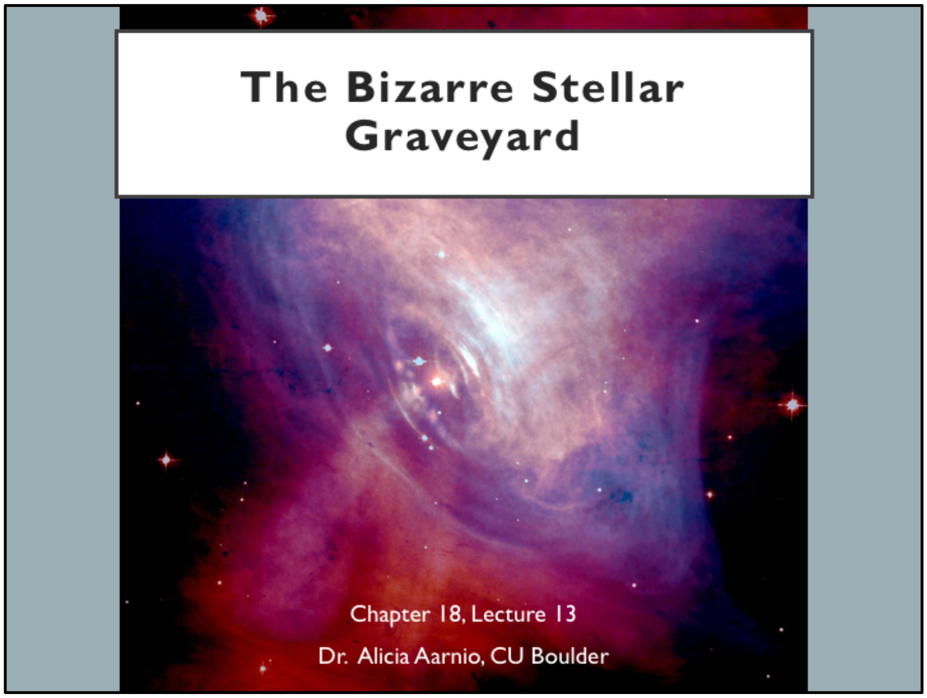

The Bizarre Stellar Graveyard
Chapter 18, Lecture 13
Dr. Alicia Aarnio, CU Boulder

