Agenda for Ast 309N, Nov. 27

- Optional HW 3 - due now; Quiz 8 – Thursday
- Next week: repeat survey (Tues), Exam 3 (Thurs)
- Feedback on black hole index cards
- Black hole basics
- Video clips
- Index Card for participation point
- Reminder: Exam 3 next Thurs., Dec. 6 is a unit exam (not comprehensive). There will be office hours, help session, and a Study Guide for it.

Black Holes in Terms of Escape Velocity

- Last Tuesday we discussed black holes in terms of escape velocities: the event horizon is the location at which $v_{(esc)}$ reaches *c*.
- Thus, the *event horizon* is a theoretical surface: the outer boundary of a region in space from which light cannot escape.
- It is located at a certain distance (radius) from the center of mass; the mass is at the central *singularity,* where the density is infinite.

The Anatomy of a (Simple) Black Hole

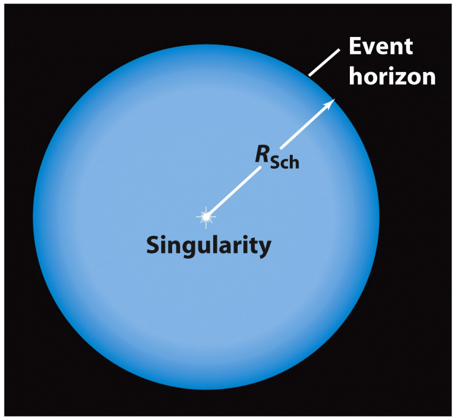


Figure 22-18
Universe, Eighth Edition

The *event horizon* is a hypothetical boundary of a region in space; the mass is located at the central *singularity*, where the density is infinite.

The event horizon is a "one-way" membrane; things can fall in, but never come out!

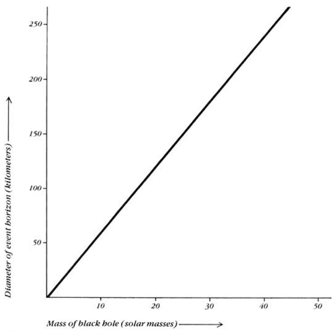
What's another example of a hypothetical surface?

How Big is the Event Horizon?

The event horizon (called R_s, the Schwarzschild radius) is the place where the escape velocity reaches the speed of light, c. The value is:

$$R_S = 3.0 \times M \text{ (in } M_\odot \text{) km}$$

The event horizon of a 10 $M_\odot$ black hole is 3 x 10 = 30 km.



Types of "Compact Objects"

Object	Supported by	Approx. Radius	Maximum Mass
White Dwarf	electron degeneracy pressure	R_{earth} = 0.01 $R_\odot$	1.4 $M_\odot$
Neutron Star	neutron degeneracy pressure	10 – 12 km (small city)	2 – 3 $M_\odot$
Black Hole	not supported!	3 km x mass in $M_\odot$	no limit

Black Holes: Concepts

- A "black hole" is the ultimate victory of gravity over pressure.
- All matter in the star collapses into a point of infinite density: the "singularity"
- At a certain distance from the singularity, gravitational bending of light is so severe, even light rays travelling directly "outward" are turned back in.

Bending Light: Closing of the "Light Cone"

