appreciation of Chinese art as molded by the philosophies, religions, and history of China. Not offered 2016–17.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. *9 units (3-0-6); first term.* This course examines the ways in which spectacle has been used in early modern and nineteenth-century Europe. Drawing on aesthetic writings about the impact of size and scale on audiences, but also examining historical accounts of the workings of spectacle on spectators, it looks at a number of case studies focusing on the technologies spectacles employed, the sites at which they were staged, the purposes and aims of their creators, and the controversies they engendered. Topics covered include English court masques, the rituals of absolute monarchy (especially those of Louis XIV), the changing presentation of plays and works of art, the public exhibition of torture, punishment, and human dissection, cabinets of curiosity and scientific demonstrations, religious, civic, and political ritual commemoration, the development of mixed media, panoramas and dioramas, and the staging of international exhibitions. Not offered 2016–17.

ASTROPHYSICS

Ay 1. The Evolving Universe. *9 units (3-3-3); third term; This course is intended primarily for freshmen not expecting to take more advanced astronomy courses and will satisfy the menu requirement of the Caltech core curriculum.* Introduction to modern astronomy that will illustrate the accomplishments, techniques, and scientific methodology of contemporary astronomy. The course will be organized around a set of basic questions, showing how our answers have changed in response to fresh observational discoveries. Topics to be discussed will include telescopes, stars, planets, the search for life elsewhere in the universe, supernovae, pulsars, black holes, galaxies and their active nuclei, and Big Bang cosmology. This class will be offered in a "flipped classroom" mode: the students will be required to watch the video lectures first, and then discuss them and work out problems in the classroom. A field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Djorgovski/Hallinan

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. *6 units (2-0-4); second term.* For course description, see Freshman Seminar. Instructor: Kulkarni

Ge/Ay 11 c. Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 20. Basic Astronomy and the Galaxy. *10 units (3-1-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc or instructor's permission.* The electromagnetic spectrum and basic radiative transfer; ground and space observing techniques; "pictorial Fourier description" of astrophysical optics; Kepler's laws; exoplanets; stellar masses, distances, and motions; the birth, structure, evolution, and death of stars; the structure and dynamics of the Galaxy. Lessons will emphasize the use of order-of-magnitude calculations and

scaling arguments in order to elucidate the physics of astrophysical phenomena. Short labs will introduce astronomical measurement techniques. Instructor: Sargent

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); second term. Prerequisites: Ma 1 abc, Ph 1 abc or instructor's permission.* Cosmological models and parameters, extragalactic distance scale, cosmological tests; constituents of the universe, dark matter, and dark energy; thermal history of the universe, cosmic nucleosynthesis, recombination, and cosmic microwave background; formation and evolution of structure in the universe; galaxy clusters, large-scale structure and its evolution; galaxies, their properties and fundamental correlations; formation and evolution of galaxies, deep surveys; star formation history of the universe; quasars and other active galactic nuclei, and their evolution; structure and evolution of the intergalactic medium; diffuse extragalactic backgrounds; the first stars, galaxies, and the reionization era. Instructor: Djorgovski

Ay 30. Introduction to Modern Research. *3 units (2-0-1); second term.* Weekly seminar open to declared Ay majors. At the discretion of the instructor, nonmajors who have taken astronomy courses may be admitted. Course is intended for sophomores and juniors. This seminar is held in faculty homes in the evening and is designed to encourage student communication skills as they are introduced to faculty members and their research. Each week a student will review a popular-level article in astronomy for the class. Graded pass/fail. Instructor: Sargent

Ay 31. Writing in Astronomy. *3 units (1-0-2); third term*. This course is intended to provide practical experience in the types of writing expected of professional astronomers. Example styles include research proposals, topical reviews, professional journal manuscripts, and articles for popular magazines such as Astronomy or Sky and Telescope. Each student will adopt one of these formats in consultation with the course instructor and write an original piece. An outline and several drafts reviewed by both a faculty mentor familiar with the topic and the course instructor are required. This course is most suitable for juniors and seniors. Fulfills the Institute scientific writing requirement. Instructor: Sargent

Ay 43. Reading in Astronomy and Astrophysics. *Units in accordance with work accomplished, not to exceed 3.* Course is intended for students with a definite independent reading plan or who attend regular (biweekly) research and literature discussion groups. Instructor's permission required. Graded pass/fail. Instructor: Staff.

