Lecture 11: Stellar Remnants:
White Dwarfs, Neutron Stars, and Black Holes
A2020 Prof. Tom Megeath

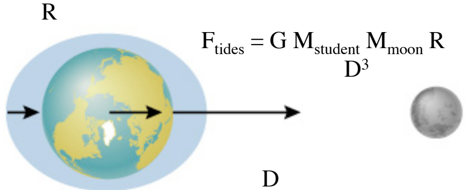
First: Some Physics

1. Tides

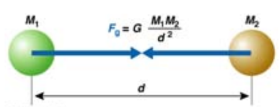
2. Degeneracy Pressure

Concept 1: How does gravity cause tides?

$$F_{tides} = \frac{G\, M_{student}\, M_{moon}\, R}{D^3}$$



- Moon's gravity pulls harder on near side of Earth than on far side
- Difference in Moon's gravitational pull stretches Earth
- Tides change roughly every
- 12 hours as Earth rotates

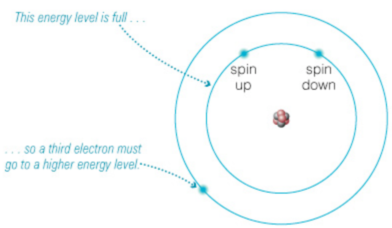


Tides on the Earth

Both Sun and Moon affect tides.
Size of tides depends on phase of Moon
When Sun and Moon are aligned (new moon and full moon) - the tides are higher.

Concept 2: Degeneracy Pressure

Exclusion in Atoms

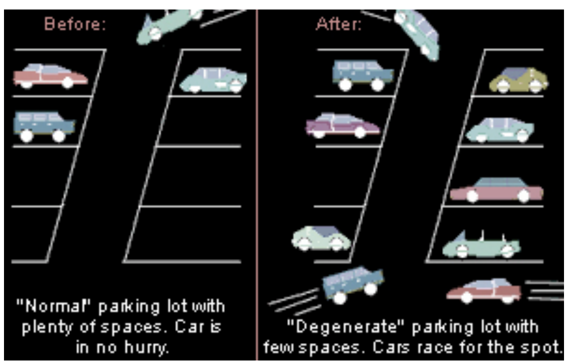


- Two electrons, one with spin up and the other with spin down can occupy a single energy level
- A third electron must go into another energy level
- This is called the Pauli Exclusion principle.
- It is the basis of chemistry.

Degeneracy Pressure

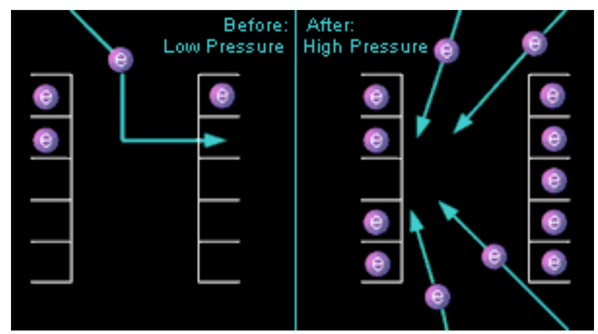
- Laws of quantum mechanics create a different form of pressure known as *degeneracy pressure*
- Squeezing matter restricts locations of its particles, increasing their uncertainty in momentum
- But two particles cannot be in same quantum state (including momentum) at same time
- There must be an effect that limits how much matter can be compressed—degeneracy pressure

Degeneracy Pressure



http://chandra.harvard.edu/xray_sources/white_dwarfs.html

Degeneracy Pressure



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Degeneracy Matter

Electrons are packed as close as they can - with two to a given quantum state.

Electrons resists being compressed.

Quantum mechanical effect based on Heisenberg Uncertainty Principle:

$\Delta X \, \Delta P > h/2\pi$

Where P is momentum (mass x velocity)

Means that the more precisely you know the position of a particle, the less well you know the momentum. Only important for subatomic particle.

As you compress particles ΔX goes down and ΔP must go up

As ΔP goes up, pressure goes up, and matter resists collapse

Now some Astronomy

1. White dwarfs
2. Accretion disks
3. Neutron Stars & Pulsars

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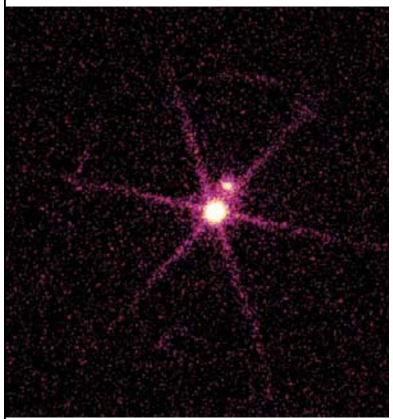
White Dwarfs

