Astrobiology: Exploring Other Worlds

Course Description

How are astronomers approaching their search for life in the universe? What have we learned from the surge of exoplanets discoveries? How likely is it that Earth does not host the only life in the Universe? In this course we explore astrobiology, an emerging multidisciplinary field. Progress in astrobiology is driven by telescopes on the ground and in space, and by new insights on how biology emerged on Earth and its diversity. The first detection of life beyond the Earth may happen in the Solar System or by seeing biology's alteration of an exoplanet's atmosphere. A long shot approach is the search for extraterrestrial intelligence (SETI). Topics in this course range from the science of how exoplanets are detected, to the definition of habitability, to the chemistry that supports the argument that the ingredients for life are common in the universe. Astrobiology poses one of the most profound questions we can ask in science: are we alone?

Class Schedule

Six sessions, each 10-12am, on Jan 23, Jan 30, Feb 6, Feb 13, Feb 20, and Feb 27. The typical structure is a 50-minute lecture, a 10-minute break, a 40-minute lecture, then 20 minutes for questions and discussion. All the class meetings are in the Rubel Room of the Poetry Center.

Course Reading List

The single book most suitable for this course is Chris Impey's recent book on exoplanets, listed first below. The other four books offer varied perspectives on the search for life beyond Earth.

Worlds Without End: Exoplanets, Habitability, and the Future of Humanity (MIT Press, 2023)
https://www.penguinrandomhouse.com/books/718149/worlds-without-end-by-chris-impey/

Envisioning Exoplanets by Michael Carroll (Smithsonian, 2020)
https://smithsonianbooks.com/store/aviation-military-history/envisioning-exoplanets-searching-for-life-in-the-galaxy/

Imagined Life by James Trefil and Michael Summers (Smithsonian, 2019)
https://smithsonianbooks.com/store/science-nature/imagined-life-a-speculative-scientific-journey-among-the-exoplanets-in-search-of-intelligent-aliens-ice-creatures-and-supergravity-animals/

Ethical Foundations & Social Implications of Astrobiology edited by Chris Impey (Arizona, 2013)
https://uapress.arizona.edu/book/encountering-life-in-the-universe

Talking About Life: Conversations on Astrobiology edited by Chris Impey (Cambridge, 2010)
https://www.cambridge.org/us/academic/subjects/physics/planetary-systems-and-astrobiology/talking-about-life-conversations-astrobiology?format=HB

Weekly Lectures

January 23: Planets in the Solar System and Beyond

Objectives

- Explain the difference between a planet and an exoplanet.
- Recognize that our solar system is composed of examples of general types of planets.
- Describe the basic steps in the planet formation process.
- Recognize that planet formation is part of the general star formation process.
- Explain why rocky planets form closer to a star than gas giants.
- Recognize that planets can and do migrate within exoplanet systems.
- Recognize that entirely new types of planets have been found around other stars.
- Compare our solar system to exoplanet systems.
- Discuss the number of exoplanets and the likelihood and scale of future discoveries.

Topics

1. Exoplanets: Defining planets, exoplanets, and the discovery of exoplanets.
2. Planet Formation: Star formation, planet formation, accretion, differentiation, f(p) = The fraction of stars with planetary systems.
3. Planets and Moons: Characteristics of rocky planets, gas giants, and how moons form.
4. Our Solar System: Tour of inner and outer solar system.
5. Hot Jupiters and Planet Migration: What are hot Jupiters, why are they relevant, how does planetary migration work.
6. Water Worlds: Ice giants, mini-Neptunes, super-Earths and examples of water worlds in the solar system.
7. The Census of Exoplanets in the Milky Way: Planet demographics by type (hot Jupiter, ice giant, super-Earth), the detection limit; future of exoplanet hunting.

January 30: Hunting for Exoplanets

Objectives

- Recognize that the speed of light is invariant.
- Recognize that planets and stars interact gravitationally.
- Explain what the Doppler shift is and how it is caused.
- Interpret exoplanet radial velocity data.
- Interpret exoplanet transit method data.
- Recognize advantages and limitations of each type of detection method.
- Demonstrate methods used to determine exoplanet mass, radius, and density.
- Distinguish between mass and density.

Topics

1. Gravity and the Doppler Shift: Law of gravity, more mass is more gravity, center of mass, reflex motion; electromagnetic spectrum and nature; Doppler shift.

2. The Radial Velocity Method: Doppler wobble, first exoplanet detected; exoplanet mass (examples, hot Jupiter v. super earth); limitations of the method.
3. The Transit Method: Transits, exoplanet size, size v. mass; limitations.
4. Learning from Observations: Kepler's laws; calculating exoplanet mass, radius, volume, density.
5. Density: Defining density (mass, size, distinction, and range of planet composition), comparative planetology.
6. Microlensing, Imaging and Selection Effects: Direct imaging, coronagraphs, and gravitational microlensing; selection effects.

February 6: Biology and Habitability

Objectives

- Recognize that the ingredients for life are ubiquitous.
- Describe why the ingredients for life on Earth also exist in most planet forming regions.
- Explain why water and complex molecules are the two common denominators for life.
- Give examples of how liquid water is a prerequisite for biological life.
- Examine the distribution of organic compounds throughout the galaxy.
- Define the habitable zone.
- Relate the definition of the habitable zone to the luminosity from the host star.
- Describe why mass is the critical aspect that defines a star.

