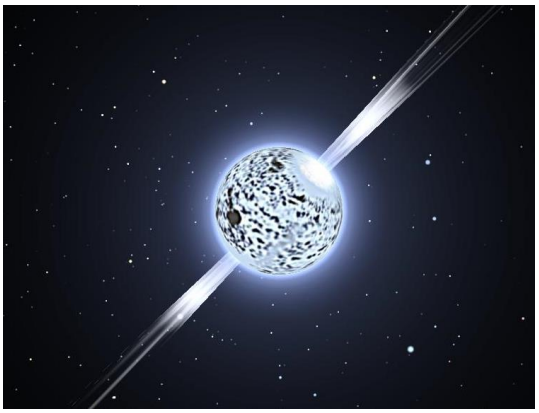
Chapter 13
Neutron Stars and Black Holes
Strange States of Matter

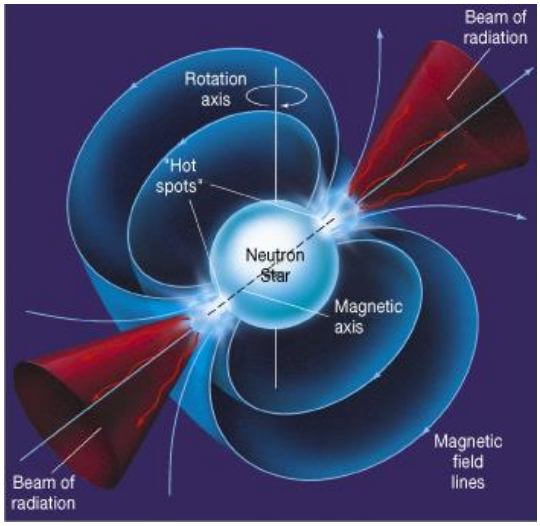
13.1 Neutron Stars



Neutron Star (Pulsar)

- When a Carbon-Detonation (Type I) Supernova explodes, there is nothing left
- When a Type II Supernova explodes, the rebounding neutrons create a shockwave that blasts the outside of the star into interstellar space, but the core of neutrons are left behind
- A Neutron Star is an ultra-compressed ball of neutrons
  - They are very small and very massive
    - Approximately 20 km across but with more mass than the Sun
    - Density can be as high as 10^{17} or 10^{18} kg/m^3 (a billion times more than white dwarf)
    - One thimbleful of neutron star would weigh 100 million tons

13.2 Pulsars



Structure of a Pulsar

- A Pulsar is an object emitting radio radiation in the form of rapid pulses that consist of a .01 second burst of radiation separated by exactly 1.34 seconds from the next pulse
  - Discovered by Jocelyn Bell in 1967
- A Pulsar Model
  - A neutron star that has two "hot spots" that are constantly emitting radiation at the stars magnetic poles
  - The beams sweep through space like a revolving lighthouse beacon, which makes this model often being called the Lighthouse Model
  - The period of the pulses is the star's rotation period
  - Most emit in the radio region, but some will emit in other regions of the EM spectrum such as the visible, X-Ray, or even Gamma Ray regions
  - Their Doppler measurements indicate that they are traveling much faster than the other stars around them
    - Thought to be due to a "kick" from asymmetries of the supernova from which they were formed
- Neutron Stars and Pulsars
  - All pulsars are neutron stars, but not all neutron stars are pulsars
    - Could be that they are pulsing, but not in a direction visible to us on Earth
    - Could be that they have lost enough energy over time that they do not pulse anymore

