

ASTR 1040: Stars & Galaxies



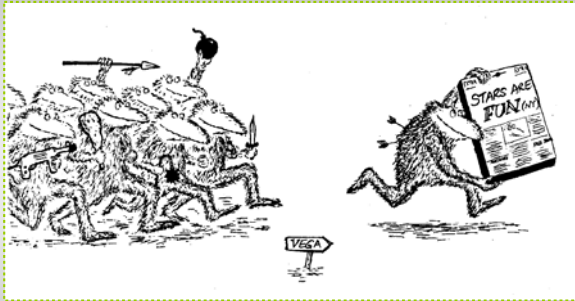
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Lecture 19 Tues 21 Mar 2017
zeus.colorado.edu/astr1040-toomre

Joy's of Black Holes

- **Black holes**, their general properties, and their "care and feeding" – and **Mr. Einstein's work** S.2 (special relativity), S.3 (general relativity)
- How to **detect black holes** (indirectly) in close binary systems (read 18.3)
- Best "stellar-mass" black hole candidates: Cygnus X-1, SS433
- **Gamma-ray bursts** (hypernova?)
- **Our Milky Way Galaxy** in overview, aspects of any **spiral galaxy** – and a fine **SONG**
- **Overview read Chap 19 "Our Galaxy"**
- **Observatory session tonight**

So did we really love this exam?



RESULTS FROM SECOND MID-TERM EXAM

SECOND MID-TERM EXAM

- **Grade boundaries**, based on 122 points (graded on a "curve"):
- If 106/122 (87%) or over, **A's [36%]**
- 94/122 (77%) or over, **B's [43%]**
- 79/122 (65%) or over, **C's [16%]**

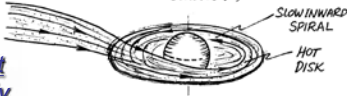
Also +, plain, and – within these ranges

Go through answer sheet – and talk to us if do not understand our choices. Keep exam + answers for future review (comp final)

ACCRETION DISKS

USUALLY MASS TRANSFERRED IN BINARY HAS TOO MUCH **ANGULAR MOMENTUM** (SIDEWAYS, ROTATIONAL MOTION)

TO FALL STRAIGHT IN ⇒ **FORMS DISK** (FLATTENED VERSION OF VORTEX IN BIRTHTUBES!)



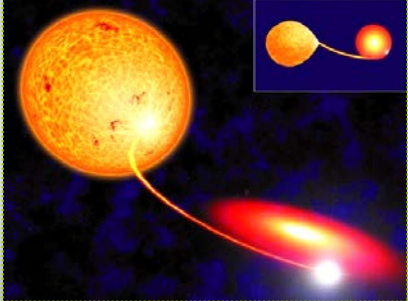
disk gets very hot – radiates brightly

makes neutron stars and black holes visible!

GAS HEATS UP AS IT SPIRALS IN ⇒ **RADIATES** VISIBLE, UV, X-RAY....

"Compact Companions" in Binary Systems

- **Again: mass transfer from red giant companion spirals onto accretion disk**
- **Inner parts become VERY hot -- glow in UV, X-rays**

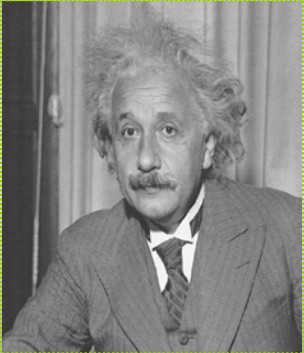


Reading ahead Clicker – Black Holes

- 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

GR and Spacetime

- 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



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 **"SR"** 1905
 - ASTRONAUTS (16 km/sec) TIME SLOWS DOWN $\sim \frac{1}{2} \times 10^{-9} \sim 30^{-3}$ sec/week (APPEARS MORE SLOOZY AS VIEWED BY US)
 - RADIOACTIVE PARTICLE IN ACCELERATOR MOVING ALMOST AT SPEED OF LIGHT C LIVES 300 - 3000 TIMES LONGER AS VIEWED BY US
2. OBJECTS IN STRONG GRAVITY **"GR"** 1911
 - ON EARTH: TIME SLOWS DOWN BY 1 PART IN 30 BILLION
 - WHITE DWARF: 1 PART IN 3000
 - NEUTRON STAR: TIME IS 70% SLOWER
 - BLACK HOLE: TIME STOPS
 - TIME APPEARS TO SLOW DOWN IF YOU OBSERVE OBJECT DEEP IN A GRAVITATIONAL FIELD!

