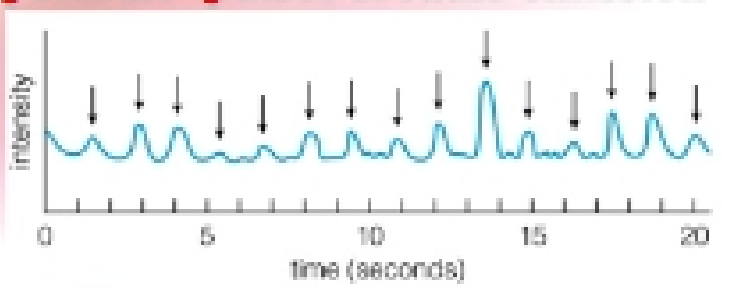
Announcements

- Midterm Tuesday November 8
  - Covers all material.
    - See lecture notes for content emphasis.
  - Closed book, no calculators or electronics.
- Review sessions Monday
  - BTW, PST starts Sunday

This Week
- White Dwarfs
- Supernovae
- Neutron Stars
- Black Holes
- Space Curvature

Learning Goals: Black Holes
- Basic properties
- Formation
- Their effects outside
- Evidence for their existence
- Supermassive BHs in galaxies
- BH 's as gravitational "lenses"

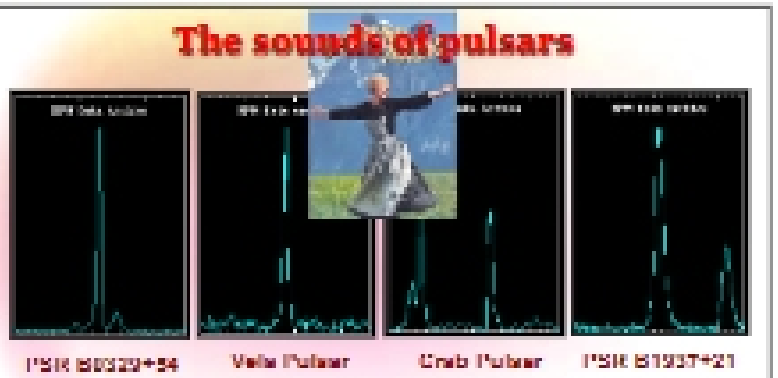
Something in the sky flashes at very regular intervals – "periodic" pulses of radio emission



- Had to be SMALL! (size < speed of light X duration, or else pulses would be smeared)

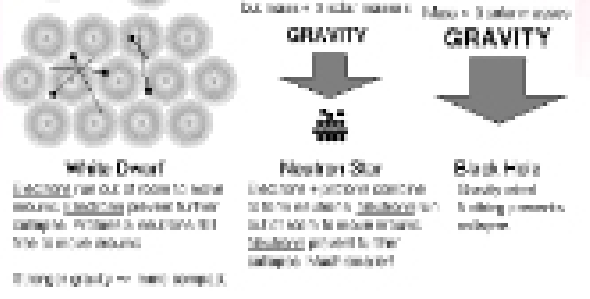
Neutron Star!

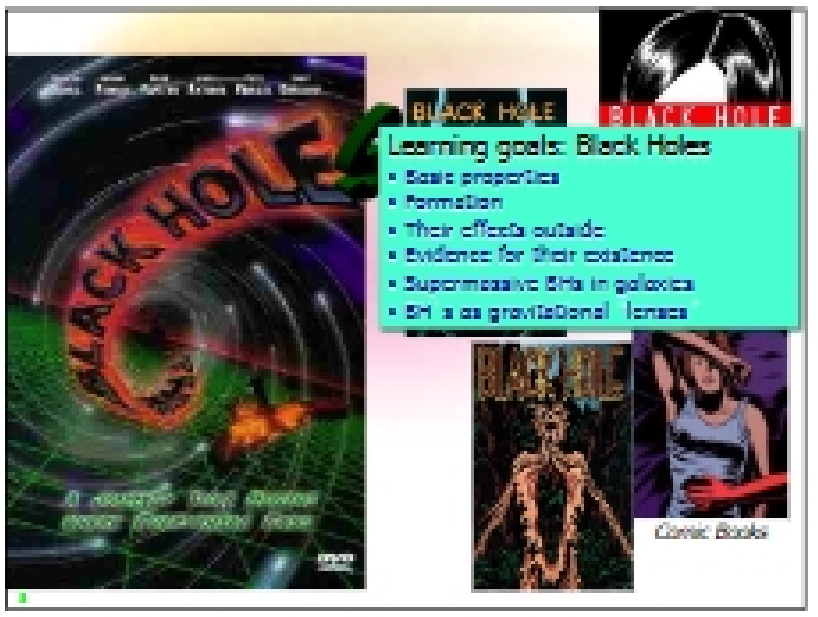
The sounds of pulsars



http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Stable Neutron Stars are Supported by Neutron Degeneracy





Obese Neutron Stars

- Remember why obese white dwarfs collapse when they gain too much mass (> 1.4 M_{sun})?
  - Electron degeneracy can't take it
- In the same way obese neutron stars collapse when they have too much mass (> ~3–5 M_{sun})
  - Neutron degeneracy can't take it

Neutron Degeneracy has its limits.

