Stars, Galaxies & the Universe
Announcements

- **Exam #2 on Wednesday**
  - Review sheet and study guide posted by Thursday
  - Use office hours and Astronomy Tutorial hours
  - Covers material since Exam #1 (plus background material)

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Stars, Galaxies & the Universe
Lecture Outline

1. Neutron Stars
   - properties of neutron stars
   - pulsars

2. Black holes
   - Einstein's view of gravity
   - Properties of black holes

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Stellar remnants II

Neutron Stars

(progenitor star $1.4 < M < 3\ M_{sun}$)

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Life of a High Mass Star (25 Mo)

LT MS: 5 million years
LT P-MS: <1 million years

- blue main sequence (CNO cycle of hydrogen burning)
- Red supergiant
- He-burning supergiant
- Multiple shell supergiant (all the way to Iron core)
- collapse of star onto inert iron core → supernova explosion
- neutron star/black hole and supernova remnant

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Neutron Stars - Forming

- Degenerate stars heavier than 1.4 solar masses collapse to become neutron stars
- Formed in supernova explosions
- Electrons are not separate
  - Combine with nuclei to form neutrons
- Neutron stars are *degenerate gas* of neutrons

→ (White dwarfs were an electron degenerate gas)

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Neutron Stars - Properties

- Very compact – about 10-15 km radius
- Very dense – one teaspoon of neutron star material weighs as much as all the buildings in Manhattan
- Spin rapidly – as fast as 600 times per second
- High magnetic fields – compressed from magnetic field of progenitor star

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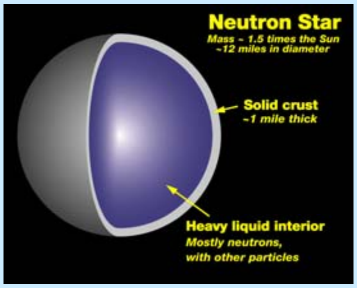

• one teaspoon full – 1 billion tons
• surface gravitational field – 300,000 times that of Earth
normal laws of physics start to break down (Monday!)
• in order for an object to escape from a neutron star, it would have to be traveling at 1/2 the speed of light!

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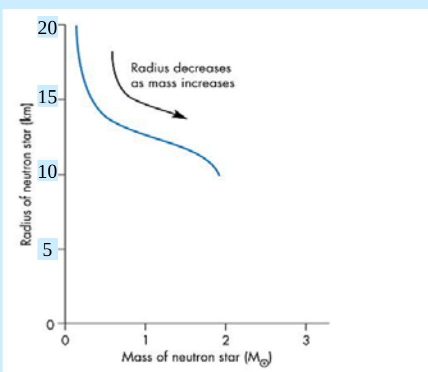

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Theoretical Properties of Neutron Stars

• ***must rotate rapidly because of their small sizes***

Star like the Sun takes about a month to rotate on its own axis

→ if the Sun were collapsed to the size of a neutron star, it would rotate 10000x per second!

artist's conception of
a rotating neutron star

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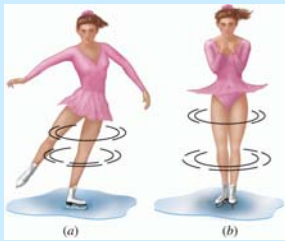
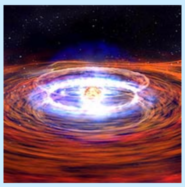
Spinning of neutron star

Collapse of star increases both spin and magnetic field





artist's conception of a rotating neutron star

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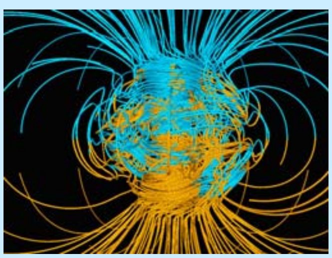
Theoretical Properties of Neutron Stars

- MUST BE STRONGLY MAGNETIC –
  with a radius=15 km, Sun's magnetic field would be 10^{10}x as strong!

Magnetic field for regular star: a few Gauss (G)
Strongest magnetic field produced in a laboratory (for a few sec): 10^{6} G
Magnetic field for neutron star: 10^{15} G



theoretical cartoon of an object with a strong magnetic field

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Neutron star and black hole formation
(History channel video)

http://www.youtube.com/watch?v=jT2wkbPfUYc

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How do we detect neutron stars?

