new generation of stars. Gravity assembles stars out of more diffuse material, a process that includes the formation of planetary systems. The course shows how, taken together, these physical processes naturally lead to the ingredients necessary for the emergence of life, namely elements like carbon, nitrogen, and oxygen, and planets in stable orbits around long-lived stars. The course features quantitative analysis of data; any tools needed beyond pre-calculus algebra will be taught as part of the course. (L)
Instructor(s): Fausto Cattaneo (Summer Quarter); Damiano Caprioli (Autumn Quarter) Terms Offered: Autumn
Summer Quarter instructor is Fausto Cattaneo.
Equivalent Course(s): PHSC 12700

ASTR 12710. Galaxies. 100 Units.
Galaxies have been called island universes, places where stars are concentrated, where they are born, and where they die. The study of galaxies reaches back to the Renaissance; Galileo Galilei first pointed a telescope skyward in 1610 and confirmed a then 2000 year-old Greek conjecture about the nature of our own galaxy -- the Milky Way. This course will use extensive modern observational data from a wide range of telescopes to trace the modern picture for the formation and evolution of galaxies and the stars in them. Galaxies will then be used as
markers of yet larger scale structures, in order to explore the influence of gravity over cosmic time. The object of study in this course is galaxies, and the narrative arc traced through that extensive data and understanding will highlight our profound discovery that most of the mass in galaxies (and the Universe as a whole) is in fact an exotic form of matter -- dark matter -- that we cannot directly see. Quantitative analysis will be an important part of the course in both laboratory work and lectures, but mathematics beyond algebra and some geometric understanding will not be required. This course will feature several observationally-oriented labs that will allow students to directly experience how some of the modern understanding of galaxies has arisen. (L)

Instructor(s): Jeffrey McMahon Terms Offered: Winter
Prerequisite(s): PHSC 10800, PHSC 12600 or PHSC 12700. PHSC 12710 can be taken as the first course in a sequence combined with PHSC 12720.
Equivalent Course(s): PHSC 12710

ASTR 12720. Exoplanets. 100 Units.
The past two decades have witnessed the discovery of planets in orbit around other stars and the characterization of extra-Solar (exo-) planetary systems. We are now able to place our Solar System into the context of other worlds and a surprising conclusion that most planetary systems look nothing like our own. A challenging next step is to find planets as small as the Earth in orbit around stars like the Sun. The architecture of planetary systems reflects the formation of the parent star and its protoplanetary disk, and how these have changed with time. This course will review the techniques for discovery of planets around other stars, what we have learned so far about exoplanetary systems, and the driving questions for the future, including the quest for habitable environments elsewhere. Although quantitative analysis will be an important part of the course, students will not be expected to employ mathematics beyond algebra. (L)

Instructor(s): Daniel Fabrycky Terms Offered: Spring
Prerequisite(s): PHSC 10800, PHSC 10100, PHSC 12700 or PHSC 12710.
Equivalent Course(s): PHSC 12720

ASTR 13300. Introduction to Astrophysics. 100 Units.
The course is intended for first-year students intending to major in Astrophysics as an introduction to the range of important physical processes that operate in astrophysical environments, and how these govern structures across a wide range of scales, from planets to superclusters to the Universe. Throughout the course, we will see that similar physical principles (gravity, radiation, particle physics) come in at different stages and systems (planets, stars, galaxies, the Universe). We will also incorporate into each class relevant current active research areas in Astrophysics, especially focusing on connection with research in the department. We anticipate a highly interactive class with a large number of group activities, demos and discussions.

Instructor(s): Chihway Chang Terms Offered: Spring
Prerequisite(s): PHYS 13300; may be taken concurrently. Students intending to pursue the BS in Astrophysics Chemistry Variant may enroll without PHYS 13300.

ASTR 18000. The Search for Extraterrestrial Life. 100 Units.
The origin of life is one of the biggest questions of modern science. While substantial progress has been made in understanding how life arose on our planet, such research represents just a single case study in how life originates and evolves. This course covers the search for life beyond Earth from the planets and moons of the Solar System to planets orbiting other stars and intelligent life that may have left its mark on macroscopic scales. The discovery of life beyond Earth would be transformative for our understanding of humanity’s place in the universe. A range of ongoing and planned experiments have the potential to detect or put strong constraints on the existence of life during the next few decades. This class will mix traditional lectures with flipped classroom problem-solving sessions.