EFFECTS OF GRAVITY ON LIGHT ... COURTESY OF EINSTEIN

Effects of strong gravity on light

can act like lens

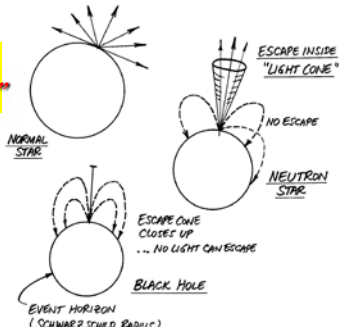
can redshift light

1. STRONG GRAVITY CAN BEND LIGHT: USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY → GRAVITATIONAL LENSES!
 - Primary (brighter) image
 - Secondary (dimmer) image
 - Black hole
2. LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED: "GRAVITATIONAL REDSHIFT"
 - PHOTONS LOSE ENERGY FIGHTING GRAVITY
 - REDDER PHOTONS = LOWER FREQUENCY

Light and "escape cones"

cone narrows as gravity forces get more intense

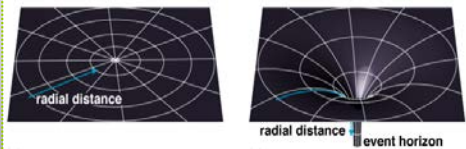
ESCAPE OF LIGHT FROM AN OBJECT



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

Black Holes

- Escape velocity $v_{esc}^2 = 2 \times G \times \text{mass} / R$ (sec 4.5)
- 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



"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

light cones
 LIGHT CONE OPENS UP WITH DISTANCE FROM "COLLAPSED OBJECT"

SOME SCHWARZSCHILD RADIUS:
 EARTH MASS $3 \times 10^{-6} M_\odot$
 SUN M_\odot
 GALAXY $10^{11} M_\odot$

BLACK-HOLE RADIUS:
 0.9 cm!
 3 km
 0.05 LIGHT YEAR

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

"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 TUBULAR OF SPACE-TIME JUST OUTSIDE EVENT HORIZON

FLYBY THROUGH ERGOSPHERE CAN CATCHUP TRAVELLER BACK INTO SPACE WITH ADDED "UNRA" ... CAN EXTRACT ENERGY FROM HOLE'S ROTATION!

SPINNING BLACK HOLE

Only three numbers describe BH!

Ergosphere: spinning BH drags nearby spacetime along

Warping of Space by Gravity

radial distance

radial distance event horizon

- 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"

squeezed stretched

event horizon

3 aspects of falling into a black hole:
 1) Spaghettified

- As matter approaches the singularity...
 - tidal forces (difference between gravitational force at two points) are tremendous
 - Your feet would feel a much stronger pull of gravity than your head
 - object would be "spaghettified"

squeezed stretched

event horizon

3 aspects of falling into a black hole:
 2) Gravitational Redshift

From mothership's view

- As the probe gets closer and closer to the event horizon, the light becomes more and more redshifted
 - Photons lose energy climbing out of the black hole gravity well
 - At the EH (from our view), photons are redshifted out of existence (zero energy)

event horizon

00:15

00:50

From probe's view:

- Outside world gets blueshifted
 - Photons gain energy falling into the black hole gravity well

3 aspects of falling into a black hole:
 3) Time Dilation

From mothership's view

- As the probe gets closer and closer to the event horizon, its clock appears to slow down
- The probe (and clock) never get to the event horizon
 - It moves slower and slower, eventually freezing at the EH

event horizon

00:15

00:50

From probe's view:

- it heads straight into the black hole
 - Nothing special at the event horizon
- Outside world clock appears to be sped up

Black Holes Don't SUCK!