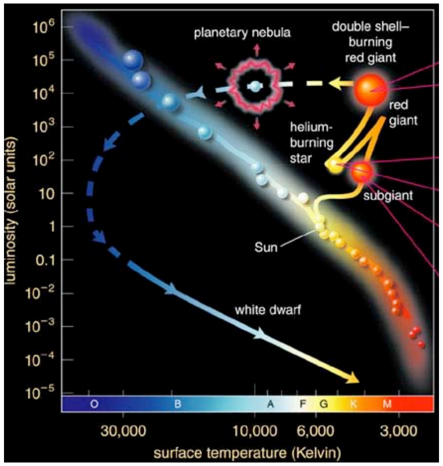


- White dwarfs are the remaining cores of dead stars
- Electron degeneracy pressure supports them against gravity
- Can be very hot (> 30,000 K) and detected in UV, optical and X-ray observations.

X-ray image of the bright A star sirius and its white dwarf companion.

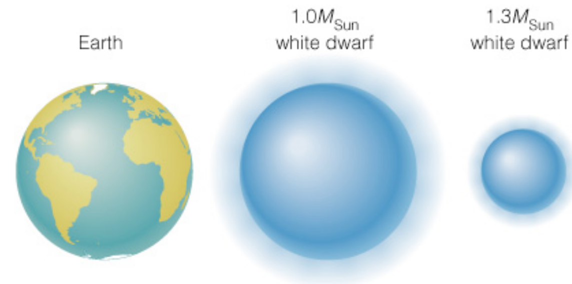
White Dwarfs in Planetary Nebulae

- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf
- The hot white dwarf ionized and heats the expanding gases.



White dwarfs cool off and grow dimmer with time.

Size of a White Dwarf



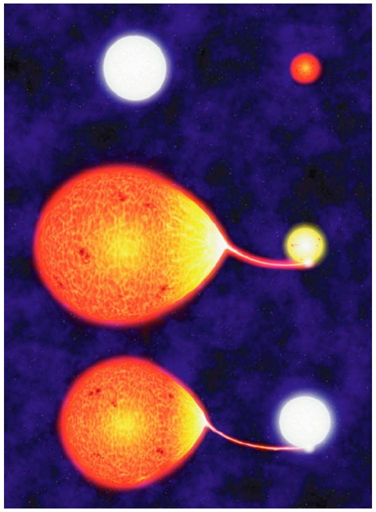
- White dwarfs with same mass as Sun are about same size as Earth (remember, the sun has 300,000 times the mass of the Earth!)
- Higher mass white dwarfs are smaller

The Sun as a white dwarf

http://chandra.harvard.edu/xray_sources/white_dwarfs.html

The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space
- As a white dwarf's mass approaches $1.4M_{Sun}$, its electrons must move at nearly the speed of light
- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{Sun}$, the *white dwarf limit* (or *Chandrasekhar limit*)

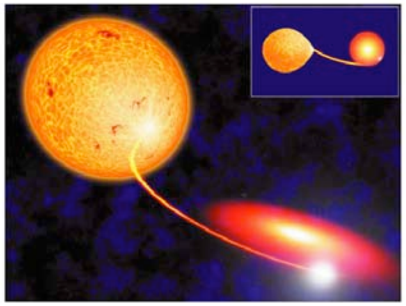


Star that started with less mass gains mass from its companion

Eventually the mass-losing star will become a white dwarf

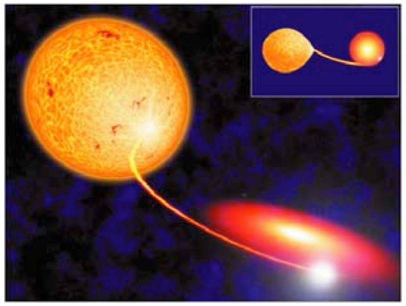
What happens next?

Accretion Disks



- Mass falling toward a white dwarf from its close binary companion has some angular momentum
- The matter therefore orbits the white dwarf in an *accretion disk*

Accretion Disks



- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow
- White dwarf binaries emit strong X-ray and UV radiation.

Thought Question

What would gas in disk do if there were no friction?