Instructor(s): Jacob Bean Terms Offered: Autumn
Note(s): Can be used as a third course in physical sciences to meet the general education requirement (of six courses total in the biological, physical, and mathematical sciences). Not recommended for students who have taken ASTR/PHSC 12720 Exoplanets.
Equivalent Course(s): PHSC 18000

ASTR 18100. The Milky Way. 100 Units.
Within a largely empty universe, we live in a vast stellar "island" that we call the Milky Way. As we survey the stellar and interstellar components of the Milky Way-the distribution and motions of stars and interstellar gas, and how these dynamic, ever-changing components interact with each other during their life cycles inside the Milky Way-we will follow the path of ancient astronomers, wonder at their mistakes and prejudices, and form our own understanding.

Instructor(s): Nick Gnedin Terms Offered: Spring
Prerequisite(s): Any two-course 10000-level general education sequence in chemistry, geophysical sciences, physical sciences, or physics. Can be used as a third course in physical sciences to meet the general education requirement (of six courses total in the biological, physical, and mathematical sciences).
Equivalent Course(s): PHSC 18100

ASTR 18200. The Origin and Evolution of the Universe. 100 Units.
This course provides a comprehensive introduction to modern cosmology for students wishing to delve deeper into the subject than PHSC 12620 (which is not a prerequisite) but at a similar mathematical level. It will discuss how the fundamental laws of physics allow us to understand the origin, evolution, and large-scale structure of
the universe. After a brief review of the history of cosmology, the course will cover the expansion of the universe, Newtonian cosmology, Einstein's Special and General Relativity, black holes, dark matter, dark energy, the Cosmic Microwave Background radiation, Big Bang nucleosynthesis, the early universe, primordial inflation, the origin and evolution of large-scale structure in the universe, and cosmic surveys that are probing inflation and cosmic acceleration.

Instructor(s): Edward Kolb
Terms Offered: Winter
Prerequisite(s): Any two-course 10000-level general education sequence in chemistry, geophysical sciences, physical sciences, or physics. Can be used as a third course in physical sciences to meet the general education requirement (of six courses total in the biological, physical, and mathematical sciences).
Equivalent Course(s): PHSC 18200

ASTR 18300. Searching Between the Stars. 100 Units.
With the advent of modern observational techniques (e.g., radio, satellite astronomy), it has become possible to study free atoms, molecules, and dust in the vast space between the stars. The observation of interstellar matter provides information on the physical and chemical conditions of space and on the formation and evolution of stars.

Instructor(s): Doyal Harper
Terms Offered: Spring
Prerequisite(s): Any two-course 10000-level general education sequence in chemistry, geophysical sciences, physical sciences, or physics. Can be used as a third course in physical sciences to meet the general education requirement (of six courses total in the biological, physical, and mathematical sciences).
Equivalent Course(s): PHSC 18300

ASTR 18900. Mapping the Heavens: Early Astronomical Surveys. 100 Units.
By making a map of the stars and galaxies in the sky, we can learn about our position in the Milky Way and beyond, and build a physical picture of the visible Universe. When thousands of stars are included in the map, we see clusterings on relatively small and relatively large scales, leading to the question: How did these structures come to be? This question motivated the earliest sky maps as well as current surveys that explore the expanding Universe. Throughout most of the 19th century the positions of stars were recorded visually with a telescope. By the late 19th century, photographic glass plates had become competitive with the human eye and created a permanent record. In addition to stars, photographs revealed patches of light (nebulae), many fainter than could be seen by eye through a telescope. This course will explore how the scientific questions of the day (How far can we see? How do stars move through space? What are the nebulae, and why are they distributed the way they are?) were addressed by making photographic atlases of the sky, and in turn how these atlases raised more questions. All of the astronomical background needed to follow the story will be introduced within the course. We will be using primary sources including journal papers and catalogs of stars and galaxies, and digital scans of glass plates from circa 1900, and will make our own star catalogs and compare our measurements to the work of astronomers such as Edwin Hubble.

Instructor(s): Rich Kron
Terms Offered: Winter
Prerequisite(s): Can be used as a third course in physical sciences to meet the general education requirement (of six courses total in the biological, physical, and mathematical sciences).
Equivalent Course(s): HIPS 18900, PHSC 18900

ASTR 20500. Introduction to Python Programming with Applications to Astro Statistics. 100 Units.
The course will introduce students to programming using Python language and will review basic code elements and data structures commonly used in Python. It will introduce Python libraries, such as numpy and scipy and the concepts of vector operations that greatly aid scientific computations with Python. Plotting of graphs and data using Matplotlib library will also be introduced. Programming techniques will be illustrated and applied to basic statistical concepts that are used in astronomical research.