- Black holes have gravity, just like "normal" stars, planets etc.
- The only problem is that you can get SO close to the concentrated gravity near a black hole that you can't get out again

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


... ONLY THROUGH EFFECTS ON NEARBY MATTER

How to "detect" a black hole

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 \Rightarrow MASS $\geq 3 M_{\odot}$
2. TOO SMALL IN RADIUS TO BE DETECTABLE AS A NORMAL STAR



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

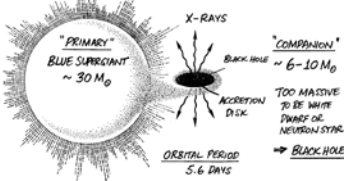
Observing a black hole:

Cygnus X-1



CYGNUS X-1 :
MOST VIABLE BLACK-HOLE CANDIDATE

- ECLIPSING BINARY SYSTEM IN SN REMNANT (CYGNUS LOOP)
- STRONG X-RAY SOURCE , VERY RAPID FLUCTUATIONS
- DOPPLER VELOCITY VARIATIONS OF PRIMARY IMPLY A MASSIVE COMPANION (NOT SEEN DIRECTLY)



"PRIMARY" BLUE SUPERGIANT $\sim 30 M_{\odot}$

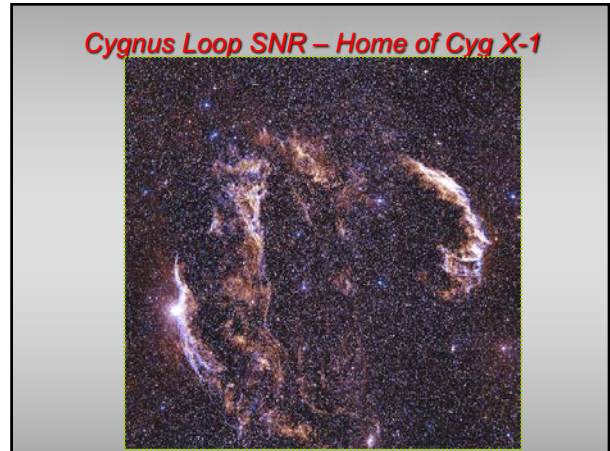
"COMPANION" BLACK HOLE $\sim 6-10 M_{\odot}$

ACCRETION DISK

ORBITAL PERIOD 5.6 DAYS

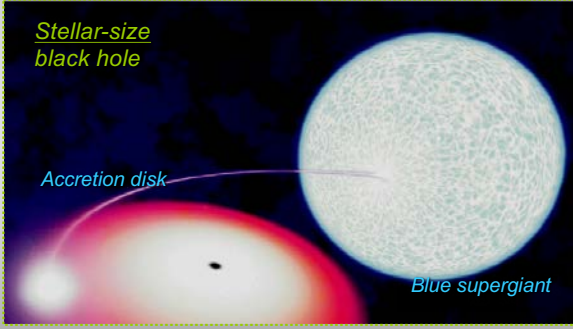
TOO MASSIVE TO BE WHITE DWARF OR NEUTRON STAR \Rightarrow BLACK HOLE

- STELLAR WIND POURS MATTER ONTO HUGE ACCRETION DISK
- INFALLING GAS HEATED AS SPIRALS INWARD, GETS SO HOT THAT EMITS X-RAYS AT INNER EDGE OF DISK



Cygnus X-1: Blue supergiant (strong winds) pours H + He onto accretion disk of black hole

Stellar-size black hole



Views of "Veil Nebula"

Such SNR may have a BH lurking!
.. but not this one



SS 433
top candidate for wild object!
another stellar-size black hole

SS 433 : BIZARRE ECLIPSING X-RAY BINARY
 MASS FLOW FROM COMPANION ONTO ACCRETION DISK AROUND NEUTRON STAR (OR BLACK HOLE?)

Blue-shifted radiation observed from Earth
 0.26c
 Axis of 164-day precession
 Two narrow jets with velocities at 0.26 c (!) perpendicular to disk, which precesses
 H & He spectral emission lines show remarkable Doppler shifts, with 164-day period
 Massive star: 13-24 M_{\odot}
 Compact object: 1.4-1.8 M_{\odot}
 15 times farther so stars onto accretion disk than only way out is along rotation axis?
 Blue-shifted radiation observed from Earth
 Direction to Earth
 Accretion disk
 Equal beam of matter
 Gas cools enough to emit visible emission lines
 10-day orbital motion
 Water spalled at 280K
 0.26c

SS 443
BH + jets

Gamma-Ray Bursts
HYPERNOVA ?
 Collapse of very massive star > BH

Luminosity ~ 10^6 to 10^3 times output from galaxy
 Visible from across the universe !

