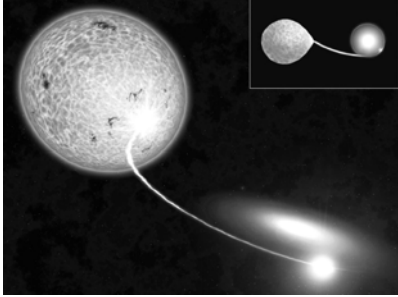


ASTR 1120: Stars & Galaxies



Prof. Juri Toomre TA: Ben Brown
Lecture 25 Wed 9 Mar 05
zeus.colorado.edu/astr1120-toomre

Today's Joys

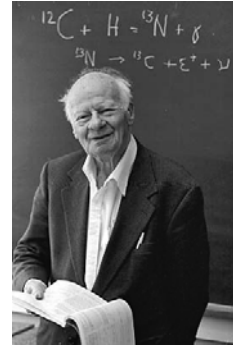
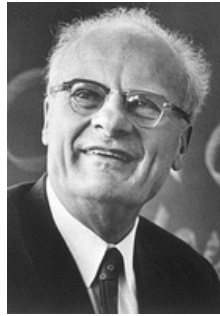
- What happens in presence of very strong gravity
→ light is red-shifted, passage of time slows down (all courtesy of Einstein)
- Black holes, their general properties, and their "care and feeding"
- How to detect BH, even supermassive ones
- Mystery of fantastic explosions far away: Gamma Ray Bursts (GRBs)
- Second Mid-Term Exam this Friday 11 Mar; Review Session by Ben tonight, here 7pm-9pm
- New Homework Set 7 given out today; HW 6 + answers returned today; crib sheet winners

Reading Needed

- Re-read 18.4 Black Holes
- Overview read S3 Spacetime and Gravity, and more carefully S3.4 New View of Gravity
- For next Monday, overview read Chap 19 Our Galaxy

Hans Bethe

Nobel Prize 1967: nuclear reactions in stars

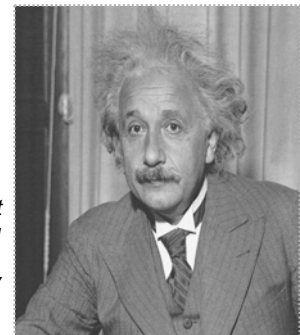


Clicker – Black Holes

- What do we mean by the event horizon of a black hole? **C.**
- A. The distance from black hole at which stable orbits are possible
- B. The very center of the black hole
- C. The sphere inward from which neither light nor anything else can escape
- D. The place where x-rays are emitted

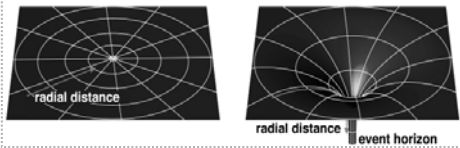
Black Holes – sort of courtesy of Albert

- Einstein's (1911) General Theory of Relativity: gravity is really the warping of spacetime around an object with much mass
- Light travels in "straight lines" – and its bending comes from spacetime being curved by gravity



Black Holes

- Escape velocity $v_{esc}^2 = 2 \times G \times \text{mass} / R$ (sec 5.5)
- Mitchell & Laplace in 1700's (post Newton) speculated about objects so compact that v_{esc} exceeds speed of light
- Einstein showed space and time are not distinct (if speed of light c is constant) → SPACETIME singularity in spacetime → black hole



Time slowed down by moving fast or strong gravity

Einstein's Special / General Theories of RELATIVITY

Our sense of time is relative ..

if nothing can move faster than speed of light, space and time are linked → spacetime

TIME DILATION MEASUREMENTS OF TIME ARE RELATIVE

TIME RUNS SLOWER FOR:

1. FAST MOVING OBJECTS EINSTEIN 1905 (SPECIAL THEORY OF RELATIVITY)

ASTRONAUTS (16 km/sec)
TIME SLOWS DOWN ~ $1/10^9 \sim 10^{-9}$ sec/year
(AGES MORE SLOWLY AS VIEWED BY US)