Instructor(s): Andrey Kratsov
Terms Offered: Autumn
Prerequisite(s): Placement into MATH 15100 or higher, or by consent.

ASTR 21100. Computational Techniques in Astrophysics. 100 Units.
This course will introduce basic computational techniques most often used in astronomical research, such as interpolation, transforms, smoothing, numerical differentiation and integration, integration of ordinary differential equations, and Monte Carlo methods, and elements of basic computer algorithms, data structures, and parallel programming using Python as the main course programming language with heavy use of NumPy, SciPy, and Matplotlib packages. Practical examples where these numerical techniques are applied will be covered via homework and in class exercises using real-world astronomical problems and results of recent papers with emphasis on implementing the algorithms from scratch. The course will cover the access to astronomical archival data, and how to search it efficiently, focusing specifically on the Sloan Digital Sky Survey, but with introduction to other data sets. Machine learning methods will be introduced to illustrate how large data sets can be mined for interesting information.

Instructor(s): Andrey Kratsov
Terms Offered: Spring
Prerequisite(s): ASTR 20500 or CMSC 12100 or consent of instructor.
Equivalent Course(s): ASTR 31200

ASTR 21200. Observational Techniques in Astrophysics. 100 Units.
This course will prepare students for independent research by introducing observation and analysis techniques in a field of astrophysics chosen by the instructor. Students will learn basics
of astronomical instrumentation and will apply that knowledge in a practical context (for example, using an on-campus telescope or telescopes controlled robotically from campus). The process of data reduction and calibration will be illustrated, leading to the extraction of scientifically meaningful results.

**Instructor(s):** Al Harper
**Terms Offered:** Winter

**Prerequisite(s):** ASTR 13300 or consent of instructor. ASTR 20500 or CMSC 12100 recommended.

### ASTR 21400. Creative Machines and Innovative Instrumentation. 100 Units.

An understanding of the techniques, tricks, and traps of building creative machines and innovative instrumentation is essential for a range of fields from the physical sciences to the arts. In this hands-on, practical course, you will design and build functional devices as a means to learn the systematic processes of engineering and fundamentals of design and construction. The kinds of things you will learn may include mechanical design and machining, computer-aided design, rapid prototyping, circuitry, electrical measurement methods, and other techniques for resolving real-world design problems. In collaboration with others, you will complete a mini-project and a final project, which will involve the design and fabrication of a functional scientific instrument. The course will be taught at an introductory level; no previous experience is expected. The iterative nature of the design process will require an appreciable amount of time outside of class for completing projects. The course is open to undergraduates in all majors (subject to the pre-requisites), as well as Master's and Ph.D. students.

**Instructor(s):** Scott Wakely (Autumn), Erik Shirokoff (Winter), Stephan Meyer (Spring)
**Terms Offered:** Autumn Spring Winter

**Prerequisite(s):** PHYS 12200 or PHYS 13200 or PHYS 14200; or CMSC 12100 or CMSC 12200 or CMSC 12300; or consent of instructor.

**Equivalent Course(s):** CMSC 31400, ASTR 31400, PHYS 20200, CHEM 32000

### ASTR 22060. What Makes a Planet Habitable? 100 Units.

This course explores the factors that determine how habitable planets form and evolve. We will discuss a range of topics, from the formation of planets around stars and the delivery of water, to the formation of atmospheres, climate dynamics, and the conditions that allow for the development of life and the evolution of complex life. Students will be responsible for periodically preparing presentations based on papers in peer-reviewed journals and leading the discussion.

**Instructor(s):** Edwin Kite
**Terms Offered:** Winter

**Equivalent Course(s):** GEOS 32060, ASTR 32060, GEOS 22060

### ASTR 23900. Physics of Galaxies. 100 Units.

This course will provide a comprehensive introduction to galaxies, the interstellar and intergalactic mediums. We will examine the basic properties of galaxies and the physical process involved in their structure and evolution. Topics will include the stellar content of galaxies and the dynamics of stars within galaxies, the Milky Way galaxy, the physical state of the interstellar medium, central supermassive black holes and active galactic nuclei, galaxy clusters and the hot intergalactic medium. We will discuss the formation of galaxies and processes that shape the distribution of dark matter and baryonic matter.

**Instructor(s):** Irina Zhuravleva
**Terms Offered:** Winter

**Prerequisite(s):** ASTR 24100 and PHYS 23400 or PHYS 23410 or consent of instructor.

### ASTR 24100. The Physics of Stars. 100 Units.

This course develops the physical theory of the internal structure of stars and how their structure changes with time. The material illustrates how to build model stars based on these physical principles and covers observational constraints on these models, such as the neutrino flux from the core of the Sun. Topics include supernovae and the end states of stars-white dwarfs, neutron stars, and black holes.