Ay 78 abc. Senior Thesis. *9 units. Prerequisite: To register for this course, the student must obtain approval of the astronomy option representative and the prospective thesis adviser.* Previous SURF or independent study work can be useful experience. Course is open to senior astronomy majors only. Research must be supervised by a faculty member. Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the astronomy option representative. The student will work with an advisor to formulate a research project, conduct original research, present

new results, and evaluate them in the context of previously published work in the field. The first two terms are graded pass/fail and the grades are then changed at the end of the course to the appropriate letter grade for all three terms. In order to receive a passing grade for second term, a work plan and a preliminary thesis outline must be submitted. The written thesis of 20–100 pages must be completed and approved by the adviser and the option representative before the end of the third term. Instructor: Staff.

Ay 101. Physics of Stars. *11 units (3-2-6); second term. Prerequisite: Ay 20 is recommended.* Physics of stellar interiors and atmospheres. Properties of stars, stellar spectra, radiative transfer, line formation. Stellar structure, stellar evolution. Nucleosynthesis in stars. Stellar oscillations. Instructor: Kirby

Ay 102. Physics of the Interstellar Medium. *9 units (3-0-6); third term. Prerequisite: Ay 20 is recommended.* An introduction to observations of the inter-stellar medium and relevant physical processes. The structure and hydrodynamic evolution of ionized hydrogen regions associated with massive stars and supernovae, thermal balance in neutral and ionized phases, star formation and global models for the interstellar medium. Instructor: Hillenbrand

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 1, Ph 2 ab.* This course is designed primarily for junior and senior undergraduates in astrophysics and physics. It covers the physics of black holes and neutron stars, including accretion, particle acceleration and gravitational waves, as well as their observable consequences: (neutron stars) pulsars, magnetars, X-ray binaries, gamma-ray bursts; (black holes) X-ray transients, tidal disruption and quasars/active galaxies and sources of gravitational waves. Not Offered 2016–2017

Ay 105. Optical Astronomy Instrumentation Lab. *10 units (1-5-4); third term.Prerequisites: Ay 20.* An opportunity for astronomy and physics undergraduates (juniors and seniors) to gain firsthand experience with the basic instrumentation tools of modern optical and infrared astronomy. The 10 weekly lab experiments include radiometry measurements, geometrical optics, polarization, optical aberrations, spectroscopy, CCD characterization, vacuum and cryogenic technology, infrared detector technology, adaptive optics (wavefront sensors, deformable mirrors, closed loop control) and a coronography tuturial. Instructor: Mawet.

Ay 111 a. Introduction to Current Astrophysics Research. *3 units; first term.* This course is intended primarily for first-year Ay graduate students, although participation is open and encouraged. Students are required to attend seminar-style lectures given by astrophysics faculty members, describing their research, to attend the weekly astronomy colloquia, and to follow these with additional readings on the subject. At the end of each term, students are required to summarize in oral or written form (at the discretion of the instructor), one of the covered subjects that is of most interest to them. Instructor: Phinney

Ge/Ay 117. Statistics and Data Analysis. *9 units (3-0-6); Prerequisites: CS 1 and instructor's permission.* For course description, see Geological and Planetary Sciences.

Ay 119. Methods of Computational Science. *9 units (3-0-6); third term.* Open to graduate and upper-division undergraduate students in all options. Practical computational science methods useful in disciplines dealing with large and/or complex data sets. Topics include: Scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. Not Offered 2016–2017

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisite: Ph106bc, Ph 125 or equivalent (undergraduates).* The interaction of radiation with matter: radiative transfer, emission, and absorption. Compton processes, coherent emission processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructor: Kirby

Ay 122 abc. Astronomical Measurements and Instrumentation. *9 units (3-0-6); first term (a), second term (b). Prerequisites: Ph 106bc or equivalent.* Measurement and signal analysis techniques througout the electromagnetic spectrum. Courses may include lab work and field trips to Caltech observatories. Ay 122a concentrates on infrared, optical, and ultraviolet techniques: telescopes, optics, detectors, photometry, spectroscopy, active/adaptive optics, coronography. Imaging devices and image processing. Ay 122b concentrates on radio through submillimeter techniques: antennae, receivers, mixers, and amplifiers. Interferometers and aperture synthesis arrays. Signal analysis techniques and probability and statistics, as relevant to astronomical measurement. Ay 122c (not offered 2016–17) concentrates on X-ray through gamma-ray techniques. Instructors: (a) Kasliwal, Mawet, (b) Hallinan, Kulkarni.