13.3 Neutron Star Binaries

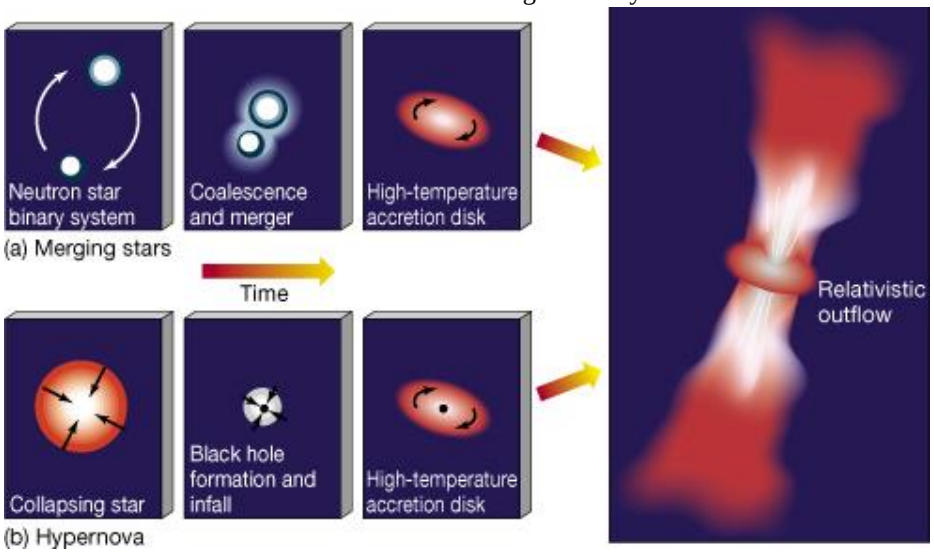
X-Ray Burster

- X-Ray Sources
  - When X-Ray telescopes went up in 1970's, many X-Ray sources were discovered in centers of galaxies as well as in the centers of some globular clusters
    - X-Ray Bursters are neutron starts that are member s of binary systems where the neutron star pulls gas off of the other star similar to the white dwarf binary systems
      - Gas builds up on the neutron star's surface and the temperature rises to temperatures hot enough to fuse hydrogen
        - This fusion quickly emits a burst of X-Rays
        - It is more violent than a white dwarf supernova because of the stronger gravity on the surface of the neutron star

- Millisecond Pulsars
  - In the mid-80's, astronomers discovered a class of pulsars that spin hundreds of times per second
    - A Millisecond Pulsar is a pulsar that has a pulse period that are milliseconds apart
    - This speed puts the equator moving at more than 20% the speed of light
      - This speed is almost fast enough to rip the object apart from centrifugal force
  - Some are found in the middle of globular clusters that should have slowed them down to a stop
    - Something had to have "spun-up" these objects
    - It is believed that X-Ray Bursters will eventually become Millisecond Pulsars as they absorb more and more matter increasing the rotation of the gas surrounding the star
- Pulsar Planets
  - In 1992 there were observed fluctuations in a millisecond pulsar 500 pc from Earth
    - Objects between the star and Earth produce the fluctuations
      - Object #1 has mass about 3x Earth's, distance of 0.4 AU, and period of 67 days
      - Object #2 has mass about 3x Earth's, distance of 0.5 AU, and period of 98 days
    - Upon closer observations there is actually a 3rd object
      - Object #3 has mass equal to the Moon and orbits about 0.2 AU from the star
  - These were the first evidence of planets outside of our solar system

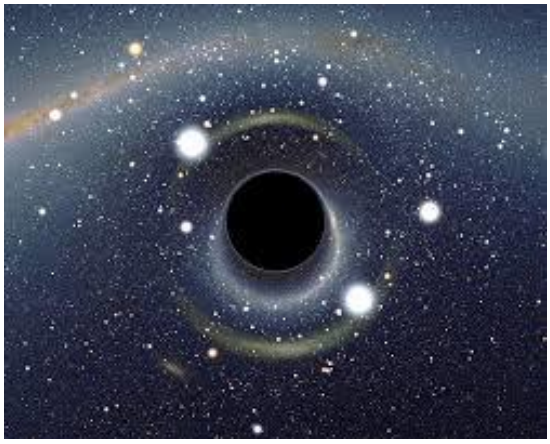
13.4 Gamma-Ray Bursts

- In the 1960's, military satellites looking for evidence of nuclear weapons tests detected gamma rays
  - A Gamma Ray Burst is a burst of bright, irregular flashes of gamma rays that lasts a few seconds
  - Originally they thought they were just scaled up X-Ray Bursters, but now know they are not
- Distances and Luminosities
  - Resolution on gamma ray telescopes is not good and can only be narrowed down to about one arc degree of space
    - Distances are instead calculated by finding a "counterpart" with the burster that can have its distance detected in some other way
      - In 2007, a spectroscopic distance-measurement technique was used to calculate a gamma ray burst at a distance of 2 billion parsecs from Earth
    - Luminosities are VERY large in order for us to detect them from this far away
- What Causes Bursts?
  - There are two models for how astronomers think gamma ray bursts are created

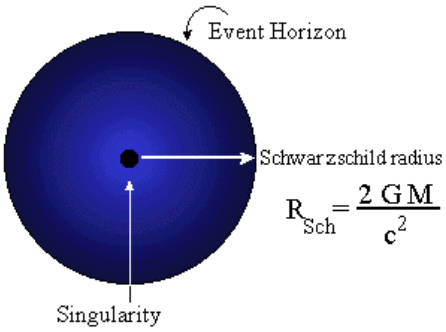


    - Merging Stars
      - Two neutron stars gravitationally pull into one another
      - After collision, gasses not in center create a very high temperature accretion disk
    - Hypernova
      - An extremely massive star collapses and as it goes supernova, creates a black-hole at the center which stalls the supernova
      - Accretion disk becomes so hot, it then goes supernova in area around black hole