**Instructor(s):** Robert Rosner
**Terms Offered:** Winter

**Prerequisite(s):** ASTR 25400 or PHYS 23400 or PHYS 23410 or consent of instructor.

### ASTR 24300. Cosmological Physics. 100 Units.

This course will provide a comprehensive introduction to the principal topics in cosmology, including theoretical and observational foundations. Key topics will include the expansion of the Universe, dark matter and energy, cosmic microwave background, hot Big Bang, and the origin and evolution of structure.

**Instructor(s):** Wayne Hu
**Terms Offered:** Spring

**Prerequisite(s):** ASTR 24100 and PHYS 23400 or PHYS 23410 or consent of instructor. PHYS 27900 recommended.

### ASTR 24500. The Physics of the Dark Universe. 100 Units.

Approximately 85% of the mass in our universe is "dark matter," which is not made of familiar particles in disguise. The evidence for this remarkable fact comes from galactic dynamics, the clustering of matter on cosmological scales, the cosmic microwave background, gravitational lensing, and the yields of light elements formed shortly after the big bang. However, despite this vast body of evidence, the microscopic nature of dark matter is currently unknown and there are many candidate theories which make different predictions about its non-gravitational interactions with visible matter. In this course we will survey the evidence for the existence of dark matter, introduce some of the most commonly studied theories (e.g. WIMPs and axions), and explore their testable implications.

**Instructor(s):** Gordan Krnjaic
**Terms Offered:** Winter

**Prerequisite(s):** ASTR 24100 and PHYS 23400 or PHYS 23410, or consent of instructor. PHYS 27900 recommended.
ASTR 25000. Order-of-Magnitude Astrophysics. 100 Units.
In physics and astrophysics, an approximate answer is often just as (if not more) useful than an exact answer. Making order-of-magnitude estimates is helpful to develop physical intuition, to verify numerical solutions, and to evaluate whether a research problem is worth pursuing. In this course, students will receive coaching and practice in physics-based reasoning, back-of-the-envelope estimation, and thinking on their feet. Students will be encouraged to take a broad perspective, to think critically, and to have fun using physics to understand the universe around them.
Instructor(s): Leslie Rogers Terms Offered: Autumn
Note(s): Open to 3rd and 4th year undergraduates in the Physical Sciences by instructor consent.
Equivalent Course(s): ASTR 35000

ASTR 25400. Radiation Processes in Astrophysics. 100 Units.
Most of what we know about the Universe comes from detection of electromagnetic radiation emitted by individual sources or by diffuse media. Once we understand the processes by which the radiation was created and the processes by which the radiation is scattered or modified as it passes through matter, we can address the physical nature of the sources. The physics of radiation processes includes electricity and magnetism; quantum mechanics and atomic and nuclear structure; statistical mechanics; and special relativity.
Instructor(s): Fausto Cattaneo Terms Offered: Autumn
Prerequisite(s): MATH 18400 or MATH 18500 (recommended) and PHYS 22500 or PHYS 23400 or PHYS 23410 or consent of instructor.

ASTR 25800. Astrophysics of Exoplanets. 100 Units.
Extrasolar planets, a.k.a. exoplanets, are planets orbiting other stars. First definitively detected in the mid 1990s, the planet count has rapidly expanded and their physical characterization has sharpened with improved observational techniques. Theoretical studies of planetary formation and evolution are now attempting to understand this statistical sample. The field also aspires to address questions about life in the universe. This course emphasizes hands-on activities, like working with real astronomical data to find and characterize exoplanets. Topics are the radial velocity, transit, and other discovery and characterization techniques; statistical distributions of known planets; comparisons among planet structure and planetary system types; formation in a protoplanetary disk and subsequent dynamical evolution; the goal of finding life on an exoplanet; colonization of exoplanets; and the Fermi paradox.
Instructor(s): Daniel Fabrycky Terms Offered: Winter
Prerequisite(s): ASTR 24100 and PHYS 23400 or PHYS 23410 or consent of instructor.
Equivalent Course(s): GEOS 32080

ASTR 28500. Science with Large Astronomical Surveys. 100 Units.
The last several years have seen a veritable explosion of novel astronomical survey programs covering large areas of sky with unprecedented sensitivity. This course will explore the wide variety of science that can be done with surveys like the Sloan Digital Sky Survey, the Dark Energy Survey, the Gaia satellite, and the upcoming Large Synoptic Survey Telescope. Science topics will include our solar system, our Galaxy, the Local Group, distant galaxies, and cosmological measurements of our Universe. We will familiarize ourselves with the hardware and software components of astronomical surveys, before diving into hands-on analysis of public data sets. Students will learn computational and statistical techniques for analyzing large astronomical data sets.
Instructor(s): Alex Drlica-Wagner Terms Offered: Spring
Prerequisite(s): Third- or fourth-year standing in the College and completion of intermediate-level courses in the Physical Sciences; or by consent of instructor.