Ay 123. Structure and Evolution of Stars. *9 units (3-0-6); first term. Prerequisites: Ay 101; Ph 125 or equivalent (undergraduates).* Thermodynamics, equation of state, convection, opacity, radiative transfer, stellar atmospheres, nuclear reactions, and stellar models. Evolution of low- and high-mass stars, supernovae, and binary stars. Instructor: Hillenbrand

Ay 124. Structure and Dynamics of Galaxies. *9 units (3-0-6); second term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Stellar dynamics and properties of galaxies; kinematics and dynamics of our galaxy; spiral structure; stellar composition, masses, and rotation of external galaxies; star clusters; galactic evolution; binaries, groups, and clusters of galaxies. Instructor: Hopkins

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 106 and Ph 125 or equivalent (undergraduates).* High-energy astrophysics, the final stages of stellar evolution; supernovae, binary stars,

accretion disks, pulsars; extragalactic radio sources; active galactic nuclei; black holes. Instructor: Kasliwal

Ay 126. Interstellar and Intergalactic Medium. *9 units (3-0-6); third term. Prerequisite: Ay 102 (undergraduates).* Physical processes in the interstellar medium. Ionization, thermal and dynamic balance of interstellar medium, molecular clouds, hydrodynamics, magnetic fields, H II regions, supernova remnants, star formation, global structure of interstellar medium. Instructor: Kulkarni

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); second term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Cosmology; extragalactic distance determinations; relativistic cosmological models; galaxy formation and clustering; thermal history of the universe, microwave background; nucleosynthesis; cosmological tests. Instructor: Staff

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6);* For course description, see Geological and Planetary Sciences.

Ay 141 abc. Research Conference in Astronomy. *3 units (1-0-2); first, second, third terms.* Oral reports on current research in astronomy, providing students an opportunity for practice in the organization and presentation of technical material. A minimum of two presentations will be expected from each student each year. In addition, students are encouraged to participate in a public-level representation of the same material for posting to an outreach website. This course fulfills the option communication requirement and is required of all astronomy graduate students who have passed their preliminary exams. It is also recommended for astronomy seniors. Graded pass/fail. Instructors: (a) Mawet/Phinney; (b) Kirby/Sargent; (c) Hallinan/Hillenbrand

Ay 142. Research in Astronomy and Astrophysics. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of research outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy for graduate students. Graded pass/fail.

Ay 143. Reading and Independent Study. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of reading and independent study outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy for graduate students. Graded pass/fail.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 190. Computational Astrophysics. *9 units (3-0-6); second term. Prerequisites: Ph 20–22 (undergraduates).* Introduction to essential numerical analysis and computational methods in astrophysics and astrophysical data analysis. Basic numerical methods and techniques; N-body simulations; fluid dynamics (SPH/grid-based); MHD; radiation transport; reaction networks; data analysis methods; numerical relativity. Not offered 2016–17.

Ay/Ge 198. Special Topics in the Planetary Sciences. *9 units (3-0-6); third term.* Topic for 2015–16 is Extrasolar Planets. Thousands of planets have been identified in orbit around other stars. Astronomers are now embarking on understanding the statistics of extrasolar planet populations and characterizing individual systems in detail, namely star-planet, planet-planet and planet-disk dynamical interactions, physical parameters of planets and their composition, weather phenomena, etc. Direct and indirect detection techniques are now completing the big picture of extra-solar planetary systems in all of their natural diversity. The seminar-style course will review the state of the art in exoplanet science, take up case studies, detail current and future instrument needs, and anticipate findings. Not Offered 2016–17.

Ay 211. Contemporary Extragalactic Astronomy. *9 units (3-0-6); third term. Prerequisites: Ay 123, Ay 124, and Ay 127.* Topics in extragalactic astronomy and cosmology, including observational probes of dark matter and dark energy; cosmological backgrounds and primordial element abundances; galaxy formation and evolution, including assembly histories, feedback and environmental effects; physics of the intergalactic medium; the role of active galactic nuclei; galactic structure and stellar populations; future facilities and their likely impact in the field. Not offered 2016–17.

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term.* Course for graduate students and seniors in astronomy and planetary science. Students will be required to lead some discussions. Topic will be selected based on student interest. Not offered 2016–17.

Ay 218. Extrasolar Planets. *9 units (3-0-6); third term.* Not offered 2016–17.

Ay 219. Elements in the Universe and Galactic Chemical Evolution. *9 units (3-0-6); second term. Prerequisites: Ay 121, 123, 124, 126.* Survey of the formation of the elements in the universe as a function of cosmic time. Review of the determination of abundances in stars, meteorites, H II regions, and in interstellar and intergalactic gas. Overview of models of galactic chemical evolution. Participants will measure elemental abundances from the Keck spectrum of a star and construct their own numerical chemical evolution models. Not offered 2016–17.