PHSC 12610 "Black Holes"

Prof. Craig Hogan, Spring 2021

"The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time. And since the general theory of Relativity provides only a single unique family of solutions for their descriptions, they are the simplest objects as well."

Subrahmanyan Chandrasekhar, "The Mathematical Theory of Black Holes"

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 a pure vacuum, "made of " only extreme space-time curvature; they radiate more power than anything else, even though most of their radiation may not even be made of light; they are mathematically the most perfectly understood of any physical structure, but their enigmatic behavior is still the subject of heated disagreements, even among experts, that highlight our ignorance of how quantum physics relates to gravity, what happens inside them, and even whether their interiors are part of "reality". They are real objects in the universe that also represent real boundaries of our space-time. 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, and their importance at frontiers and boundaries of fundamental physics. A special focus will be a new field of science, the study of the universe by direct measurement of gravitational radiation.

This course is intended as a general Physical Sciences course, accessible to students with a high school background in science or mathematics. By the end of the course, students will be able to summarize the historical development and quantitative scientific basis, including theoretical foundations and experimental results, for our modern understanding of space and time, especially for the extreme space-time structures we call black holes. They will gain experience in contact with the physical world through carefully designed experiments, and in scholarly research and presentation.

Canvas

Assignments and lab reports are posted and collected on Canvas,

https://canvas.uchicago.edu/courses/33971

Lectures

Students are expected to attend and participate in lectures Wednesdays and Fridays, 1:50-3:10 PM, March 31 to May 28, on Zoom:

https://uchicago.zoom.us/j/95675971920?pwd=bFRDajFNREVQRTltZlpMUFdEZEc1UT09

Meeting ID: 956 7597 1920

Passcode: 768576

Labs: This is where you get practice thinking like a scientist by conducting experiments to create knowledge and writing reports to disseminate it. Laboratory times will also be used for student presentations based on projects. Every student must enroll in a lab section. **Please download the separate lab syllabus from Canvas**.

Office Hours: Prof. Hogan will remain on zoom most days after class.

Contact Information

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Reading

Books are available as ibook, Kindle, paperback or hardcover.

The first part of the course follows:

Kip Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*

Two books used in PHSC 12600 can also be read for additional background:

Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality (Kumar)

To Explain the World: The Discovery of Modern Science (Weinberg)

Additional reading during the course:

Albert Einstein, "*Relativity: the Special and General Theory*" (also available as ebook, Kindle, etc.)

Albert Einstein, "*Autobiographical Notes*" (from the Einstein Festschrift, pdf on canvas)

Albert Einstein, "*Does the Inertia of a Body Depend on its Energy Content*?" (the famous, very short E=mc^2 paper, pdf on canvas)

Albert Einstein, "*On the Electrodynamics of Moving Bodies*" (the original Special Relativity paper, pdf on canvas)

Niels Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics" (from the Einstein Festschrift, pdf on canvas)

Frank Shu, "The Great Laws of Microscopic Physics" (book chapter on canvas)

Frank Shu, "The Great Laws of Macroscopic Physics" (book chapter on canvas)

Readings assigned from the web will also include Nobel lectures, LIGO science papers, reviews, and other resources available online .

Homework and Grades

The mapping of numbers onto letter grades will not be less favorable than A88, A-81, B+74, B67, B-60, C+53, C 46, C-39, D+32, D25, D-18. This scheme is designed to maximize the dynamic range and discrimination of the number system.

In addition to **lab write-ups**, there will be **homework assignments**, including a longer **project assignment including both a paper and in-class student presentations with slides**. Grades will be based on a combination of these assignments and labs. Details of expectations, grading, late policy and rubrics for labs are shared separately in the lab syllabus.

Crisis-related absences and extensions

This is an uncertain time for all of us. If you are impacted by events related to the COVID-19 pandemic, civic unrest, or other crises as they emerge, please reach out to us. We may be able to connect you to university resources, and the more you communicate to keep us updated, the easier it is for us to be flexible about course policies. We will all need to continue to adapt, and we are all in this together. If you need an extension, please do so before the deadline.

Late penalty

There will be ten percent penalty per calendar day for late assignments, up to a maximum of fifty percent.