ASTR 29001. Field Course in Astronomy and Astrophysics I. 100 Units.
In this two-quarter course students will explore an area of astrophysical research through weekly seminars in preparation for a four-night visit to an observatory during the spring break. In the second quarter of the course students will analyze data collected during their observing experience and will collaborate to produce a single paper similar in format to scientific papers published in professional journals. Students must enroll in both ASTR 29001 and ASTR 29002.
Instructor(s): Michael Gladders Terms Offered: Winter
Prerequisite(s): Open to third-year students majoring in Astrophysics who have completed ASTR 13300, ASTR 21200 and ASTR 29800.

ASTR 29002. Field Course in Astronomy and Astrophysics II. 100 Units.
In this two-quarter course students will explore an area of astrophysical research through weekly seminars in preparation for a four-night visit to an observatory during the spring break. In the second quarter of the course students will analyze data collected during their observing experience and will collaborate to produce a single paper similar in format to scientific papers published in professional journals. Students must enroll in both ASTR 29001 and ASTR 29002.
Instructor(s): Michael Gladders Terms Offered: Spring
Prerequisite(s): ASTR 29001

ASTR 29700. Participation in Research. 100 Units.
Students are assigned to work in the research group of a member of the faculty. Participation in research may take the form of independent work on a small project or assistance to an advanced graduate student or faculty member in his or her research.
Instructor(s): Contact the Academic Affairs Administrator in the Department of Astronomy and Astrophysics for information. Terms Offered: Autumn Spring Summer Winter
Prerequisite(s): Third- or fourth-year standing and consent of instructor. Students must submit a completed Reading and Research Course Form to the Academic Affairs Administrator in Astronomy and Astrophysics before instructor consent will be given.
Note(s): Students must arrange with instructor in advance of the start of the term. Students are required to submit the College Reading and Research Course Form. Available for either quality grades or for P/F grading. Students may register for this course for as many quarters as they wish; they need not work with the same faculty member each time.

ASTR 29800. Undergraduate Research Seminar. 100 Units.
In this course students will engage with various scientific practices to prepare them for participation in research. Students will critically analyze research presented in popular and scholarly scientific literature and practice computational, statistical, and observational techniques to explore astrophysical problems. The course will emphasize student-led discussions and interactive presentations to synthesize previous coursework and strengthen scientific thinking and communication skills. Guest lectures by members of research groups will highlight projects undertaken by faculty in the Astronomy and Astrophysics Department to acquaint students with possibilities for research participation.
Instructor(s): Hsiao-Wen Chen Terms Offered: Spring
Prerequisite(s): ASTR 13300 and (ASTR 20500 or CMSC 12100) and ASTR 21200; or consent of instructor.
Note(s): Intended for students in the Astrophysics Major program.

ASTR 29900. Honors Thesis. 100 Units.
ASTR 29900 Honors Thesis is an independent research course, supervised by a faculty member in the Department of Astronomy and Astrophysics, in which the student either contributes to a faculty research project or engages in an approved independent research project. Eligible students enroll in ASTR 29900 for one quarter during their fourth year. Students intending to complete the Honors Thesis must meet with the Director of Undergraduate Studies in Astronomy and Astrophysics before the third week of Autumn Quarter to obtain Guidelines for the Honors Thesis Course and complete the Honors Thesis Form.
Instructor(s): Contact the Academic Affairs Administrator in the Department of Astronomy and Astrophysics for information. Terms Offered: Autumn Spring Winter
Prerequisite(s): Open to students who are majoring in Astrophysics with fourth-year standing. The student must earn a GPA of 3.50 or higher in the required courses for the Major and 3.0 overall, or obtain consent from the Assistant Chair for Academic Affairs, and have an approved research project that will be supervised by a faculty member. Students are required to submit the College Reading and Research Course Form to the Academic Affairs Administrator in Astronomy and Astrophysics in the quarter in which they enroll in the course.
Note(s): Students intending to complete the Honors Thesis must meet with the Director of Undergraduate Studies before the third week of Autumn Quarter to obtain Guidelines for the Honors Thesis Course and complete the Honors Thesis Form.