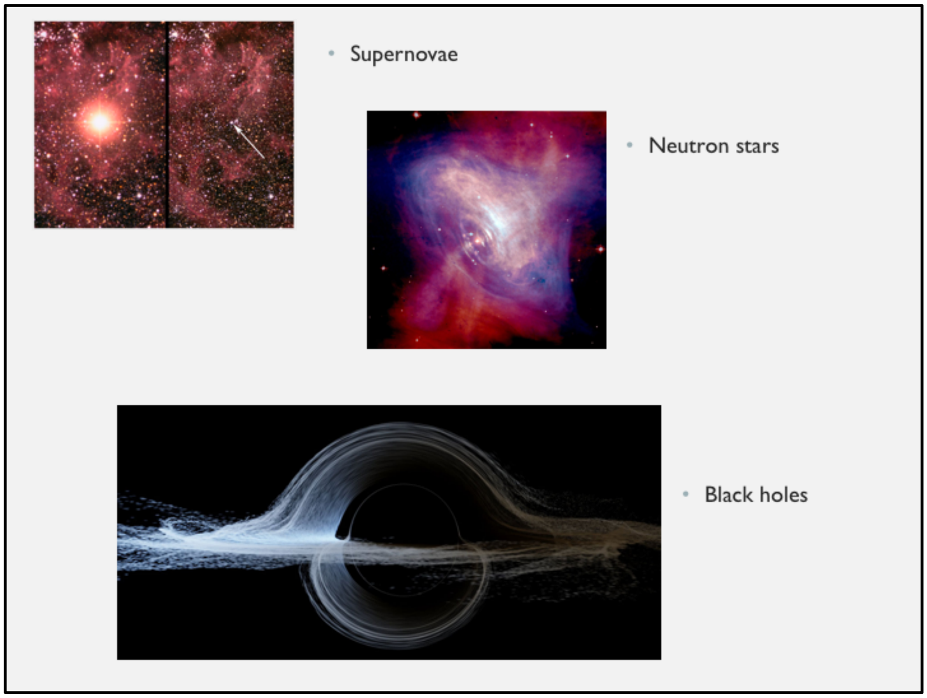


Image 1: Supernova 1987A after exploding in February 1987 (left), and an image taken before the explosion (right). Credit: David Malin / Australian Astronomical Observatory.
Image 2: NASA/CXC/ASU/J. Hester et al.[1]
image 3: still from Gargantua simulation, produced for the movie Interstellar: https://io9.gizmodo.com/the-truth-behind-interstellars-scientifically-accurate-1686120318

Notes for class

- I don't ban laptops- follow along with the slides as needed (links and references in slide comments):
  - bit.ly/uncg_ast235_lec13
- Use clickers as "confusion buttons" to let me know to slow down/explain something in more detail! (yelling out, 'Hey, Alicia' works, too)
- Move around as needed
- No question is a bad question!

Recap: summary of stellar lives

LOW MASS STARS (~1MSUN)

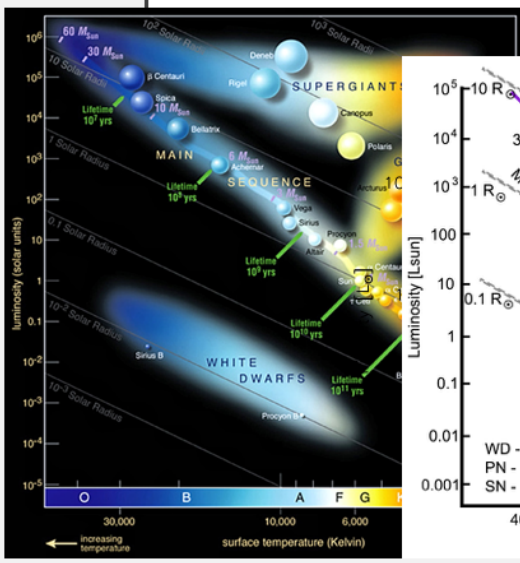
- 11.5 billion year lifetime
  - protostar,
  - yellow main sequence star,
  - red giant star,
  - helium core-fusion star,
  - double shell-fusion red giant,
  - planetary nebula,
  - white dwarf

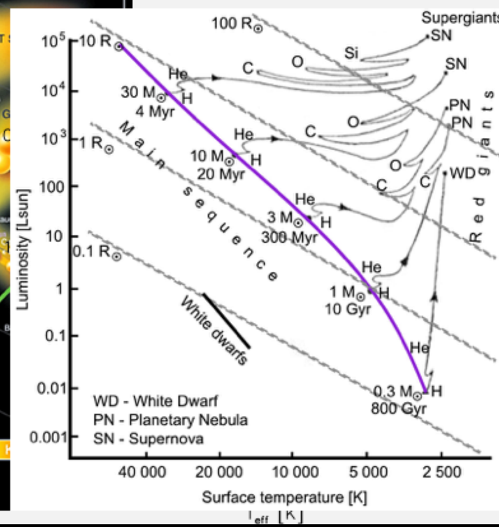
HIGH MASS STARS (~25MSUN)

- 6 million year lifetime
  - protostar,
  - blue main sequence star,
  - red supergiant,
  - helium core-fusion supergiant,
  - multiple shell-fusion supergiant,
  - supernova,
  - neutron star or black hole

Pg 550 in the textbook
11.5billion years = 10 months on cosmic calendar
6 million years = 4 hours on cosmic calendar