A. It would orbit indefinitely.
B. It would eventually fall in.
C. It would blow away.

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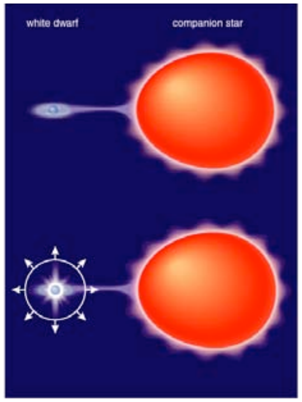
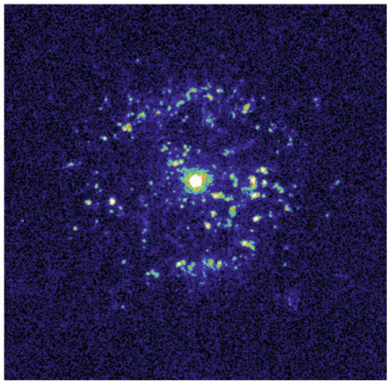
Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion
- Fusion begins suddenly and explosively, causing a *nova*

Nova



- The nova star system temporarily appears much brighter (100,000 times brighter than the Sun)
- The explosion drives accreted matter out into space
- In the end, the white dwarf may lose or gain mass (it is not known - and may differ from nova to nova)
- Novas can happen repeatedly - the time between novas can be as small as a few decades or as large as 10000 years.

Image of nova T Pyxidis. The central source is a binary system containing the nova, the surrounding stuff are blobs of gas ejected by the Nova

Thought Question

What happens to a white dwarf when it continues to gain mass (despite periodic nova episodes) and accretes enough matter to reach the 1.4 M_{Sun} chandrasekhar limit?

A. It explodes
B. It collapses into a neutron star
C. It gradually begins fusing carbon in its core

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Two Types of Supernova

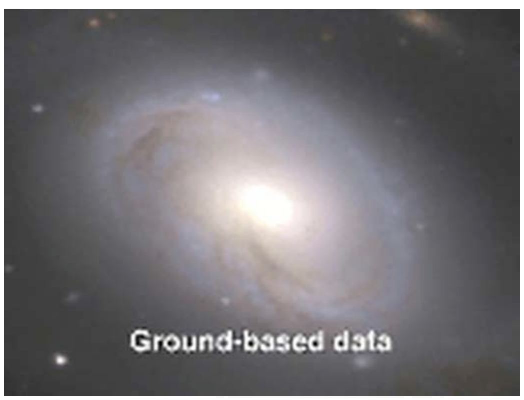
Massive star supernova:

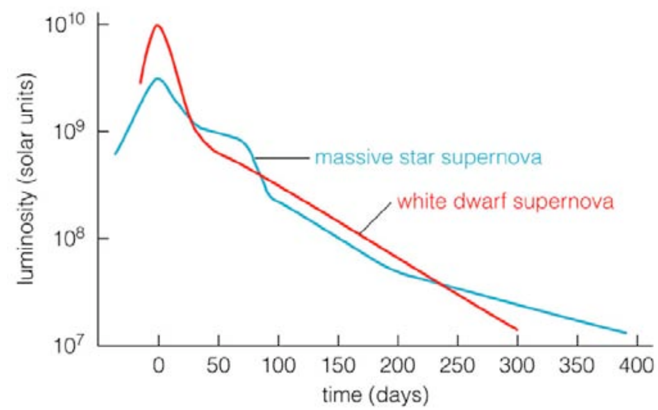
Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

White dwarf supernova:

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion
or
the merging of two white dwarf binaries.

Rung 5 (the ultimate rung): White Dwarf Supernova





One way to tell supernova types apart is with a ***light curve*** showing how luminosity changes with time

Triggering White Dwarf Supernova

White dwarf fed by accretion disk until it exceeds 1.4 solar masses

White dwarf binary combines and exceeds 1.4 solar masses

http://chandra.harvard.edu/photo/2010/type1a/animations.html

Nova or White Dwarf Supernova?

- Supernovae are MUCH MUCH more luminous!!! (about 10 million times)
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind

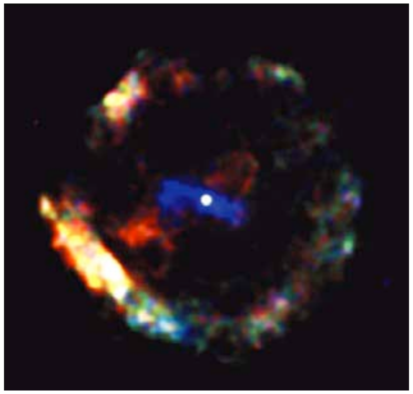
Supernova Type: Massive Star or White Dwarf?

- Light curves differ
- Spectra differ (exploding white dwarfs don't have hydrogen absorption lines)

What have we learned?