13.5 Black Holes



- The Final Stage of Stellar Evolution
  - It is estimated that a neutron star cannot exceed three times the mass of the Sun
  - Above this mass and compacted down to this small of a space, there is no force that can counteract the force of gravity
    - If the amount of material that is left behind after a supernova explosion, or there is enough matter that gets pulled into a neutron star to exceed this limit, gravity takes over
    - This is the fate of any star that is more than 25 times the mass of the Sun
  - A Black Hole is the core of a very massive star that collapses in on itself and vanishes forever
- Escape Speed
  - Most of physics obeys the laws of Newtonian Mechanics
    - These laws cannot adequately describe conditions near black holes
    - The modern theory of gravity (Einstein's General Theory of Relativity) comes into effect
      - Fact #1 from relativity = Nothing can travel faster than the speed of light
      - Face #2 from relativity = All things, including light, are attracted by gravity
  - A body's escape speed is proportional to its mass divided by the square root of its radius
    - As an object gets smaller, the escape speed will double every time the radius is cut to ¼
      - If an object gets small enough for its mass, the speed required to escape the gravity could get up to the speed of light (or beyond)
- The Event Horizon
  - There is a critical radius at which the escape speed from an object would reach the speed of light and the object would no longer be able to be seen
    - The Schwarzschild Radius is the name of the radius of any object would need to shrink to in order to become a black hole
      - Earth is 1 cm, Jupiter is 3 m, the Sun is 3 km
      - Basic rule is the distance is 3 km multiplied by the mass measured in solar mass

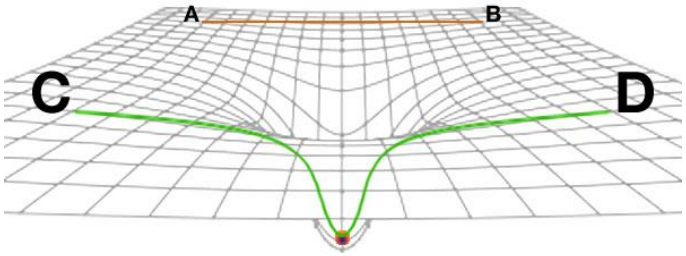


    - The Event Horizon is the three dimensional sphere having a radius equal to the Schwarzschild radius centered on a collapsing star
      - It is basically the "surface" of a black hole

13.6 Einstein's Theories of Relativity

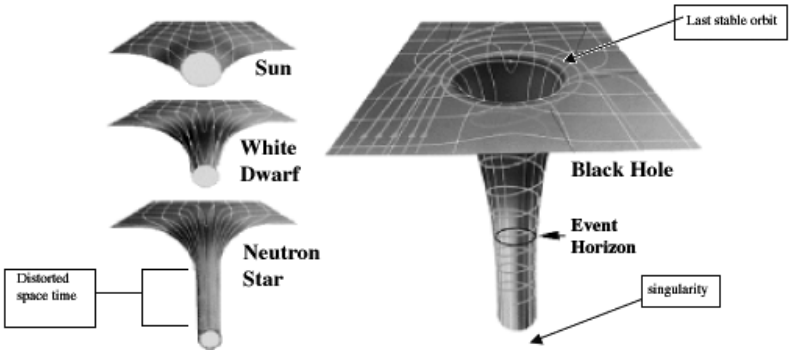
- Special Relativity
  - In 1887, A.A. Michelson and E.W. Morley tried to measure the difference in the speed of light by measuring it on different times of day as well as different days of the year
    - For Newtonian Mechanics, the speed of an object is added to or subtracted from the speed of the observer depending on whether traveling in the same or opposite direction
    - They were unable to detect any answer other than 299,792.458 km/s
  - This led to the three essential features of Special Relativity
    - The speed of light, c, is the maximum possible speed in the universe, and all observers will measure the same value for c, regardless of their motion
    - There is no absolute from of reference in the universe, but only relative velocities can be determined and measured
    - Neither space nor time can be considered independent of one another, but rather they are components of a single entity called spacetime.
  - Special Relativity produces the same result as Newtonian Mechanics for nonrelativistic speeds (not comparable to light), but gives different results for relativistic speeds

- General Relativity
  - Einstein's theory of general relativity is the current working theory of gravity
  - It states that all matter warps the fabric of spacetime and causes acceleration of objects that would otherwise be moving in a straight line like Newton predicted
    - The more massive the object, the more it will warp spacetime
    - Think of it as if you are trying to roll a ball across a trampoline with or without a weight in the center