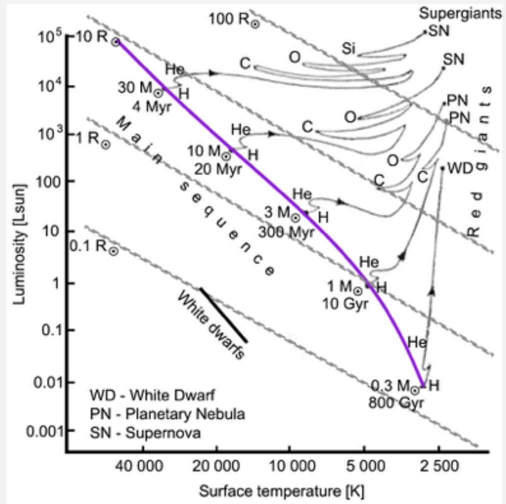
H-R Diagram, in time

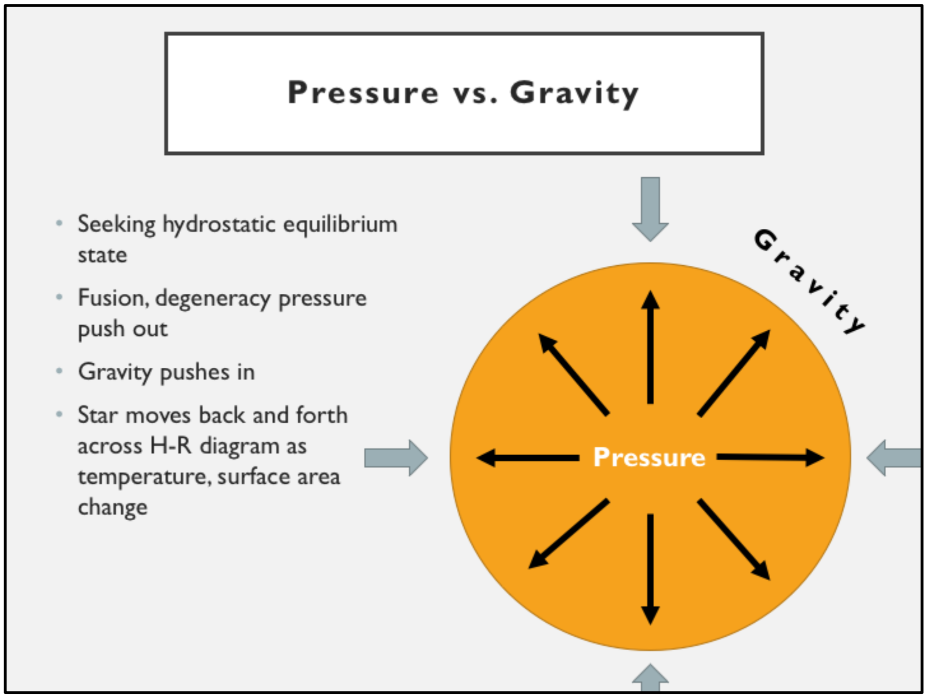




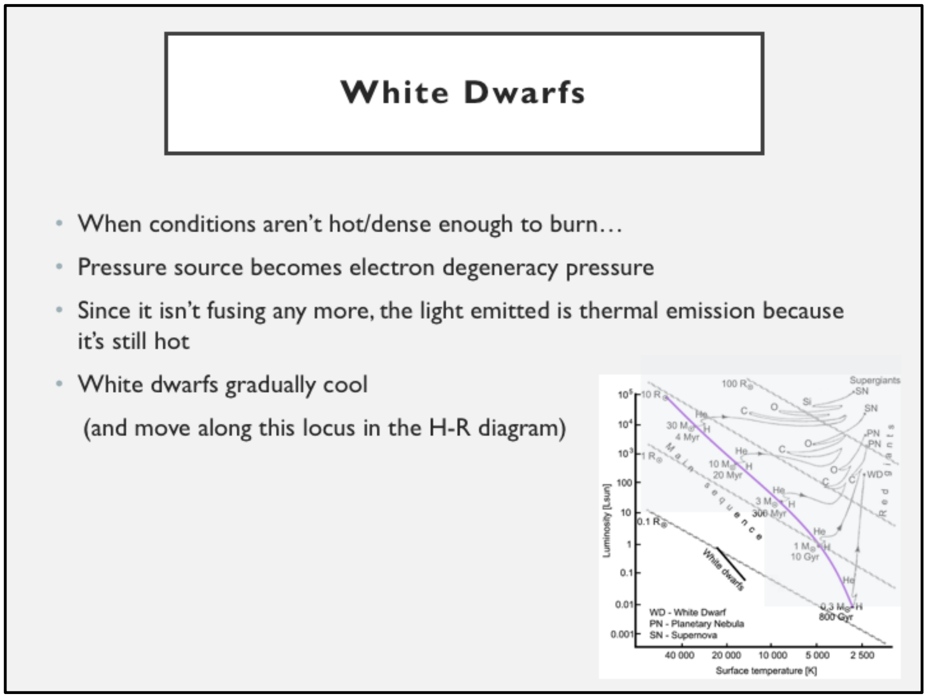
Think – pair – share

- Why are the post-main sequence tracks so strange?





This is really important- most of the rest of class will have to do with the balancing (or not) of pressure and gravity



Electron degeneracy pressure is a consequence of the Pauli Exclusion Principle; it's a resistance to quantum state degeneracy and not an electrostatic repulsion.

White Dwarfs

- A white dwarf's composition reflects the products of the star's final nuclear burning stage
  - The lowest mass stars leave helium white dwarfs
  - The remnant of a 1 M_{sun} star contains mostly carbon
  - Intermediate-mass stars end their lives as oxygen white dwarfs or those containing heavier elements