- **neutron stars are very very small (10-15 km)**
- **even though very hot, no direct detection!**

1. **Pulsars – radio detections of 'pulsing' signals**
   spinning radio beams pointed toward us

2. **X-ray binaries –**
   2 stars in orbit
   1. **main sequence/giant/supergiant**
   2. **neutron star**

   big star loses mass onto neutron star
   explosions on surface, X-ray emission

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The discovery of pulsars proved neutron stars exist

1967: Jocelyn Bell
student of Anthony Hewish
at Cambridge U., England

Built a radio telescope to study
variations in the solar wind by
looking at "twinkling" of radio sources
as they pass through the solar wind/corona

- Jocelyn Bell discovered a regular radio signal every ~ 1 second

Thought it could be detection of ET – "LGM1"

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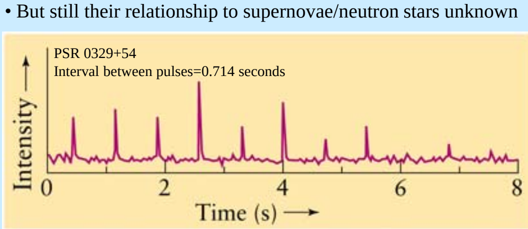
- Pulsations were much more rapid than any known type of astronomical object

→ one of the most plausible ideas was a rotating white dwarf's hot spot but *only* if pulses were approximately every 1 second
→otherwise the white dwarf would fly apart

- Soon many of these sources were detected and called "pulsars"
- Their periods range from 0.25 to 1.5 seconds
- But still their relationship to supernovae/neutron stars unknown



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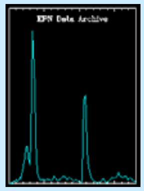
Major clue to nature of "pulsars" occurred when a pulsar was discovered at the heart of the Crab Nebula

Period of this pulsar: 0.0333 seconds or rotations 30x a second!
→could not be a white dwarf
→Had to be an even more compact object: a neutron star!



Pulsar sounds webpage

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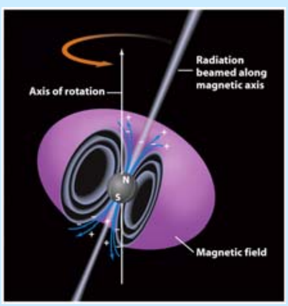
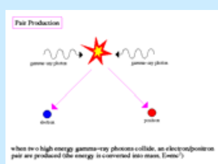
Unusual physics near the surface of a pulsar creates radiation



- due to strong magnetic fields
- due to intense rotation

- intense electric field set up near surface, where electrons can be made through pair production



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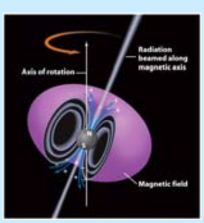
BEAMS of radio emission originate close to poles



- electrons made through pair production interact with strong magnetic fields

- generate SYNCHROTRON radiation
→ at radio (X-ray,optical) wavelengths

- we observe pulses as the neutron star spins, bringing beam into our sight line

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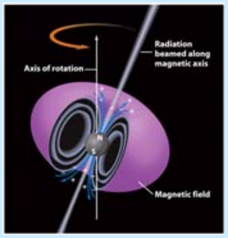
Observational Properties of PULSARS



Observations of pulsars confirmed theoretical ideas

In order to explain "pulses"

- Neutron stars emit radio emission from their 'poles'

2. The BEAM must be directed toward us in order to detect it

- Because they are spinning so fast (1-1000x/s) we see "pulses"
- Two Nobel prizes came out of pulsars:
  1. Hewish (1967) – first discovery of pulsed signals (really the work of Jocelyn Bell)
  2. Taylor & Hulse (1993) – discovery of a pulsar binary!

