PHSC 12610 "Black Holes"

Prof. Craig Hogan

Winter 2019

"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". 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 brand new field of science, the study of the universe by direct measurement of gravitational radiation.

In Winter 2019, this course is being offered for the fourth time at the University of Chicago. It is intended as a general Physical Sciences course, accessible to students with no advanced background in science or mathematics.

Canvas

https://canvas.uchicago.edu/courses/18938

Lectures

Students are expected to attend and participate in lectures.

Time: Tuesdays and Thursdays 9:30-10:50 a.m.

Location: Hinds 101

Labs

A mandatory part of the course is hands-on laboratories and write-ups. Attendance is mandatory. 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**.

Location: Kersten Physics Teaching Center, 3^{rd} floor

Week 1: project planning discussion

Weeks 2 through 6: formal labs

Weeks 7 through 9: student presentations

Lab Section Schedule (seat limit 12/lab)

L03 - M 6:30 -- 8:20p Mark Klehfoth

L04 - T 1:30 -- 3:20p Fei Xu

L05 - W 10:30a -- 12:20p Mark Klehfoth

L06 - W 6:30 -- 8:20p Fei Xu

Office Hours: Prof. Hogan will be at ERC 443 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*

Supplemented by:

John Wheeler with Kenneth Ford, *Geons, Black Holes and Quantum Foam: a Life in Physics*

Two books that were used in PHSC 12600 should also be read early in the course:

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, and other resources available online (see below).

Homework and Grades

In addition to the **4 lab write-ups**, there will be **5 homework assignments**, as well as 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.

There will be a penalty for late assignments. Details of expectations, policies and rubrics for assignments, labs and projects are shared elsewhere.

It is OK to work together and consult/troubleshoot collaboratively, but apart from collaborative parts of labs, detailed work should be done individually.

All work you turn in should be your own original effort: no "sharing"!

Calendar of Assignments

upload all assignments and lab writeups as pdf to Canvas

For the project paper, please submit both pdf and hardcopy printout

Grade penalty for late assignments

Late submissions are penalized 10% for the first 24 hours, 20% for the second, and so on, up to a maximum penalty of 80%. The last moment to turn anything in for the course is March 12 at 11:59pm. *Technological issues are not considered a valid reason for changing the deadline.*

There are four lab write-ups

Each laboratory write up is due before your next lab section

Detailed instructions are in the lab syllabus

The **five homework assignments** will be due by **5PM on Fridays**:

First assignment is due **Jan 18**

Second assignment is due **Jan 25**

Third assignment is due **Feb 8**

Fourth assignment is due **Feb 15**

Fifth assignment is due **Feb 22**

Student presentations will be during lab sections: weeks of February 12, 19 and 26 (times will be scheduled individually)

Final project paper write-up and final presentation slides in pdf format are due by **5PM on the day of the last class, March 12**

Papers should be about 10 pages long, and **submitted both as a paper printout and as a pdf file**.

Grades

The mapping of numbers onto letter grades will not be less favorable than A 88, A- 81, B+ 74, B 67, B- 60, C+ 53, C 46, C- 39, D+ 32, D 25, D- 18

Syllabus by week

Week 1. Jan. 8, 10

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”

Weinberg, “*To Explain the World*”

Einstein, “*Autobiographical Notes*”

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. Jan 15, 17

Gravity and general relativity

Reading:

Thorne, Chapter 2, “The Warping of Space and Time”

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

***Lab 1*: Wave behavior in a ripple tank**

Week 3. Jan 22, 24

Physics of stars, stellar evolution, remnants, and collapse

Reading:

Thorne, Chapters 3 to 5

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

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

Wheeler and Ford, *Geons, Black Holes and Quantum Foam: a Life in Physics*

Shu, "The Great Laws of Macroscopic Physics"

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

Topics in class:

Early development and interpretation of ideas of black holes (Michell dark stars); metrics and coordinates in curved space-time; Schwarzschild metric; 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

***Lab 2:* Wave behavior with lasers**

Week 4. Jan 29, 31

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

***Lab 3:* Michelson interferometer**

Week 5. Feb 5, 7

Electromagnetic energy from black holes in the real universe

Reading: Thorne, Chapters 8 and 9

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

***Lab 4:* Galactic Center black hole**

Week 6. Feb 12, Feb 14

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

Lab: make-up for missed labs

Week 7. Feb 19, Feb 21

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

Lab: student presentations 1

Week 8. Feb 26, 28

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

Lab: student presentations 2

Week 9. Mar 5, 7

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

Lab: student presentations 3

Week 10. Mar 12

Experimental probes of basic elements of space and time: the Fermilab Holometer experiment and cosmic structure from spooky inflationary perturbations

Reading:

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

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

https://arxiv.org/abs/1811.03283