- The mass of a white dwarf cannot exceed 1.44 M_{sun} – beyond this mass (the Chandrasekhar limit), electron degeneracy pressure can be overcome by gravity

Sooo..What happens if you go over the limit?

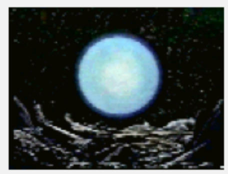
Clicker Question

What happens to a white dwarf that doesn't go above the Chandrasekhar limit?

A. It keeps cooling until you can't see it any more
B. It becomes a black dwarf
C. It cools but stays the same size
D. All of the above

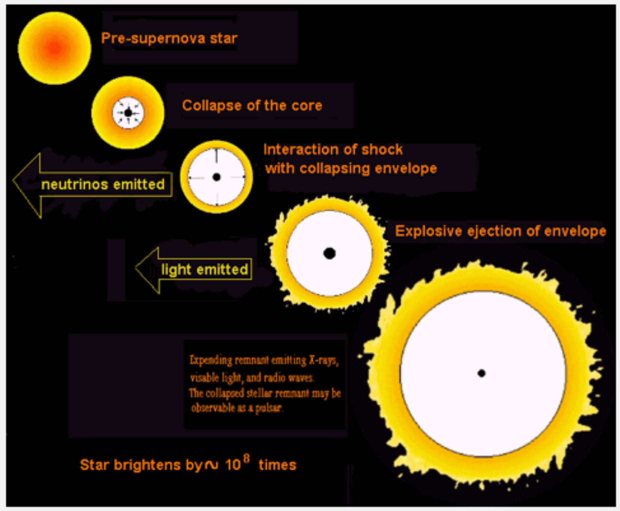
Supernovae

- If electron degeneracy pressure is overcome, electrons convert protons into neutrons
- In a fraction of a second, an iron core collapses into a ball of neutrons a few kilometers across
- The collapse stops as neutrons have their own degeneracy pressure
- It releases a huge amount of energy and results in an explosion – a **supernova**