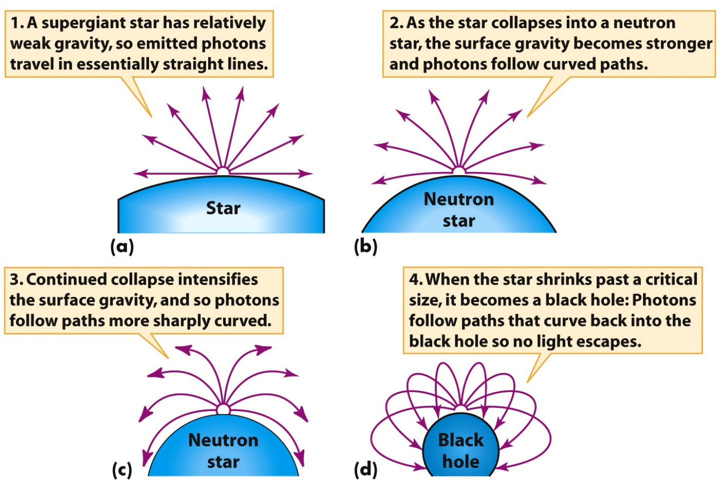


Figure 22-8
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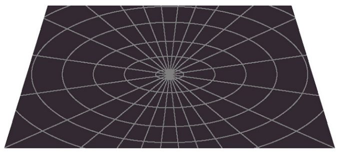
Newton's Gravity vs. Einstein's Theory

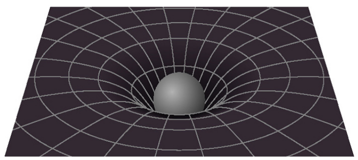
- Newton saw gravity as a force that produces acceleration; but this force acts only between (any) two objects that possess mass.
- Einstein's theory of general relativity looked at gravity in a completely different way, as a *geometrical* effect: every mass "curves" the space around it, and other things (both objects with mass, and massless things like photons) move within that curved space.

General Relativity: mass "curves" space

A region of empty space



Vicinity of a large mass



The effect of any mass is to "warp" nearby space, creating a kind of undertow for passing objects (or light rays). This is often visualized in terms of an "embedding diagram", where you can see the gravitational dip or "well" as a dimple in the surface.

Curvature of Space near a Large Mass
*(Note: This does **not** have to be a black hole!)*

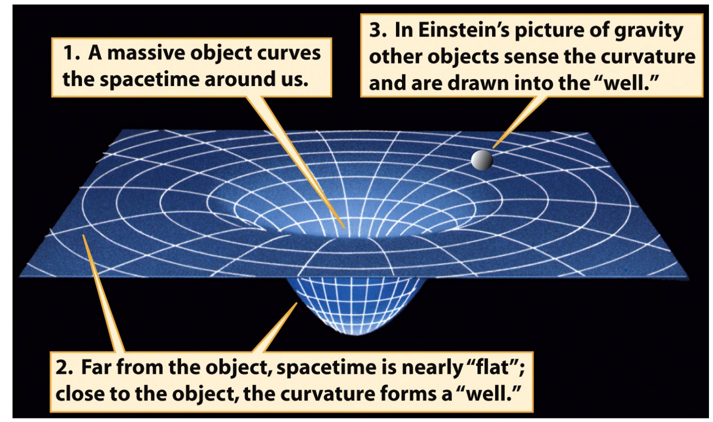


Figure 22-4
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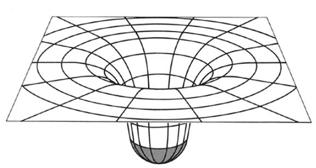
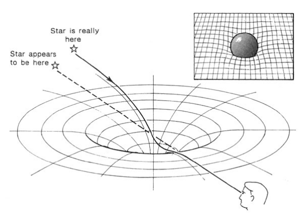
General Relativity as a Geometric Theory

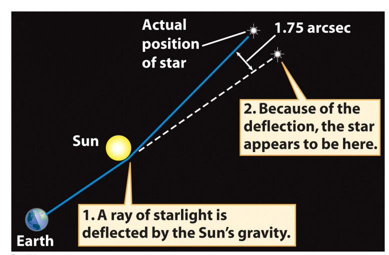
Instead of treating gravity as an interaction between two bodies (after Newton), think of an object as moving in the gravitational "field" of another mass.



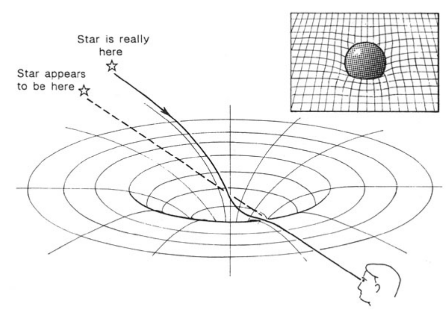


The presence of a mass creates curvature, a "well" in space, that predetermines the path which an outside something (a body, or light) will take.