HST

Clicker Poll of Advice

- How do you take notes (or listen) during lectures?
- A. I get most of it by just listening
- B. I write down some notes, then go back to book to look things up
- C. I listen, take some notes, then get copies of lecture slides from course website
- D. I enjoy talking with my buddies, and they tell me later if I missed anything
- E. I try to read the subject in advance, and then listen, taking some notes in class

OVERVIEW

Our Milky Way Galaxy

- 100-400 billion stars
- 100,000 light years in diameter, or ~ 30,000 pc = 30 kpc (kilo-parsecs)
- Sun is located about 8.5 kpc from center, in the 'Orion Arm'

Artist's sketch!

Our Milky Way Galaxy

halo star orbits (green)
 bulge star orbits (red)
 disk star orbits (yellow)

Stars and gas are all moving!

halo star orbits (green)
bulge star orbits (red)
disk star orbits (yellow)

THIS INSPIRES A SONG!

Sing our way to the Milky Way

THE GALAXY – LIGHTEN UP

Whenever life gets you down, Mrs. Brown,
And things are hard and tough,
And people are stupid, obnoxious and down,
And you feel that you've had quite enough...

Just remember that you're standing on a planet that's evolving
And revolving at 900 miles an hour.
It's orbiting at 90 miles a second, so it's reckoned,
From the sun that is the source for all our power.
The sun and you and me and all the stars that we can see
Are moving at a million miles a day
In an outer spiral arm at 40 thousand miles an hour
In the Galaxy we call the Milky Way.

Now the Galaxy itself contains a hundred billion stars.
It's a hundred thousand light-years side from side.
It bulges in the middle 16 thousand light-years thick,
But out by us it's just 3 thousand light-years wide.
We're 30 thousand light-years from galactic central point.
It'll go round every 200 million years.
And our galaxy is only one of millions and billions
In this amazing and expanding Universe.

Now the Universe itself is still expanding and expanding
In every direction it could wish
As fast as it can go, the speed of light we know,
12 million miles a minute and that's the fastest speed there is.
So remember when you're feeling very small and insecure
How amazingly unlikely was your birth,
And pray that there is intelligent life somewhere up above,
For there isn't any down here on Earth.

Lighten up, there are stars in the sky,
Lighten up, it's a good question why,
But you don't know the answer and neither do I,
So meanwhile let's just all lighten up.

And remember that you're standing on a planet that's evolving ...

Halo stars travel high above and far below the disk on orbits with random orientations.

Bulge stars also have orbits with random orientations.

Disk stars orbit in circles with the same orientation, except for a little up-and-down motion.

One-pager: ALL about us!

Sketch of Milky Way

Edge-on

Top

CARTOON SKETCH OF "OUR GALAXY" (MILKY-WAY)

EDGE-ON VIEW

RARED OPEN-ARMED SPIRAL

GLOBAL CLUSTER IN SPHERICAL HALO

OLIVY CLUSTERS ARE IN ORBIT (PARALLEL TO DISK) (MAY BE METALS)

SUN'S LOCATION

28,000 LY (~ 8 Kpc)

3,000 LY THICK (~ 1 Kpc)

BULGE OF NUCLEUS

DISK

RADIUS OF DISK ~ 40,000 LY

(DIAMETER 80,000 LY OR MORE) (~ 25 Kpc)

TOP VIEW

SUN

NUCLEUS

SPIRAL ARMS

QUANTITY STARS ARE IN SPIN ARM (PARALLEL, 5th IN METALS)

SUN'S VELOCITY AROUND CENTER OF GALAXY: ~ 220 KM/SEC

SUN'S PERIOD OF REVOLUTION ~ 230 MILLION YEARS

LUMINOSITY: $20 \times 10^9 L_{\odot}$

MASS: $150-200 \times 10^9 M_{\odot}$

NUMBER OF STARS: $\sim 400 \times 10^9$

If we might see Milky Way from outside

Spiral Sb galaxy NGC 4414

Milky Way Anatomy: Spiral Galaxy

- Disk:** includes spiral arms -- young, new star formation
- Bulge & Halo:** older stars, globular clusters