Supernovae

- Explosion could be driven by a neutrino shock wave, propagating through the star's outer layers



http://astrosun2.astro.cornell.edu/academics/courses/astro201/sn.htm

Supernovae

- Three types of supernova (how is limit exceeded):
  - White dwarf (explosion in a binary system)
  - Intermediate-mass (leaves a neutron star as remnant)
  - Massive (leaves a black hole as remnant)

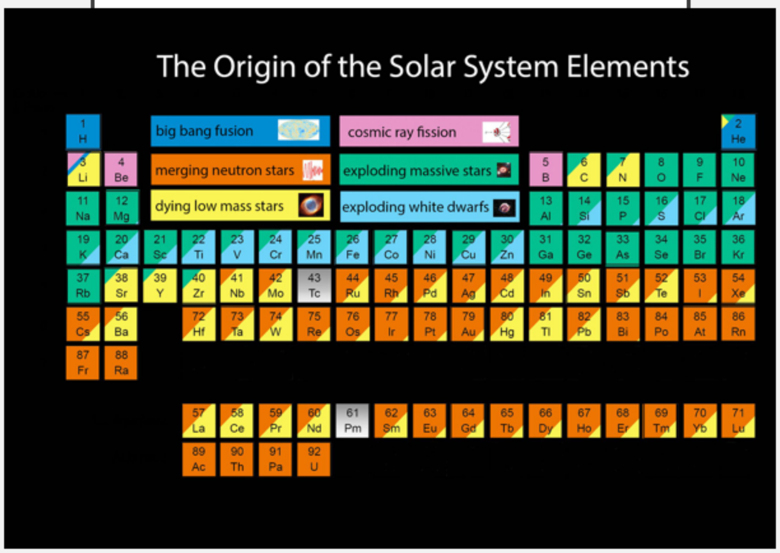
- Supernovae shine as bright as ~10 billion Suns for a few weeks
- The neutron core is called a neutron star
- If gravity overcomes neutron degeneracy pressure, the core continues to collapse → black hole

Supernova 1987a, observed by HST
http://www.spacetelescope.org/images/potw1142a/

Origin of elements

- Heavy elements (to astronomers, heavy ~ everything but H)
- How do we know heavy elements are produced by stars?
  - If massive stars do produce heavy elements and disperse them in space, then the total amount of heavy elements should gradually increase with time
  - We should expect stars born recently to contain more heavy elements than older stars
    - We do observe this! Stars in globular clusters have 0.1% of their mass in heavy elements, while young stars – 2–3%

We are all made of star-stuff



Credit: Jennifer Johnson (via Twitter)

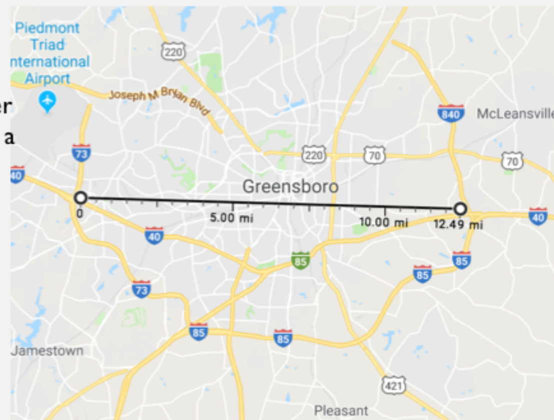
Neutron Stars

- A neutron star is created by the collapse of the iron core in a massive star supernova
- Neutron stars are supported by neutron degeneracy pressure
- Neutron stars resemble atomic nuclei, but:
  - are made of neutrons
  - are held together by gravity
  - emit photons gravitationally redshifted
    - photons lose energy loss while overcoming the strong gravitational field

Neutron Stars

- Typical size: R ~10 km (~6.21mi)
- Mass: M ~1.4 – 3 M_{sun}
- Density: ρ ~10^{14} g/cm^3

→ Piece of neutron star matter of the size of a sugar cube has a mass of ~ 100 million tons!!!



