


**ASTR 1040: Stars & Galaxies**



**M51 Whirlpool**

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Lecture 20 Thur 19 Mar 2020  
[zeus.colorado.edu/astr1040-toomre](http://zeus.colorado.edu/astr1040-toomre)

**More Joys of Black Holes + Our Galaxy**

- **Black holes**, their general properties – and **Mr. Einstein's work** S.2 (special relativity), S.3 (general relativity)
- **Requires some careful reading**
- How to **detect black holes** (indirectly) in close binary systems (read 18.3)
- **Our Milky Way Galaxy** in overview, aspects of any **spiral galaxy**
- **Overview read Chap 19 "Our Galaxy"**
- **Homework #9** due today, new **HW #10** out, all on canvas site (new labels)

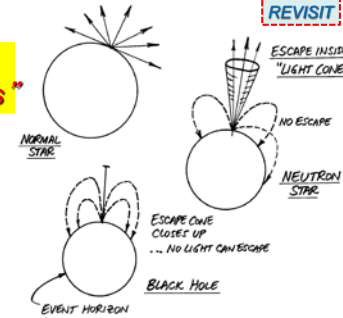
**How we will be zoom-interactive**

- **"Raise Hand"** (Max monitors "Participants")
- **"Send Chat" Message** (Max will act)
- In both cases, Juri will get to your question or comment within at most a few minutes
- Or if pressing, **Unmute your mike** and ask question
- We can adjust "how to interact", with your advice and experience

**ESCAPE OF LIGHT FROM AN OBJECT**

**Light and "escape cones"**

**cone narrows as gravity forces get more intense**



**REVISIT**

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

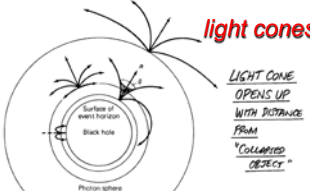
**"Event horizon"**

**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  $M_{\text{sun}}$ )

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



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

| SOME SCHWARZSCHILD RADIUS:              | BLACK-HOLE RADIUS |
|---|-------------------|
| EARTH MASS $3 \times 10^{-6} M_{\odot}$ | 0.9 cm!           |
| SUN $M_{\odot}$                         | 3 km              |
| GALAXY $10^{11} M_{\odot}$              | 0.03 LIGHT YEAR   |

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

**"Black holes have no hair"**

**Only three numbers describe BH!**

**Ergosphere:** spinning BH drags nearby spacetime along

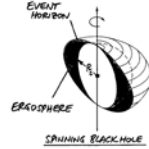
**"BLACK HOLES HAVE NO HAIR"**

ALL BLACK HOLES DESCRIBED BY JUST 3 NUMBERS:  
... THEIR TOTAL: MASS  
ELECTRIC CHARGE  
ANGULAR MOMENTUM

NO PARTIAL STRUCTURE, OR "HAIR"!

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

SPINNING BH HULL DRAGS NEARBY SPACE/TIME WITH IT  
→ **ERGOSPHERE:** ROTATING FOULDS OF SPACE/TIME JUST OUTSIDE EVENT HORIZON



**SPINNING BLACK HOLE**

FLYBY THROUGH ERGOSPHERE CAN CATASTROPHICALLY TRAVELLER BACK INTO SPACE WITH ADDED "UNRAH"  
... 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"**

### 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"

### Three 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)

**From probe's view:**

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

### Three 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

**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

## Questions or Comments

Then we use *Break-out Rooms* for ~5 minutes to exchange impressions of "how are things" and "spring-break plans"

**Survey poll Has the Pandemic affected your spring-break plans?**

- A. Yes, greatly
- B. Yes, somewhat
- C. No, not yet
- D. Trying to figure things out

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**How to "detect" black hole**

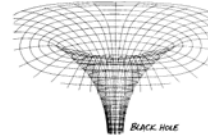
HOW TO "DETECT" A BLACK HOLE ?  
( VERY CAREFULLY !)