General Relativity

  - Tests of General Relativity
    - In 1919 during a total solar eclipse, astronomers looked up trying to locate a star that was blocked by the Sun's mass, but according to Einstein's theory, should be visible due to the gravity of the Sun warping spacetime and bending the light from the star to us
      - The star appeared and was visible despite the fact that its true location was behind the Sun proving the bending of light due to the Sun's mass
    - Mercury's orbit around the Sun would be affected by general relativistic effects as well and if we chart its orbit over long periods of time, we notice that its ellipse rotates at 43" per century around the Sun
      - The Sun's mass warps the path traveled by Mercury slightly each time it passes close to it, again proving the curvature of spacetime around a massive object
- Curved Space and Black Holes
  - As the mass warps spacetime more and more, eventually the distortion becomes so great that objects can no longer deflect unless they are traveling greater than the speed of light
  - Since this cannot happen, light cannot escape the gravity, which is the definition of a black hole



13.7 Space Travel Near Black Holes

- Tidal Forces
  - Similar to the tidal forces that produce the tides on here in Earth, the difference in force produced by a black hole can be very large over a relatively short distance producing very strong tidal forces
    - Strong enough to rip apart planets, stars, or even a human being!
- Approaching the Event Horizon
  - Remember that the speed of radiation doesn't change from the speed of light
  - As any object approaches an event horizon, any radiation emitted must work to fight against the gravitational pull of the black hole which causes it to lose energy
    - Gravitational Redshift is the shift of radiation to longer wavelengths due to the force of gravity of a nearby massive object
    - Time Dilation is the process of time slowing down that is related to gravitational redshift
      - As the clock ticks approaching the event horizon, the frequency drops just as the redshift of light does due to the gravitational field
      - We would never be able to see an object cross the event horizon as it would appear to take forever from our point of view!

- Deep Down Inside
    - General relativity predicts that without something to compete with gravity the core remnant of a star will collapse all the way to a point at which both its density and its gravity become infinite
        - The Singularity is the name for this location of infinite density and gravity
    - There is no current theory that can explain what happens within an event horizon
        - All of the rules of physics, mechanics, and relativity break down

13.8 Observational Evidence for Black Holes

- Black Holes in Binary Systems
    - The only way to really detect a black hole is to look at its effects on other objects
        - Binary systems are perfect for this because there will be an object we can see reacting to the gravity of an object we cannot see
        - We know that superheated gas will produce X-Ray and Gamma-Ray radiation
        - We also know that as gravity increases, the speed required to orbit that mass must increase as well

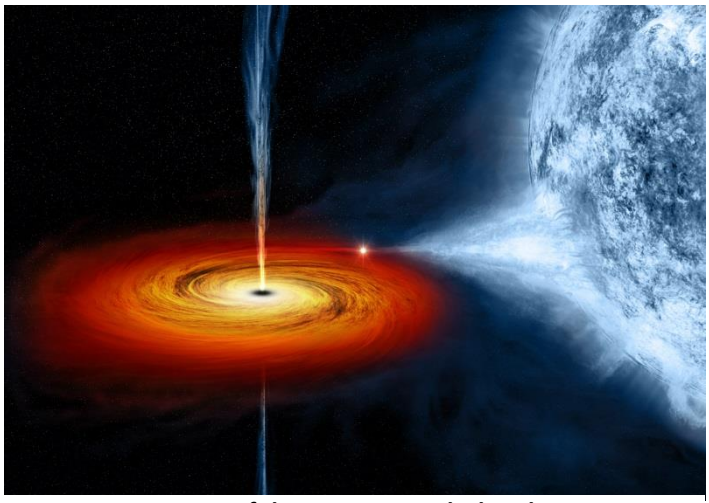


Image of the Cygnus X-1 Black Hole
Surrounded by accretion disk (red) pulling in gas from the companion blue giant companion star

    - 2000 pc from Earth, there is an X-ray source called Cygnus X-1 that was discovered in the 1970's
        - Upon further study, the orbital period of the blue B-type giant star is 5.6 days
            - This is an incredible speed for an object so big to be moving at
        - The source of X-rays comes from an "invisible" region within the orbit of the star
    - The combination of a strong X-ray source as well as the incredible speed at which the star is orbiting the source is a very strong indicator that a black hole is the center of the system
- Black Holes in Galaxies
    - The strongest evidence for black holes comes from centers of galaxies where we have discovered the stars closest to the center are moving EXTEMELY fast around a central location that is unable to be seen
        - By using Kepler's laws as well as Newtonian mechanics, the mass of the central objects can range from 100 to many thousands of times the mass of the Sun
            - What object can be that massive, yet unable to be seen?
- Do Black Holes Exist?
    - No black hole has ever been directly measured!
        - Only our predictions and models built around things we can see lead us to infer their presence in the universe
        - There have been many things in science that were "known" before they were actually discovered with direct measurements.