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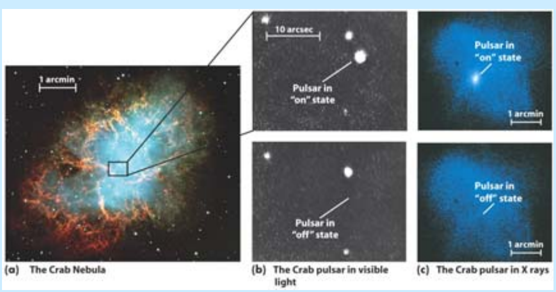

(a) The Crab Nebula (b) The Crab pulsar in visible light (c) The Crab pulsar in X rays

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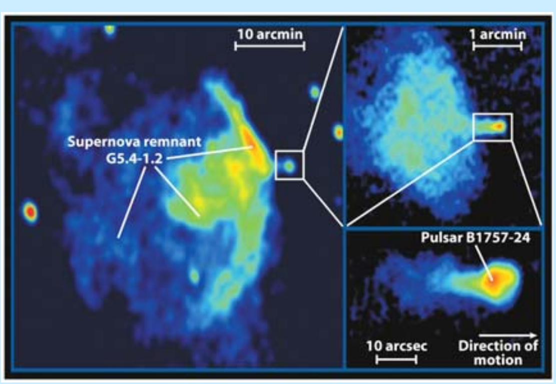

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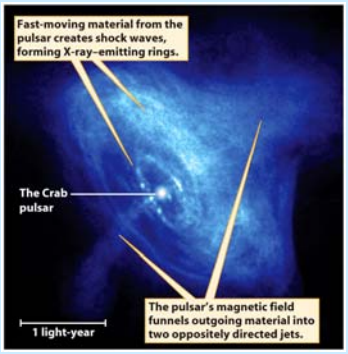
Pulsars also lose energy over time into the ISM



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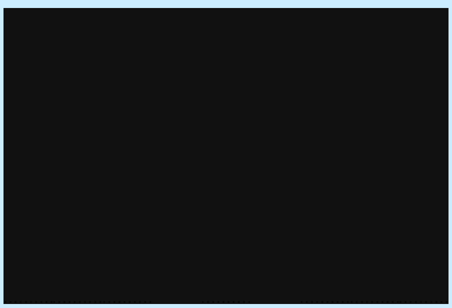
X-ray "movie" showing material flowing outwards into Pulsar Wind Nebula



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Life of a Solar Mass Star (Low-Mass)

LT MS: 10 billion years
LT P-MS: 1 billion years

- main sequence
- red giant: shell Hydrogen burning
- He-burning star (horizontal branch)
- Helium shell burning & Hydrogen shell burning (double shell burning)
- planetary nebula
- white dwarf

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Life of a High Mass Star (25 Mo)

LT MS: 5 million years
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- blue main sequence (CNO cycle of hydrogen burning)
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- Multiple shell supergiant (all the way to Iron core)
- collapse of star onto inert iron core → supernova explosion
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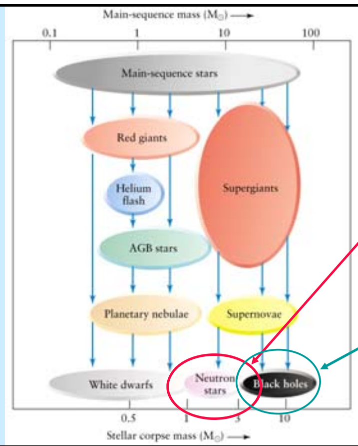

Are all pulsars neutron stars?

Are all neutron stars pulsars?

Black Holes!!

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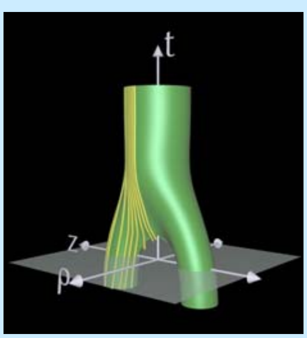
In Einstein's picture, TIME becomes another coordinate of space

"SPACETIME" – (x,y,z,t)



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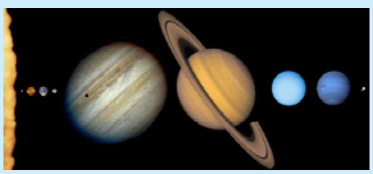
Einstein's theory of General Relativity

Einstein revised Newton's ideas on gravity in hopes of putting together a GENERAL theory of all physics; major implications were in regards to gravity, however