RADIOACTIVE PARTICLES IN ACCELERATOR
MOVING ALMOST AT SPEED OF LIGHT c
LIVES 100 - 1000 TIMES LONGER AS VIEWED BY US

2. OBJECTS IN STRONG GRAVITY EINSTEIN 1911 (GENERAL THEORY OF RELATIVITY)

ON EARTH: TIME SLOWS DOWN BY 1 PART IN 10 BILLION

WHITE DWARF: 1 PART IN 1000

NEUTRON STAR: TIME IS 70% SLOWER

BLACK HOLE: TIME STOPS

→ TIME APPEARS TO SLOW DOWN IF YOU OBSERVE PROCESS DEEP IN A GRAVITATIONAL FIELD!

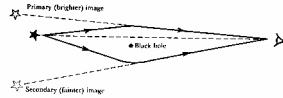
Effects of strong gravity on light

EFFECTS OF GRAVITY ON LIGHT

... COURTESY OF EINSTEIN

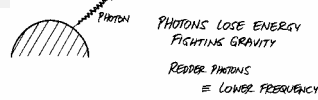
1. STRONG GRAVITY CAN BEND LIGHT:
USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY → GRAVITATIONAL LENSES!

can act like lens



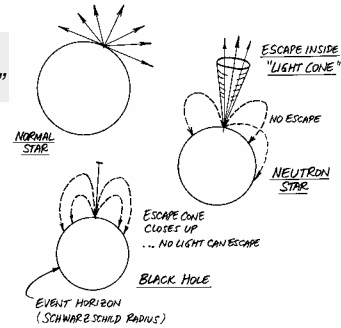
2. LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED: "GRAVITATIONAL REDSHIFT"

can redshift light



Light and "escape cones"

ESCAPE OF LIGHT FROM AN OBJECT



cone narrows as gravity forces get more intense

BLACK HOLE: GRAVITY FORCES SO STRONG NEAR "MASS SINGULARITY" THAT PHOTONS CANNOT ESCAPE!

"Event horizon"

Schwarzschild radius: where escape velocity is speed of light

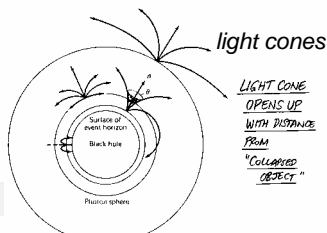
$$R_s = 2G \text{ mass} / c^2$$

most simply:
(R_s in km,

$$R_s = 3 M$$

M in M_{sun})

"EVENT HORIZON"
... SCHWARZSCHILD RADIUS FOR BLACK HOLES



SOME SCHWARZSCHILD RADIUS:	BLACK-HOLE RADIUS
EARTH MASS $3 \times 10^{24} M_0$	0.9 cm!
SUN M_0	3 km
GALAXY $10^{11} M_0$	0.03 LIGHT YEAR

BUT PROBLEM IS HOW TO SQUEEZE SO MUCH MASS INTO SUCH A SMALL VOLUME!

"Black holes have no hair"

Only three numbers describe BH!

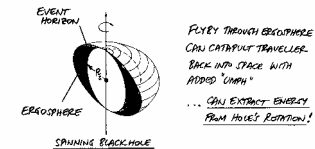
"BLACK HOLES HAVE NO HAIR"

ALL BLACK HOLES DESCRIBED BY JUST 3 NUMBERS

... THEIR TOTAL: MASS
ELECTRIC CHARGE
ANGULAR MOMENTUM
NO FURTHER STRUCTURE, OR "HAIR"!