- What is a white dwarf?
  - The remnant core of a low mass stars supported by degeneracy pressure
- How big and massive are white dwarfs?
  - A white dwarf with the mass of our sun is approximatley the size of the Earth.
  - The maximum mass of a white dwarf is 1.4 solar masses – higher mass white dwarfs are unstable.
- What can happen to a white dwarf in a close binary system?
  - Hot gas in accretion disks can emit X-rays
  - The accretion disk can dump material which may become hot and dense enough to under nuclear fusion.
- What is a white dwarf supernova
  - White dwarf accretes gas from companion until it exceeds 1.4 solar masses – which undergoes collapse and destruction
  - Two white dwarf binaries combine to form object which exceeds 1.4 solar masses – which under goes collapse and destruction.

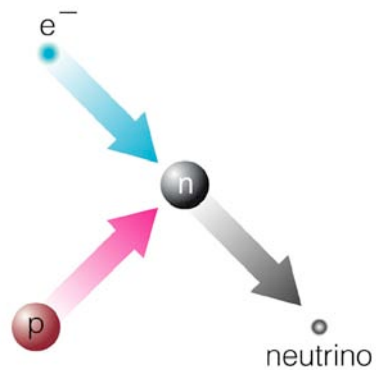
What is a neutron star?



X-ray image of supernova remnant with neutron star. This supernova was probably observed by Chinese observers in AD 386.

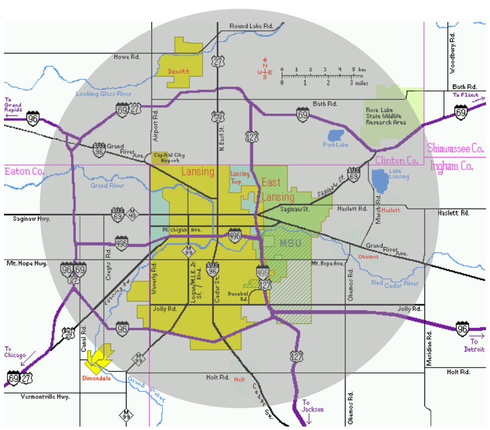
A neutron star is the ball of neutrons left behind by a massive-star supernova

Degeneracy pressure of neutrons supports a neutron star against gravity



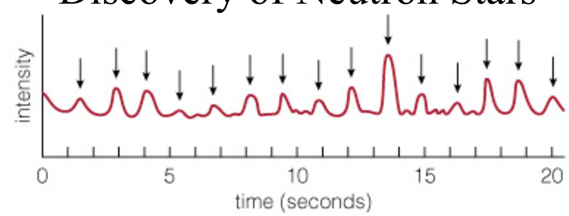
Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

Neutrons collapse to the center, forming a ***neutron star***



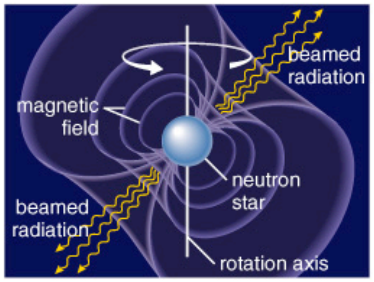
A neutron star is about the same size as a small city

Discovery of Neutron Stars



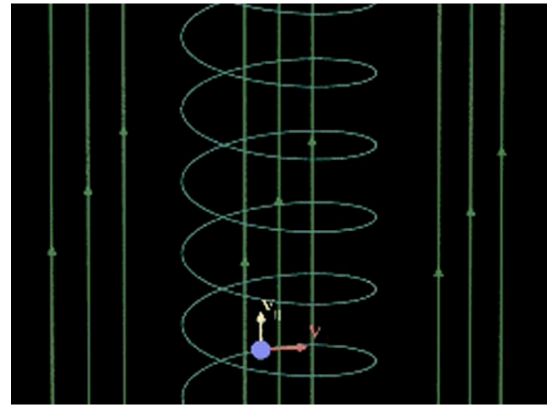
- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky
- The pulses were coming from a spinning neutron star—a *pulsar*

Pulsars



- A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis

Charged Particles in Magnetic Fields



Simple Animations of Basic Concepts in Physics and Astronomyby Dr. Michael R. Gallis
http://rt210.sl.psu.edu/phys_anim/Phys_anim.htm

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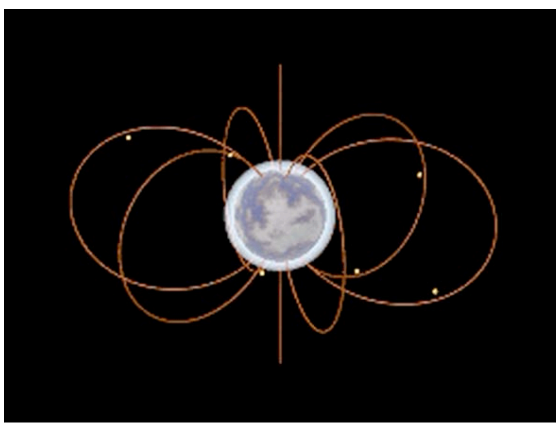