Newton's Theory of Universal Gravitation

- every pair of objects exerts a gravitational force on each other



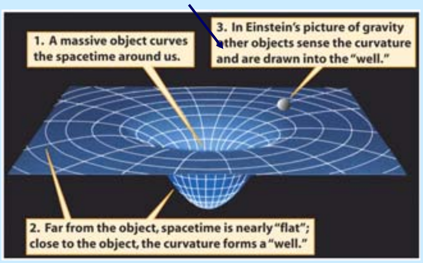
- strength of force depends on MASS of each object
  DISTANCE between two objects

NEWTON vs. EINSTEIN
View of Gravitational Force

Einstein's theory much more robust than Newton's
– 4 experiments that Newton's view fails to explain

Newton's Theory of General Relativity - Gravity

all objects feel the same curvature or "well"
this explains why different objects feel same gravity



This is why things don't get SUCKED into a black hole –
unless you are really close to a BH, you don't feel the curvature
(e.g. for a 10 solar mass BH, you will only be affected within 1000 km)

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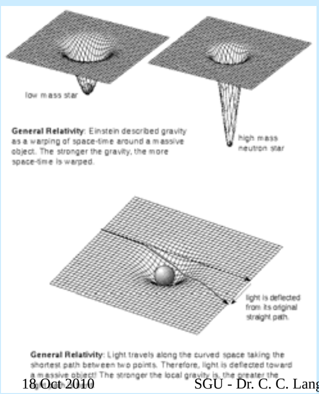
Einstein's Theory of General Relativity



- massive objects affect the SPACE and TIME around them
- "warping of space-time"
- the stronger the gravity, the more spacetime is CURVED

Light can even be deflected from its original path (something Newton's laws don't predict b/c light is massless)!

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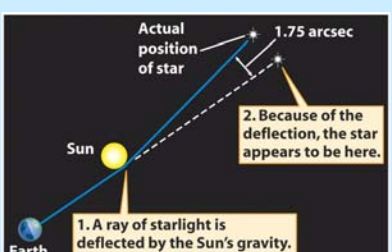
Experimental Test #1 of Einstein's Theory of General Relativity:

gravitational bending of light

- light rays travel in straight lines
- in the presence of mass, the "straight" line is bent
- happening all the time, but difficult to observe
- even happens when light from stars near Sun passes by Sun



- observe coordinates of stars very close to the Sun during eclipse
- compare these to their positions when they are not close to the Sun (in a different part of space)
- find that their positions have changed due to the light being bent around the Sun – very SMALL!

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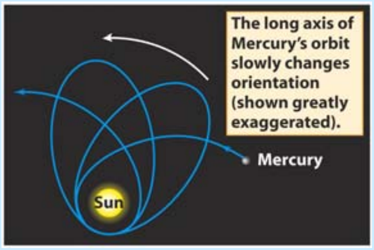
Experimental Test #2 of Einstein's Theory of General Relativity:
precession of Mercury's orbit

- the orbit of Mercury changes orientation with respect to Sun
- due to the gravitational pull of all the planets



• measure Mercury's changing orbit

• figure out how much the rest of the planets affect the orbit

• leftover amount of change MUST be due to a gravitational correction from the proximity of the Sun!

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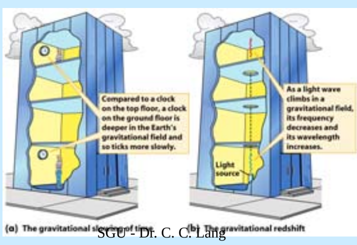
Experimental Test #3 of Einstein's Theory:
Gravitational redshift & time dilation

- mass warps time and space
- clocks on the ground floor of a building should tick more slowly
- light will become "redder" (longer wavelength) and lose energy as it travels up from ground floor because time slows down
- VERY tiny effects – not measurable – ***but important***
- this is DIFFERENT than the Doppler effect (no motion)!



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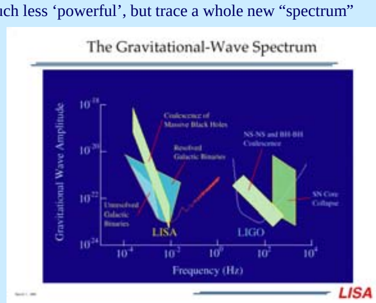
Experimental Test #4 of Einstein's Theory:
Gravitational waves!