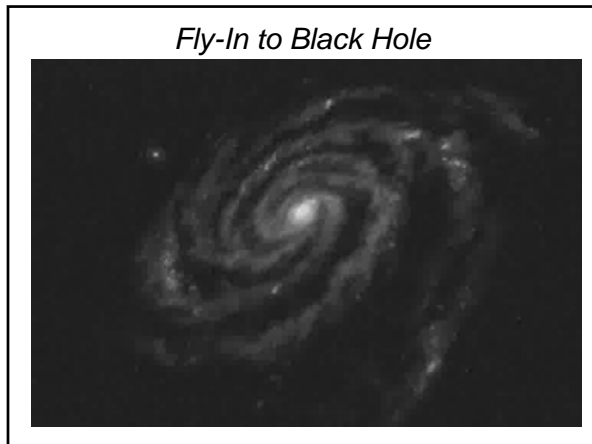
EVENT HORIZON (SCHWARZSCHILD RADIUS)
 $R_s = 2G \text{ MASS} / c^2$

SPINNING BLACK HOLE DRAGS NEARBY SPACE/TIME WITH IT
→ ERGOSPHERE: ROTATING REGION OF SPACE-TIME JUST OUTSIDE EVENT HORIZON


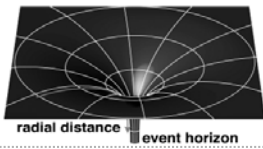


Ergosphere: spinning BH drags nearby spacetime along

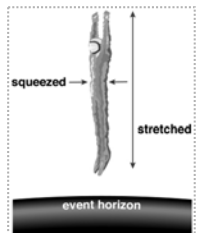
PARTY THROUGH ERGOSPHERE CAN CAPTURE TRAVELLER. BACK INTO SPACE WITH ADDED "GAINS"
... YOU EXTRACT ENERGY FROM HOLE'S ROTATION!



Warping of Space by Gravity

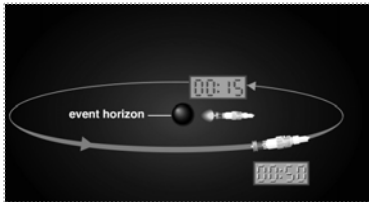



- Gravity imposes curvature on space
 - light's path through space will be "bent by gravity"
 - within the event horizon, it cannot climb out of the hole
- As matter approaches event horizon...
 - tidal forces are tremendous
 - object would be "spaghettified"



Warping of Time by Gravity

- If we launched a probe to a black hole, time slows down as it approaches the event horizon
 - it may take 50 min of time on mother ship for 15 min to elapse on probe
 - from mother ship's view, the probe takes forever to reach event horizon
 - light from probe is redshifted more and more, eventually disappears as light from it is redshifted beyond radio



From probe's view:

- it heads straight into the black hole
- light from the mother ship is blueshifted

How to "detect" a black hole

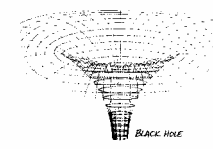
HOW TO "DETECT" A BLACK HOLE ?
(VERY CAREFULLY !)

... ONLY THROUGH EFFECTS ON NEARBY MATTER


MOSTLY LOOK AT CLOSE BINARIES AND SEARCH FOR COMPACT X-RAY SOURCES

CRITERIA :

1. "INVISIBLE" STAR IN BINARY SYSTEM IS TOO MASSIVE TO BE WHITE DWARF OR NEUTRON STAR ⇒ MASS ≥ 3M_⊙
2. TOO SMALL IN RADIUS TO BE DETECTABLE AS A NORMAL STAR

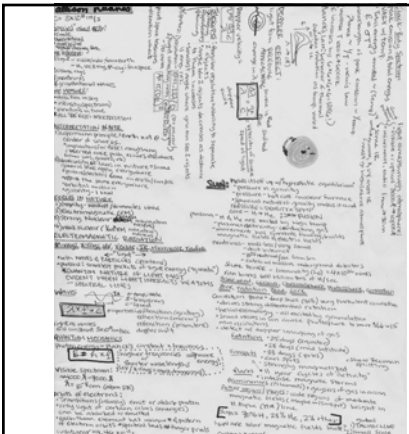


"CURVATURE OF SPACE" NEAR A BLACK HOLE NOT MEASURABLE DIRECTLY



Crib sheet with Highest Information Density

Shannon Coffey



Crib sheet with Most Aesthetic Appeal

Allison Nuanes