Topics

1. Cosmic Chemistry: HCNO most common molecules are ubiquitous, low mass stellar nucleosynthesis, high mass stellar nucleosynthesis, cycling through nebulae.
2. Essentials of Biological Life: Organic molecules and amino acids, composition of human body, organic molecules in space; versatility of carbon; significance of water.
3. Defining the Habitable Zone: What is it, how is it defined, significance of liquid water, luminosity; habitable zone candidate exoplanets; TRAPPIST system.
4. The Lifetime of Stars: Spectral type, mass, fusion, fusion rate v. mass; stellar lifetime v. mass; candidate spectral types; R* = The rate of formation of long-lived stars.
5. Stars and Exoplanets: Favorable host stars continued, habitable zone and luminosity and flux; examples of exoplanet systems; the cryogenic habitable zone.
6. Exoplanet Habitability: Exoplanets in different orbits, habitability of TRAPPIST system; f(n_e)= number of exoplanets in habitable zone.

February 13: Life on Earth and Other Worlds

Objectives

- Recognize that the geologic record allows us to infer the conditions on early Earth.
- Demonstrate an understanding of radioactive half-life.
- Explain why volcanic activity is important for habitability.
- Define the greenhouse effect.

- Understand the theories describing how life emerged on Earth.
- Explain the link between photosynthesis and oxygen on the early Earth.
- Recognize the significance of extremophiles in expanding the definition of habitability.
- Explain why moons in our solar system could be considered habitable.
- Understand the history of habitability on Mars.

Topics

1. Early Earth: Hadean earth, LHB, geological processes, radioactivity; Zircon crystal.
2. The Atmosphere and Oceans: Earth's magnetic field, Volcanic Activity, formation of the Atmosphere and Oceans, greenhouse effect, Venus.
3. Defining Life: traits of biological life, making the first cells, chemical evolution, RNA.
4. Early Life: Metabolism, prokaryotic cells, cyanobacteria, stromatolites, photosynthesis, early oxygen and the oxygen crisis.
5. Life at the Extreme: Extremophiles, Miller-Urey; f(l) = fraction of planets on which life will arise.
6. Habitable Moons: Tardigrades, Titan, Enceladus, Europa.
7. Mars: Water past and present, methane, probes, traveling to Mars.

February 20: Complex Life and Intelligence

Objectives

- Explain the difference between anaerobic and aerobic respiration.
- Demonstrate an understanding of the function of DNA.
- Describe what biosignatures are.
- Describe the process of genetic evolution.
- Describe the process of natural selection.
- Describe the evolution of intelligence.

Lesson Topics

1. Emergence of Cellular Life: Huronian Glaciation, Proterozoic eon, anaerobic/aerobic respiration, emergence of eukaryotic cells.
2. DNA and Genetics: Proterozoic eon, sexual reproduction, DNA and the genetic code, Cryogenian Glaciation.
3. Life in the Phanerozoic Eon: What/When is the Phanerozoic eon, Cambrian explosion, genetic variations, biosignatures.
4. Evolution: Evolution, Darwin, natural selection.
5. Life on Earth: Tree of life, complexity, LUCA, mass extinction events.
6. Genus Homo: Mammalian evolution after KT impact, primates, human evolution, intelligence; f_i = how often will life evolve intelligence.

February 27: SETI and Cosmic Companionship

Objectives
- Recognize that the study of astronomy is deeply embedded in human history.
- Explain why astronomy as a time-keeping device was essential for human survival.
- Explain why the Copernican revolution allowed the advance of modern science.
- Defend the importance of empirical evidence.
- Demonstrate understanding of wireless communication.
- Compare advantages of wireless communication to analog communication.
- Explain why radio wavelengths are optimal for interstellar communication.
- Recognize that the speed of light is finite.
- Explain why the finite speed of light limits chances of contact with other intelligence.
- Describe the factors in the Drake equation and their purpose.
- Defend the claim that the statistical likelihood of life beyond Earth is greater than zero.
- Recognize that current rocket technology makes interstellar travel impossible.

Lesson Topics
1. Civilizations and Culture: Astronomy in ancient cultures, importance of agriculture in allowing time for philosophical thought; astronomical study through the ages.
2. Scientific Revolution: Copernican revolution, geo- to heliocentric paradigm shift.
3. Interstellar Communication: Developing EM communication technology; f_c = The fraction of civilizations that develop the ability to communicate or travel through space.
4. SETI: History and mission of SETI; Fermi paradox; L = The length of time civilizations can persist in the communicable phase.
5. Drake Equation: Formal discussion of Drake equation and factors introduced throughout course; how to interpret example calculations.
6. Interstellar Travel: Realities of interstellar travel; example calculations for travel to nearby places of interest; revisiting the speed of light.
7. Life as Computation: The future of space travel, post-biological evolution.

Professor Bio
Chris Impey is a University Distinguished Professor of Astronomy at the University of Arizona. He has over 500 publications on education, observational cosmology, galaxies, and quasars, and his research has been supported by $20 million in grants from NASA and NSF. He has won eleven teaching awards locally and nationally and has taught four online classes with over 380,000 enrolled and 6 million minutes of video lectures watched. Chris Impey is a past Vice President of the American Astronomical Society, and he has won its career Education Prize.