- like EM radiation waves, but due to oscillating massive objects
- much less 'powerful', but trace a whole new "spectrum"



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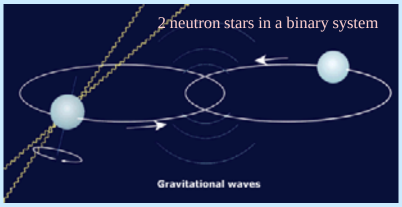
Sources of gravitational radiation: binary pulsars!

two neutron stars in a tight (small) binary system
will lose gravitational energy as they orbit each other

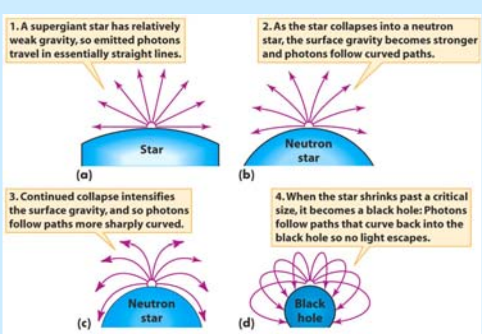


Taylor & Hulse: Nobel Prize (1993) for detecting the shrinking of an orbit of a binary pulsar system

Testing the theory of General Relativity:

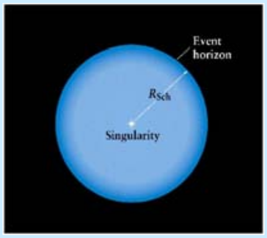
LIGO – Laser Interferometer Gravitational wave Observatory
attempting to detect gravitational waves

Black Holes are a natural consequence of Einstein's theory of gravity



A black hole has only a “center” and a “surface”

- The black hole is surrounded by an *event horizon* which is the sphere for which light cannot escape “surface”
- The distance between the black hole and its event horizon is the *Schwarzschild radius* ($R_{Sch}= 2GM/c^2$)
- The center of the black hole is a point of infinite density and zero volume, called a *singularity or “center”*



A black hole is TRULY black!

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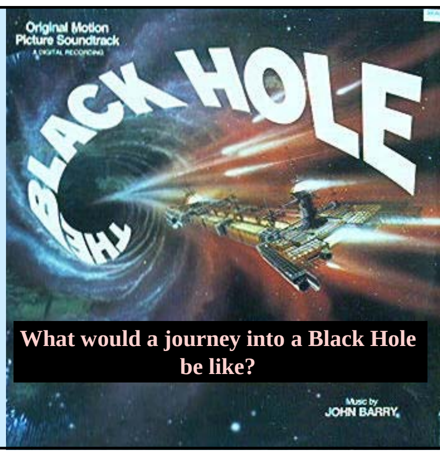

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Schwarzchild radius (R_{sh}):

- the radius at which an object MUST be a black hole
- the radius at which density is so great, no light escapes
- depends on the mass of an object – larger mass, larger R

Object	Mass	R_{sh}
massive star	10 M_o	30 km
mid-mass star	3 M_o	9 km
Sun-like star	1 M_o	3 km
Earth	3×10^{-6} M_o	9 mm
person	~60 kg (3×10^{-29} M_o)	10^{-28} m

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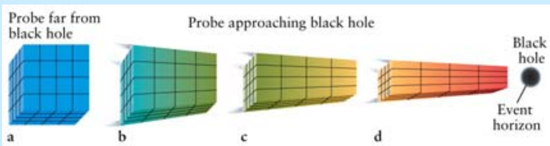
Falling into a black hole:

- get stretched along axis parallel to the path of motion
- get stretched VERY severely in one direction, squeezed in the other direction: “spaghetti-fication”
- from observer’s point of view, appear “redder” (gravitational redshift)
- because TIME slows, then you would appear to never really get there to an observer!



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What would happen if you observed me fall into a black hole ???

- I would start to fall slowly because time appears to slow down due to the high gravity
- I would also appear to contract into a thin strand by tidal forces
- I would hover at the event horizon forever from the observer’s perspective
- I would be shredded and stretched from my perspective (unpleasant!)

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