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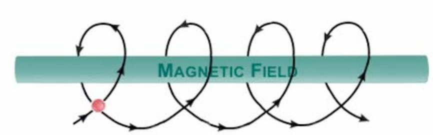
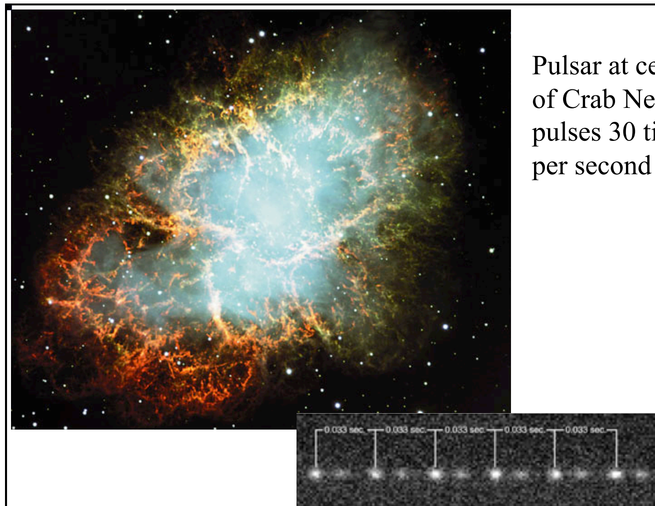
Observing Ionized Gas: Synchroton Radiation

When electrons move through magnetic fields, they produce synchrotron radiation. Often produced in Supernova remnants



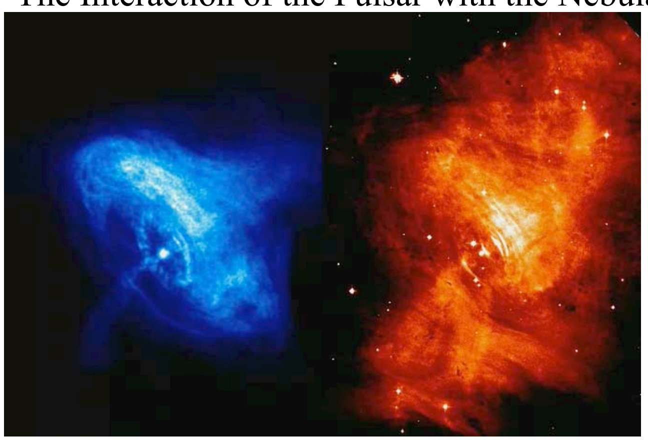
Pulsars

- The radiation beams sweep through space like lighthouse beams as the neutron star rotates



Pulsar at center of Crab Nebula pulses 30 times per second

The Interaction of the Pulsar with the Nebula



X-rays Visible light

Why Pulsars must be Neutron Stars

Circumference of NS = 2π (radius) ~ 60 km

Spin Rate of Fast Pulsars ~ 1000 cycles per second

Surface Rotation Velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

Anything else would be torn to pieces!

Thought Question

Could there be neutron stars that appear as pulsars to other civilizations but not to us?

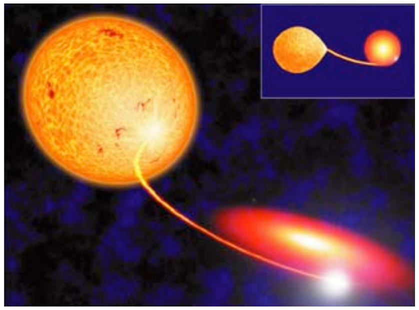
A. Yes
B. No

Thought Question

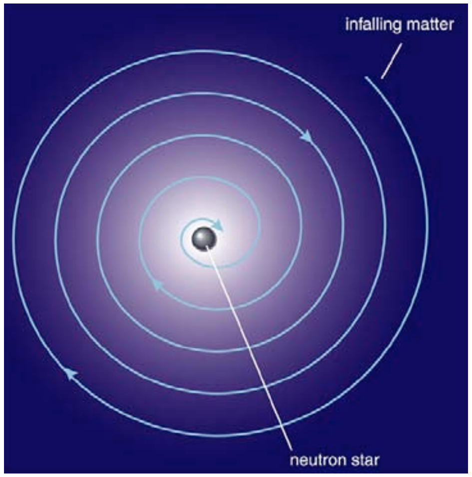
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

A. Yes
B. No

What can happen to a neutron star in a close binary system?