Lecture topics by week

Week 1. March 31, April 2

Overview of physical space and time from the ancient world to Einstein

Reading:

Thorne, Prologue, “A Voyage Among the Holes”, and Chapter 1, “The Relativity of Space and Time”

Einstein, “*Autobiographical Notes*”

(*extra background can be found in:* Weinberg, “*To Explain the World*”)

Topics in class:

Overview of the course, including labs and projects; review ideas of space, time, and gravity from ancient times; review Newton’s theories of space, time, motion, and gravity; measurements of the speed of light from measurement of Jovian moons and from aberration; Fizeau and Foucault speed of light experiments; Michelson’s improvements; Faraday’s measurements of electricity and magnetism, Maxwell’s theory of electromagnetism and the nature of light; Michelson’s interferometers; Michelson-Morley experiment, constancy of speed of light in different directions; the “Luminiferous Ether”; Lorentz-Fitzgerald contraction; Einstein’s thought experiments with light, mirrors and clocks; mixing of space and time; Einstein’s special theory relativity; relativity of simultaneity; time dilation; boosts, redshifts, angular distortions, apparent length contractions; experimental confirmations of time dilation; twin “paradox” and others; derivation of $E= mc^2$ and its implications; Minkowski’s “space-time”; invariant timelike and spacelike intervals, light cones, causal structure

Lab sections: discussions about project options

Week 2. April 7, 9

Gravity and general relativity

Reading:

Thorne, Chapters 2 and 3, “The Warping of Space and Time”, “Black Holes Discovered and Rejected”

Shu, “The Great Laws of Microscopic Physics”

Topics in class:

Newton's absolute space; motion and inertial frames; Newton's gravity; free fall, inertial and gravitational mass; orbits and tides; consistency problem of special relativity with non-invariance of gravity; precession of Mercury's perihelion; Einstein's "happiest thought", the "Principle of Equivalence"; thought experiments with freely falling frames ("elevator experiments"); Einstein's development of the general theory of relativity; gravitational time dilation and light bending; manifolds and metrics; geometrical curvature, triangles, and geodesics; curved space-time and the geometrical interpretation of gravity; geodesic trajectories and tides; early experimental tests of general relativity: precession of Mercury's orbit, bending of light around the sun; preview of modern precision tests of general relativity: gravitational redshift, binary pulsars, lunar ranging, orbiting gyroscopes, solar system time delay, gravitational lensing, etc.; consumer, commercial and military applications, global positioning system; early development and interpretation of ideas of black holes (Michell dark stars); metrics and coordinates in curved space-time; Schwarzschild metric

Week 3. April 14, 16

Physics of stars, stellar evolution, remnants, and collapse

Reading:

Thorne, Chapters 4 and 5

Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics"

Shu, "The Great Laws of Macroscopic Physics"

S. Chandrasekhar and W. Fowler Nobel lectures (online at Nobel Foundation site)

(extra background can be found in

Kumar, *Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality*)

Topics in class:

trajectories of particles and waves; physics of matter and energy; waves and particles in quantum mechanics; atoms and wave functions; microscopic and macroscopic systems of gravitating matter; pressure and stability; structure of planets, normal stars, and dwarf stars; stellar evolution and nucleosynthesis; quantum theory and Chandrasekhar's theory of degenerate dwarfs; Zwicky, Oppenheimer, and neutron stars; Wheeler and black holes

Week 4. April 21, 23

The black hole solutions of general relativity

Reading: Thorne, Chapters 6 and 7

Topics in class:

Embedding diagrams of curved spacetime and trajectories; mathematical structure of black holes; Schwarzchild and Kerr solutions of Einstein's equations; singularities, event horizons, and spin; embedding diagrams and Penrose diagrams of black holes and other curved space-times; what happens inside and around black holes; distant and freely falling observers; physical interpretations of the solutions; eternal black holes

Week 5. April 28, 30

Black holes in the real universe

Reading: Thorne, Chapters 8 and 9

Nobel Prize site, 2020:
https://www.nobelprize.org/prizes/physics/2020/summary/

Topics in class:

Interactions of black holes with external matter and magnetic fields; formation of black holes from stars; experimental signatures of black holes; new astronomical tools and transformational discoveries in the 1960's (radio galaxies, quasars, QSOs, X ray sources); energy extraction from black holes and their interaction with surrounding matter; accretion disks, magnetic fields, and jets; stellar mass X ray binaries and supermassive black holes

Radiation mechanisms and interpretation of spectra; thermal and nonthermal sources, spectral lines; observational evidence for black holes; current studies of supermassive black holes; radio sources and jets; active galactic nuclei and quasars; black holes in centers of galaxies; our Galactic Center; stellar orbits; potential for direct imaging of the event horizon; recent direct images of matter orbiting close to the innermost stable circular orbit of the Galactic center hole; signatures of black hole horizons and spin in X ray spectra

Week 6. May 5, 7

Gravitational waves

Reading: Thorne, Chapter 10 and 11

LIGO websites,

https://www.ligo.org/science.php

Topics in class:

Gravitational waves: what they are, how they work, how they are generated and detected; first evidence for gravitational radiation from binary pulsars; black hole and neutron star binary formation, evolution, populations; the LIGO revolution

Week 7. May 12, 14

Measurement of gravitational waves with interferometers with LIGO

Reading: summaries of LIGO science papers in 2016 (online at LIGO site)

2017 Nobel lectures in physics (Weiss, Barish, Thorne)

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/press.html

The Nobel site includes both a popular summary,

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/popular-physicsprize2017.pdf

and a technical science summary:

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/advanced-physicsprize2017.pdf

the Nobel lectures are published at

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.90.040501

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.90.040502

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.90.040503

summary of first event at the LIGO site:

https://www.ligo.org/science/Publication-GW150914/index.php

Topics in class:

Source populations and the LIGO program; black hole and neutron star binary chirp wave forms; distance measurement and direction measurement; determination of black hole properties from the wave form; noise spectrum and detection strategy; other sources of gravitational waves; gravitational wave spectrum; the historic first detections of black hole binaries in 2015

Week 8. May 19, 21

Recent and future developments in gravitational-wave science

Reading: online articles and websites on GW 170817; start with LIGO site:

https://www.ligo.org/science/Publication-GW170817BNS/index.php

Topics in class:

The historic neutron star binary merger event, GW 170817 and its kilonova; electromagnetic followup in radio, infrared, optical, X rays, gamma rays; new knowledge of stellar populations and evolution; new knowledge of relativity; new knowledge of nucleosynthesis; science in the age of large collaborations; latest LIGO discoveries and near term plans; effect of gravitational waves on astronomy in the future; development of space-based detectors and future study of supermassive black hole mergers; millisecond pulsar arrays as detectors; cosmological gravitational waves

Week 9. May 26, 28

Black holes and the fundamental quantum nature of space and time

Reading: Thorne, Chapters 12, 13, and 14

Topics in class: Unification of physics; mysteries in the foundations of physics; relationship(s) of matter, quantum mechanics and space-time; examples of theoretical paradoxes from blending general relativity and quantum mechanics into one world; locality; Einstein-Podolsky-Rosen thought experiment; fields, vacuum fluctuations and virtual particles; Wheeler's quantum space-time foam; black holes as a laboratory for thought experiments because they turn matter into space-time and *vice versa*; horizons and singularity theorems; area-increase theorem; thermodynamics and entropy; black hole thermodynamics; Bekenstein-Hawking entropy and evaporation; how black holes shrink and explode; description in Planck units; acceleration radiation; black hole information "paradoxes"; holographic principle; quantum gravity, string theory and loop quantum gravity;

AdS/CFT dualities; firewalls; what is “inside a black hole”; emergent gravity; nature of singularities in entropic gravity; other solutions of GR (flat space, Kerr black holes, FRW universes, de Sitter and anti-deSitter, cosmology and cosmological constant); wormholes, time machines, time warps; black holes in movies and fiction; far-future energy technologies based on black holes; experimental probes of basic elements of space and time: the Fermilab Holometer experiment and cosmic structure from spooky inflationary perturbations.

Reading:

https://news.fnal.gov/2021/02/random-twists-of-place-how-quiet-is-quantum-space-time-at-the-planck-scale/

https://cqgplus.com/2017/10/06/why-we-built-the-holometer/

https://arxiv.org/pdf/1307.2283.pdf