Clicker Question

What fundamental stellar parameter determines how long it stays on the main sequence and what happens when it leaves the main sequence?

A. Temperature

B. Metallicity

C. Mass

D. Rotation rate

Pulsars

- How do we know neutron stars exist?
- First detection of a pulsar: Jocelyn Bell, 1967; radio observations
- Fast (1.337301 second), regular pulses detected from the constellation Cygnus
- 1968: More pulsars! Found in Crab, Vela Nebulae, gaseous remnants of supernovae

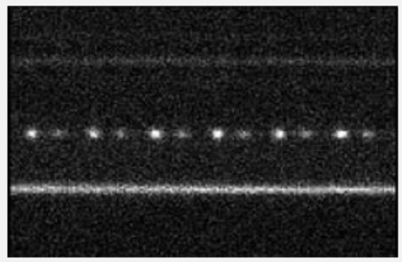
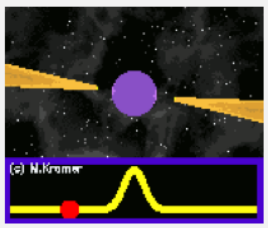
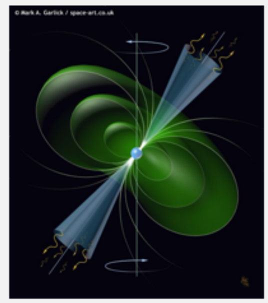


Image: Crab nebula observed with VLT (on page 563 in book)

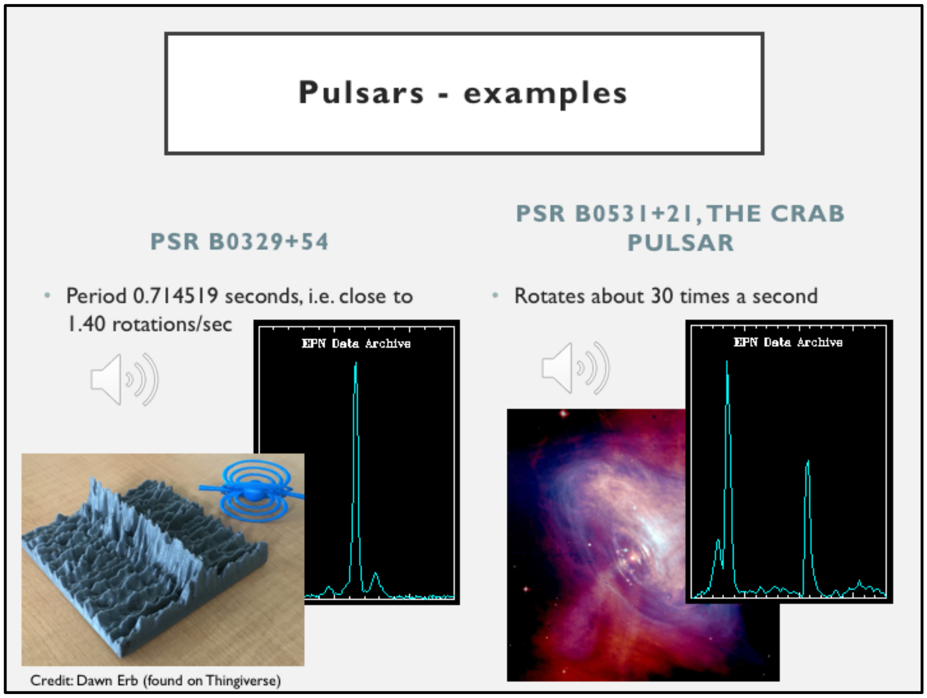
Pulsars

- Pulsations are due to rapid spinning of the neutron star (angular momentum conservation)
- Pulsars also have extremely strong magnetic fields.
- The magnetic field directs beams of radiation out along the magnetic poles.
- Pulsars slow down with time