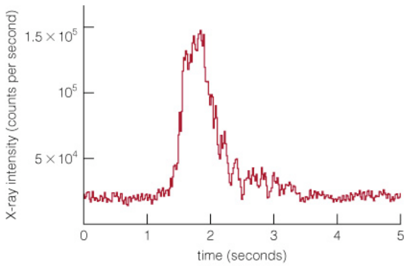
Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary



Accreting matter adds angular momentum to a neutron star, increasing its spin

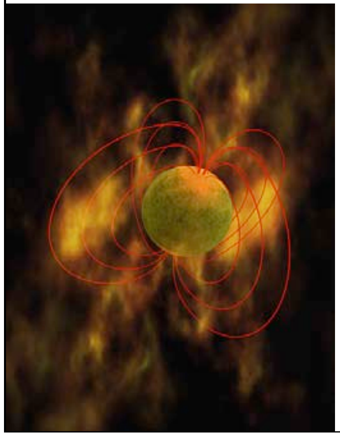
Episodes of fusion on the surface lead to X-ray bursts

X-Ray Bursts



- Matter accreting onto a neutron star can eventually become hot enough for helium fusion
- The sudden onset of fusion produces a burst of X-rays

Magnetars



A neutron star with an extremely powerful magnetic filed.

Magnetic fields 10^{10} stronger than earth's field

(lethal if you were 1000 km away).

Starquakes occur which release huge amount of energy, much of it in gamma rays.

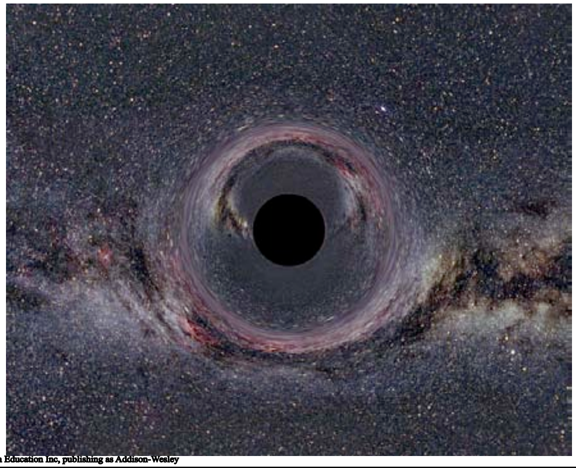
SGR 1806-20 radiated in 1/10 second the same energy our sun radiates in a year

50,000 light years away, it heated the Earth's ionosphere.

What have we learned?

- What is a neutron star?
  - A ball of neutrons left over from a massive star supernova and supported by neutron degeneracy pressure
- How were neutron stars discovered?
  - Beams of radiation from a rotating neutron star sweep through space like lighthouse beams, making them appear to pulse
  - Observations of these pulses were the first evidence for neutron stars
- What can happen to a neutron star in a close binary system?
  - The accretion disk around a neutron star gets hot enough to produce X-rays, making the system an X-ray binary
  - Sudden fusion events periodically occur on a the surface of an accreting neutron star, producing X-ray bursts
- What are magnetar
  - Neutron stars with extremely intense magnetic fields
  - Release tremendous amounts of energy in star quakes

What is a black hole?



A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

Thought Question

What happens to the escape velocity from an object if you shrink it?

A. It increases
B. It decreases
C. It stays the same

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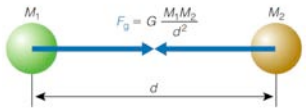
Hint:



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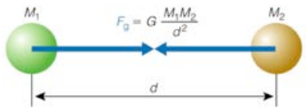


Escape Velocity

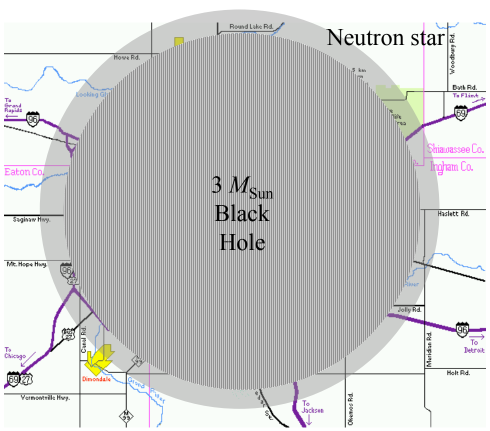
Initial Kinetic Energy	=	Final Gravitational Potential Energy

$$\frac{(\text{escape velocity})^2}{2} = \frac{G \times (\text{mass})}{(\text{radius})}$$

"Surface" of a Black Hole

- The "surface" of a black hole is the radius at which the escape velocity equals the speed of light.
- This spherical surface is known as the ***event horizon.***
- The radius of the event horizon is known as the ***Schwarzschild radius.***

Radius = 2 G M / c^2 where M = mass of the black hole, c is the speed of light, G is the gravitational constant.