Gravitational Bending of Light

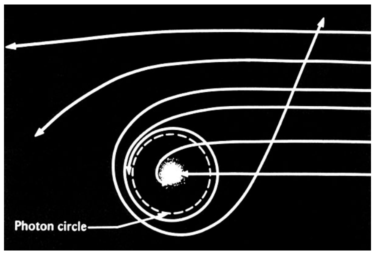


Treating gravity as a "field" rather than a force explains why light is bent even though photons have no mass. The light ray is bent because it travels through curved space.



“Embedding diagram” for a Black Hole

Denser objects curve space more sharply, so the dip has steeper “sides.” Black holes go to infinite density at the center, so they “punch a hole” in space-time.



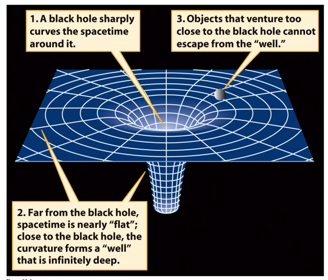


Figure 22-9
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“Journey to a Black Hole”

A popular story is to describe what happens to an object/probe/person falling into a black hole. Usually we imagine a “mother ship” orbiting the black hole at a safe distance, watching the probe fall in.

(a) Describe what the falling-in probe feels and sees.
(b) Describe what someone on the “mother ship” sees as happening to the probe.

Caveat: Some effects are consequences of relativity, while others are simply due to having strong gravity.

Ordinary (Non-Relativistic) Effects of Gravity

We express the “strength” of gravity in terms of *g*, the force per unit mass or gravitational acceleration. This has both magnitude (amount) and direction.

The magnitude is given by $(G\,M)/d^2$, which depends on both the mass of the object and *how close you are to its center*. The direction is always towards the center (gravity is a ***central force***).

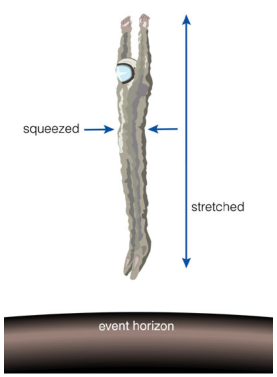
Tidal force is the difference in the gravitational force across a length (e.g. your head to your feet). This is a property of *any* mass, and does not involve relativity.

Standard Gravity: Tidal Effects

Tidal force is simply the *difference* in gravity from one end of the object to the other. Tidal forces are strong when the strength of the local gravity is changing rapidly with distance, as near an event horizon.

Tidal forces *stretch* things in the radial (inward, downward) direction.

And *compress* things in the cross-wise direction (since radial lines converge)

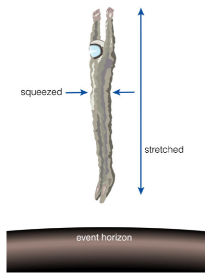


Tidal Effects near a Black Hole

Tidal forces *stretch* things in the radial direction (here, the direction of fall)

They are *compressed* in the crosswise direction (since radial lines converge)

Hence the word *"spaghettification"*



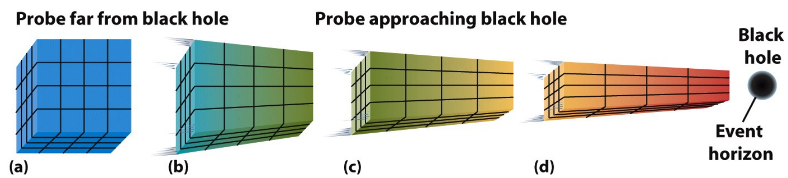


Figure 22-22
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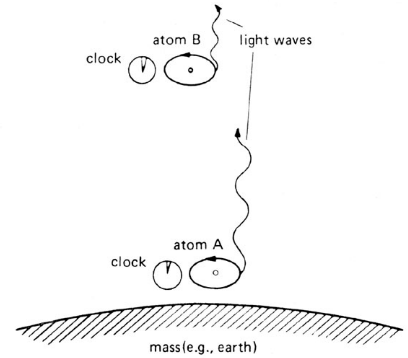
Relativistic Effect: Time Dilation