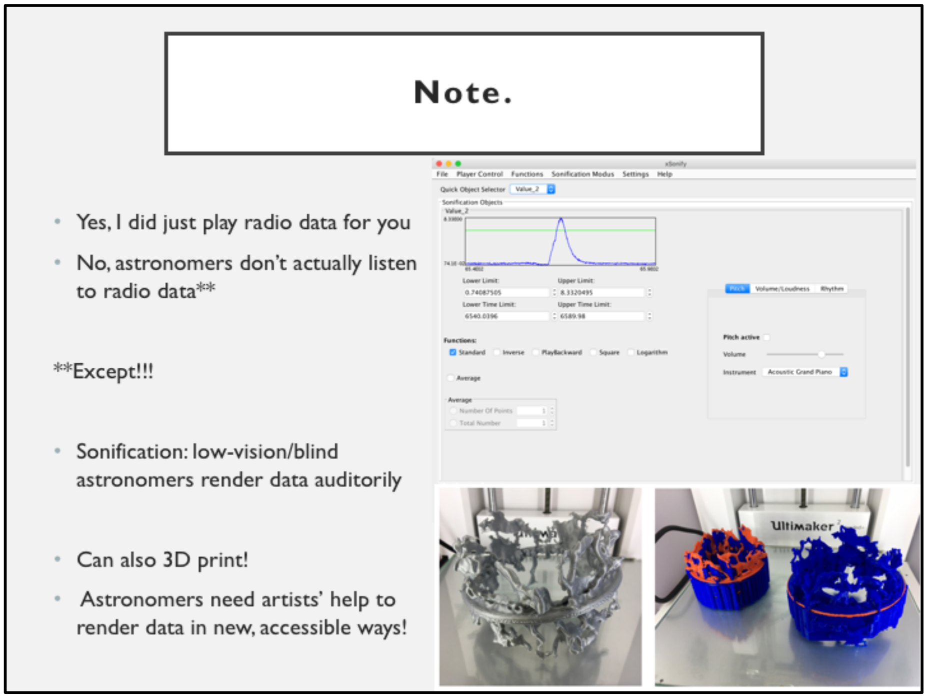




http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_deathhigh.html



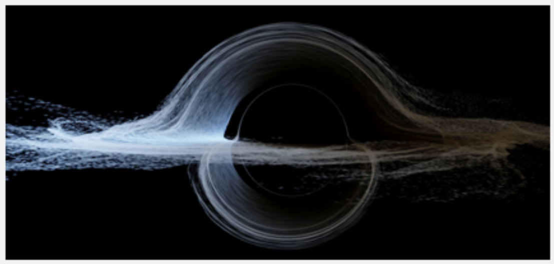
http://www.jb.man.ac.uk/pulsar/Education/Sounds/sounds.html



X-sonify:
https://www.cfa.harvard.edu/sed/projects/star_songs/pages/xraytosound.html
3d printed model, Salvatore Orlando:
http://chandra.harvard.edu/deadstar/sn1987a.html

Black holes

- So far, degeneracy pressure has thwarted gravity- can gravity ever win?



- Rev. John Michell (1783), Pierre-Simon Laplace (1796) wondered: do “Dark Stars” exist? So small, escape velocity ~ speed of light?

Escape velocity

- Speed needed to escape an object's gravitational pull

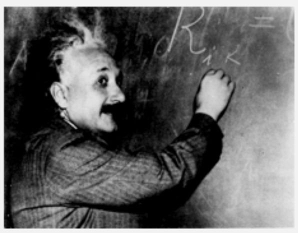
$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

- Examples:
  - Earth: V_{esc} = 27,000 miles/hour (11 km/s)
  - Sun: V_{esc} = 1.4 million miles/hour (600 km/s)