... 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  $\Rightarrow$  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:**

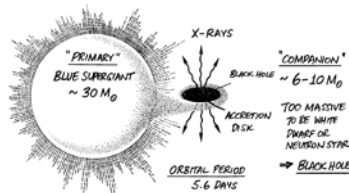
**Cygnus X-1**



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 INDICATE MASSIVE COMPANION (NOT SEEN DIRECTLY)



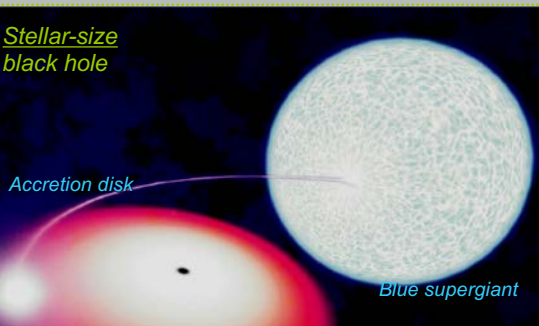
- STELLAR WIND POURS MATTER ONTO HUGE ACCRETION DISK
- INFALLING GAS HEATED AS SPIRALS INWARD, GETS SO HOT THAT EMITS X-RAYS AT INNER-EDGE OF DISK

**Cygnus Loop SNR – Home of Cyg X-1**



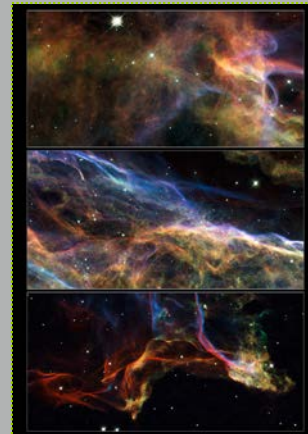
**Cygnus X-1: Blue supergiant (strong winds) pours H + He onto accretion disk of black hole**

**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?) . . . .

→ TWO NARROW JETS WITH VELOCITIES AT 0.26 c (!) PERPENDICULAR TO DISK, WHICH PRECEDES  
 H & He SPECTRAL EMISSION LINES (DON'T REMEMBER DOPPLER SHIFTS, WITH 164-DAY PERIOD)  
 MASSIVE STAR: 13-24 M<sub>⊙</sub>  
 COMPANION STAR: 1.4-18 M<sub>⊙</sub>

IS MASS TRANSFER SO STABLE ONTO ACCRETION DISK THAT ONLY WAY OUT IS ALONG ROTATION AXIS?

**SS 443**  
**BH + jets**

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

Luminosity ~ 10<sup>6</sup> to 10<sup>9</sup> times output from galaxy  
 Visible from across the universe!

HST

Questions or Comments

**Review Poll – Size of Black Hole**

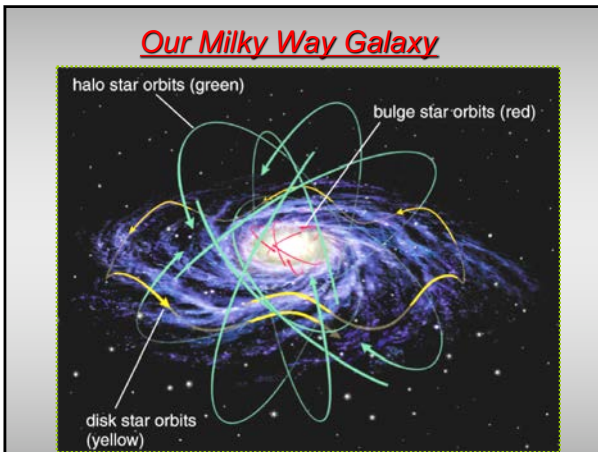
- What does the **Schwarzschild radius** of a black hole (BH) depend on? **C.**
- **A.** Both mass and chemical composition of the BH
- **B.** Radius of BH, as measured by careful observations of its size
- **C.** Only the mass of BH
- **D.** Whether BH formed in massive star supernova or in some other way

**REVISIT**  
**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!





**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 ...



**One-pager: ALL about us!**

**Sketch of Milky Way**

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

**Edge-on**

**Top**



### Milky Way Anatomy: Spiral Galaxy

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

A diagram of a spiral galaxy with labels: globular clusters, halo, bulge, disk, spiral arms, and halo.