The event horizon of a 3 M_{Sun} black hole is also about as big as a small city

No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light.
- No escape means there is no more contact with something that falls in. It increases the hole mass, changes the spin or charge, but otherwise loses its identity.

Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state
- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about 3 M_{sun}
- Neutron stars which accrete mass from companion may exceed this limit and collapse.
- Colliding neutron stars may also exceed this limit.
- Some massive star supernovae can make black hole if enough mass falls onto core

Singularity

- Beyond the neutron star limit, no known force can resist the crush of gravity.
- As far as we know, gravity crushes all the matter into a single point known as a ***singularity.***

Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

A. Increases
B. Decreases
C. Stays the same

Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

A. Increases
B. Decreases
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Thought Question

Is it easy or hard to fall into a black hole?

A. Easy
B. Hard

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B. Hard

Hint: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus

Thought Question

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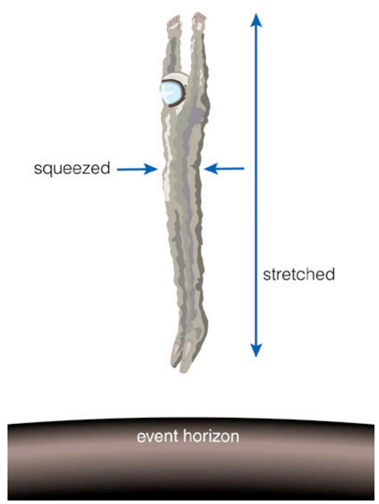
Hint: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus

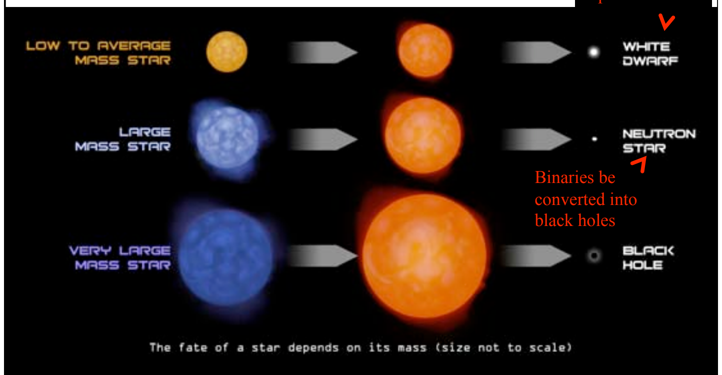


Tidal forces near the event horizon of a 3 M_{Sun} black hole would be lethal to humans

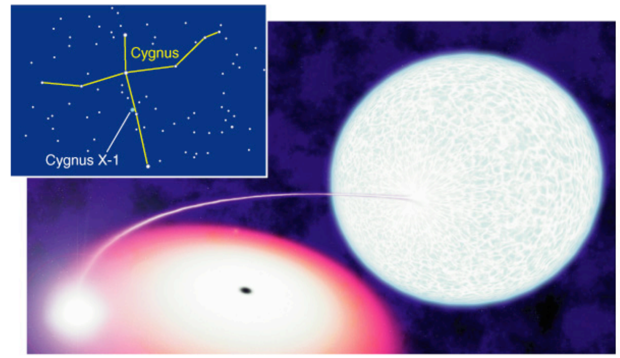
Tidal forces would be gentler near a supermassive black hole because its radius is much bigger

Creating Stellar Remnants

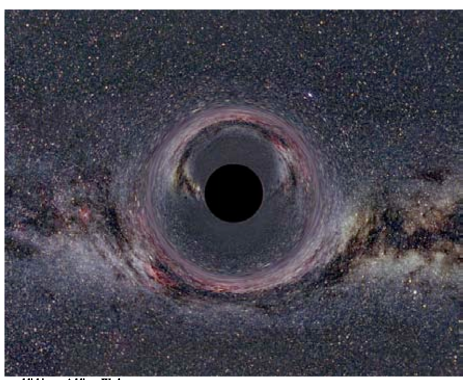
Binaries may be destroyed in white dwarf supernova



Do black holes really exist?