Gravity can overwhelm it!

BLACK HOLE

– Black holes are so dense that they wrap space and time into a closed cocoon smaller than downtown Seattle.

The fabric of space is bent and stretched near a compact mass

BHs are great cosmic bug traps

The fabric of space is bent and stretched near a compact mass

(movie)

How does gravity change outside of a Black Hole?

- Zilch. If you're *well outside* it's "event horizon" then the black hole acts precisely like any other mass.

– If the sun turns into black hole, it'll be dark
– *but our orbit won't change!*

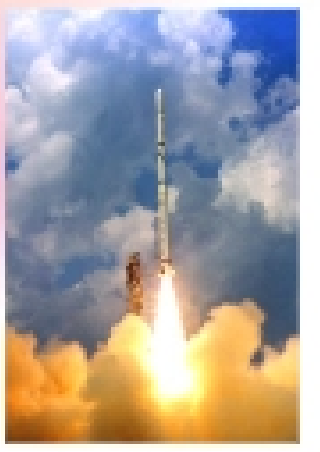
Black Holes result when too much mass occupies too small a space.

Here's a quick summary of BH physics. "No escape"

- The extreme density twists space around it so that there is no path out
- **Particles:** "escape velocity" > c
- **Photons:** from inside the horizon lose all of their energy and cease to exist
- **No light or information escapes**

Why does compactness matter?

- Recall that planets, stars, etc all have an "Escape Velocity" – how fast something has to go to escape the object's gravitational grip!
- Strength of grip is closely tied to force of gravity, which depends both on mass and distance *(inverse square law).*



Escape velocity depends on mass and size...

Moon:	2 km/s
Earth:	11 km/s
Sun:	620 km/s
White Dwarf:	7,600 km/s
Neutron Star:	160,000 km/s
Black Hole:	**>300,000 km/s**

When the escape velocity gets to be the speed of light, NOTHING CAN TRAVEL FAST ENOUGH TO ESCAPE FROM A B.H.!

So how smooshed do you have to get to be a black hole?

$$V_{escape} = C = \sqrt{\frac{2GM}{R_s}} \Rightarrow R_s = \frac{2GM}{C^2}$$

- We call R_s the Schwarzschild Radius
- If an object's mass is smaller than R_s, the escape velocity is greater than the speed of light
- We can't observe what's inside, so we can only guess.
  - Mathematically: a **SINGULARITY**
    (That's what you get when you divide by zero)

What's Your Schwarzschild Radius?

$$R_s = \frac{2GM}{C^2}$$

- M ~ 70 kg
- $R_s \sim 10^{-23}$ cm!

Smaller than a proton!

What, am I invisible?

Yes indeed.
No one would notice – until they bumped into you!

It's fun to think about Black Holes

$$R_s = \frac{2GM}{c^2}$$

- Sun: M ~ 2×10^{30} kg
- R_s ~ 2.5 km!

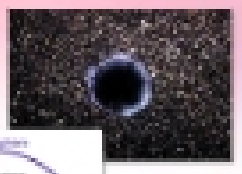
Slightly smaller than a neutron star of the same mass.

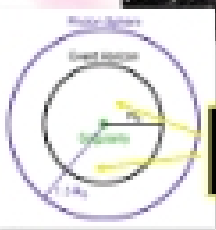
Object	R_s
Earth	1 cm
Sun	3 km
3 $M_\odot$	9 km
Milky Way	10^5 A.U.
Visible Universe	Very close to 14 billion light years

What does the Schwarzschild radius mean?

- If you're inside R_s, you can't leave!

"EVENT HORIZON"





probably mostly empty

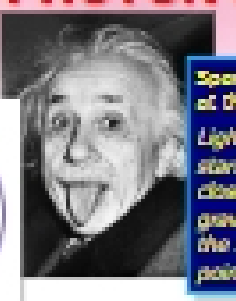
Space twists and closes back on itself at the photon sphere.

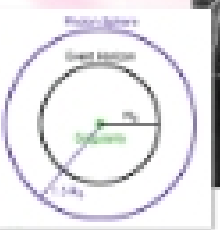
Nothing – not even light – can escape within the event horizon, or R_s, so there is no way of seeing what goes on inside.

What does the Schwarzschild radius mean?

- If you're just inside R_s, then the path of light closes on itself

"PHOTON SPHERE"





Space twists and closes back on itself at the photon sphere.

Light just outside R_s will return to its starting point — that is, go into a closed orbit. This is the result of the gravitational distortion of space where the shortest distance between two points becomes a circle.