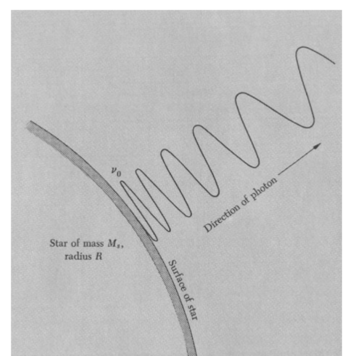
Time passes more slowly for a person or object in a stronger gravitational field: for each second of time experienced by a person deeper in the gravity field, several or many seconds pass for an observer outside the region of strong gravity.



Time Dilation near a Black Hole

- Time passes more slowly in regions of strong gravity. The clock on the falling-in probe would slow down, but you wouldn't know it.…unless you compared clocks with the observer on the mother ship.
- A longer time passes for the outside observer for each second on the clock of the envoy, so as the probe nears the event horizon of the black hole, the mother ship would see the probe slow down and reach a dead stop. .. moving in slow motion, frozen in time." (The Russian term for a BH was originally "frozen star.")

Gravitational Redshifts/Blueshifts



A photon escaping to infinity from the surface of a star gains "potential energy" and loses an equal amount of "kinetic energy." If the photon frequency at the surface is ν, the photon frequency at ∞ is $\nu' = \nu(1 - GM_s/Rc^2)$.

Light travelling out of a region of strong gravity loses energy. Since light cannot slow down, the only way for it to lose energy is for the frequency to become smaller (lower) and the wavelength to get longer: this is a *redshift*.

This was first measured in the lab as a "blueshift" of gamma rays falling into stronger gravity.

Relativistic Effect: Gravitational Red/Blueshift

- Light moving away from a source of gravity redshifts. So the probe will appear to become dimmer and redder as it descends towards the black hole.
- The converse is also true! From the probe's point of view, the mother ship above will look bluer and bluer!
- To help remember which way it works, think about a ball thrown upward losing energy as it reaches larger heights above the ground, moving slower and slower. Light can lose energy only by redshifting.

Summary: Effects of Strong Gravity Fields

Non-Relativistic Effects:

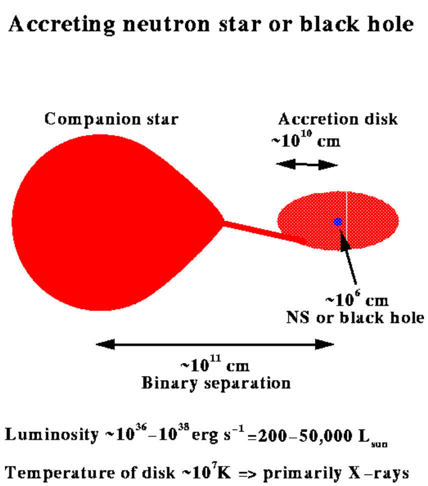
Tidal forces *stretch* things in the radial direction and *compress* things in the cross-wise direction .

Relativistic Effects:

Time passes more slowly at stronger gravity, and distances in the direction of travel are foreshortened.

Light travelling away from a region of strong gravity is redshifted; light traveling into it is blueshifted.

X-ray binaries: with NS or BH' s



Mass flows from the companion star arrives near the NS or BH with high angular momentum (from the orbit); collects in a spinning "accretion disk," a holding tank for transferred mass. The disk is hot because of viscous forces (friction), so it emits optical, UV, and X-ray light.

Group Participation Activity – Nov. 27

Suppose you have an interacting binary system containing a compact object that might be either a neutron star or a black hole. Discuss how you might be able to tell which of these is present.

(a) What observable things (kinds of electromagnetic radiation, light variations, other things) might lead you to guess that a neutron star is ***probably*** present? That a black hole is ***probably*** present?
(b) What observation could definitively ***prove*** that a black hole is present?