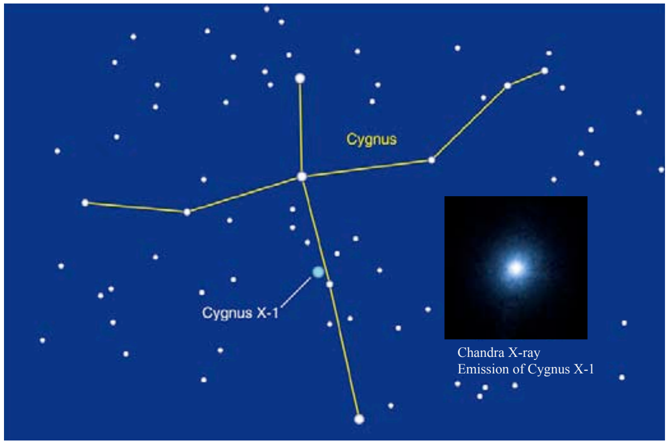


Gravitational Lenses
(a black hole has never been detected this way)

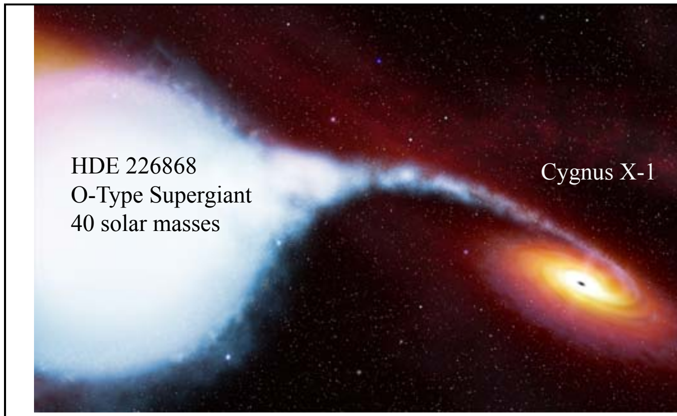


Black Hole Verification

- Need to measure mass
  - Use orbital properties of companion
  - Measure velocity and distance of orbiting gas
- It's a black hole if it's not a star and its mass exceeds the neutron star limit (~3 M_{Sun})

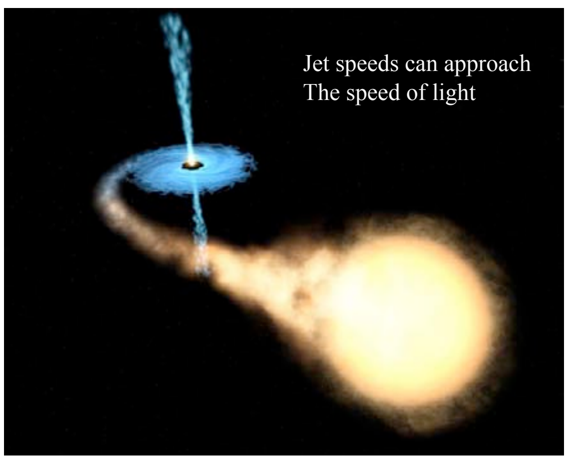


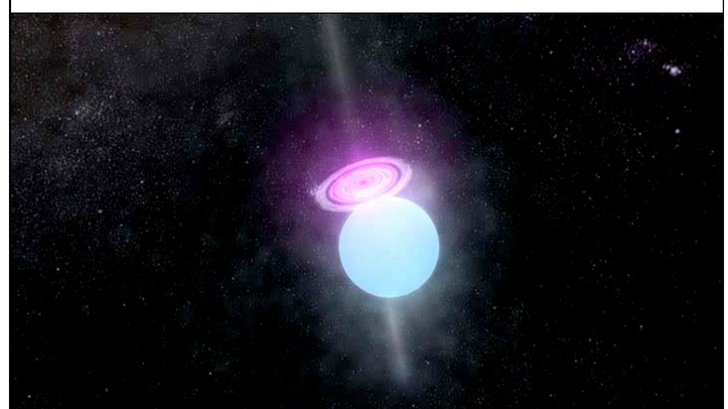
One famous X-ray binary with a likely black hole is in the constellation Cygnus



- •Wobble due orbit of Cygnus-X1 suggests black hole mass of 15-30 solar masses
- •Changes in X-ray emission due to orbit of hot gas suggest mass around 10 solar masses
- •Exceeds 3 solar mass limit for neutron stars.
- •A number of X-ray binaries with black holes have now been identified.

Cygnus X-1 and other X-ray binaries also show jets





Brief Summary

- White Dwarfs and electron degeneracy pressure
- Neutron stars with neutron degeneracy pressure
- Chandrasekhar mass
- Binaries and Accretion disks around white dwarfs, White dwarf supernova
- Pulsars
- Black holes
- Event horizons
- Singularities
- Tides around black holes
- Likely black holes have been found in binary systems that produces bright X-ray emission.