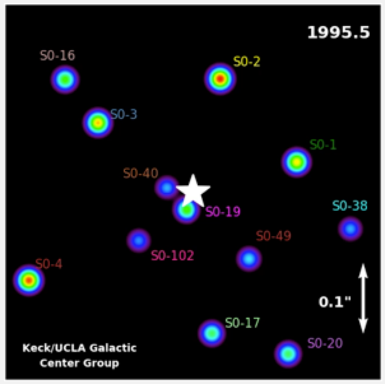
- Keeping their masses the same, for v_{esc} to be the speed of light,
  - Earth's radius R ~ 1 inch
  - Sun's radius R ~ 2 miles

Historical note

- 1915: General Relativity, Einstein's Theory of Gravity
- 1916: Karl Schwarzschild's discovery of black holes in General Relativity
- ~1960s: Black holes understood and generally accepted
- 1967: term "black hole" coined by John Wheeler
- Mid-1990's-present: Prof. Andrea Ghez observing stars' orbits around Milky Way (supermassive) BH

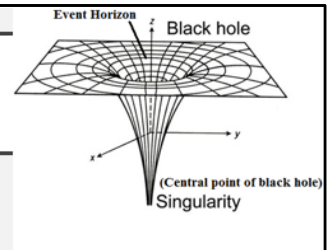


Our friendly Milky Way BH



http://www.galacticcenter.astro.ucla.edu/animations.html

Black holes



- The neutron star limit is ~3 M_{sun}
- A collapsing stellar core that weighs >3 M_{sun} becomes a black hole
- Its radius is less than $2GM/c^2$, the Schwarzschild radius; this is known as a black hole's event horizon
  - For a 10 M_{sun} black hole, it is 30 km.
- The center of a black hole is called a singularity; this is where all the black hole mass resides
- If the escape velocity is ~c, gravitational force is so strong, not even light can escape

Black hole myth-busting

- BHs are not cosmic vacuum cleaners: only inside the event horizon is matter pulled inexorably inward
- Far away from a BH, gravity is no different than for any other object with the same mass
- If a BH were to replace the sun, the orbits of planets, asteroids, moons, etc., would be unchanged (though it would get really really cold)

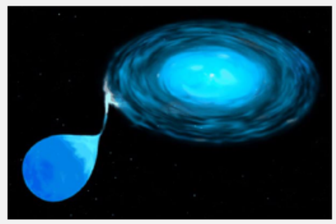
Where to find black holes?

GALAXY CENTERS

- Millions of solar masses ("supermassive" black holes)
- Generally 1 per galaxy
- We don't know how they form

BINARIES

- Likely millions of black holes per galaxy of ~10 M_{sun} or more
- Formed via massive star collapse
- One example: Cygnus X-1: 18 M_{sun} + unseen ~10 M_{sun} object



Black holes: concluding thoughts

- The theory of relativity predicts that time should run more slowly as the force of gravity grows stronger
- The light coming out of a strong gravitational field should show a gravitational redshift (recall: neutron stars do this, too)
- A body falling through the event horizon will be stretched and squeezed
- Black holes produce among the most dramatic and energetic phenomena in the universe
  - Gamma ray bursts
  - Black hole-black hole mergers
  - Galactic center black holes accrete, drive energetic outflows

Clicker Question (Bonus)

What famous physicist, author of popular science books "A Brief History of Time" and "The Universe in a Nutshell" recently passed away at the age of 76?

A. Carl Sagan

B. Percival Lowell

C. Annie Jump Cannon

D. Stephen Hawking

Lecture recap

- A star's mass fundamentally determines its fate
- Low-mass stars (0.5 – 5 M_{sun}) end their lives as white dwarfs expelling planetary nebulae. The core mass does not exceed 1.44 M_{sun}
- Intermediate-mass stars (5 – 10 M_{sun}) end their lives as neutron stars exploding as supernovae. The core mass does not exceed 3 M_{sun}
- High-mass stars ($M > 10$ M_{sun}) end their lives as black holes exploding as supernovae. The core mass exceeds 3 M_{sun}
- Binary systems with a white dwarf and mass transfer may end up as supernovae, if the white dwarf mass becomes higher than 1.44 M_{sun}