Chapter 14

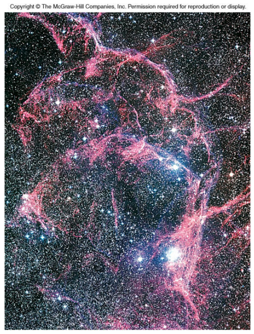
Stellar Remnants: White Dwarfs, Neutron Stars, and Black Holes

Stellar Corpses

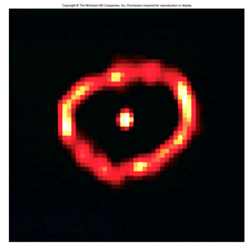
- The three end states of stars, white dwarfs, neutron stars, and black holes are known as ***compact stars***
  - Compact because their matter has been crushed into very dense exotic forms
  - A piece of white dwarf material the size of an ice cube weighs 16 tons
  - A neutron star resembles a giant atomic nucleus
  - Black holes have warped spacetime to the point that even light cannot escape

Stellar Corpses

- Compact does not mean inconspicuous
  - Capturing matter from a nearby object will convert gravitational energy into an extremely brilliant display
  - Under certain conditions, the captured matter may lead to nova and type I supernova explosions



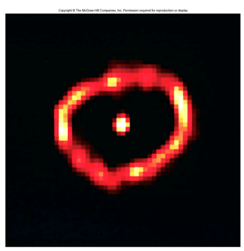
White Dwarfs



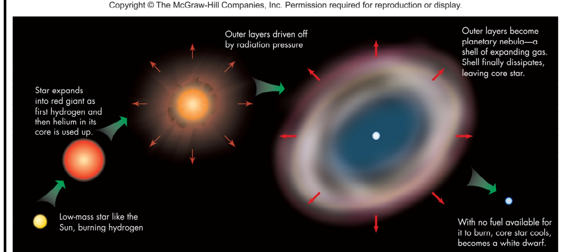
- ***White dwarfs*** are compact stars with a mass similar to the Sun's and a diameter about that of the Earth
- Despite their high surface temperature of about 25,000 K, they are very dim due to their small size
- Their light is generated from residual heat (no fusion) in the star's interior

White Dwarfs

- Being the remaining core of a low mass star (the outer layers having been propelled into space), a white dwarf is mainly carbon and oxygen with a thin hydrogen/helium surface layer
- Initially, with a surface temperature of about 150,000 K, a white dwarf will cool over time (many billions of years) until it becomes a ***black dwarf*** emitting no visible light



Origin of White Dwarfs



Structure of White Dwarfs

- White dwarfs are in hydrostatic equilibrium
  - Gravity is balanced by the pressure of electron degeneracy
  - Degeneracy allows the white dwarfs to shrink with increasing mass
- A white dwarf's mass cannot exceed a certain limit (Chandrasekhar limit) – if it does, it will collapse
- A white dwarf's high density (10^6 g/cm^3) implies that atoms are separated by distances less than the normal radius of an electron orbit

Degeneracy and the Chandrasekhar Limit

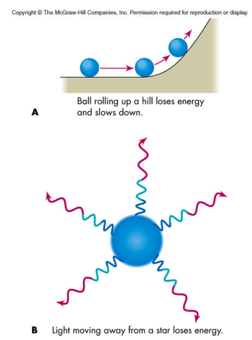
- The basis of degeneracy pressure is the ***exclusion principle:*** a law of physics that limits the number of electrons that may occupy any given volume
  - ***Degeneracy pressure*** depends only on gas density, not temperature – when a degenerate gas is compressed, it heats up, but this temperature increase does not affect the pressure
  - Degenerate gases are less "springy"

Degeneracy and the Chandrasekhar Limit

- Adding mass to a degenerate white dwarf makes it shrink and increases its gas pressure to offset the increased gravity
  - Continually adding mass will eventually make the white star collapse
  - The point of maximum mass for collapse is called the ***Chandrasekhar Limit*** and has a value of 1.4 $M_\odot$
  - All observations of white dwarf masses appear to conform to the 1.4 $M_\odot$ limit

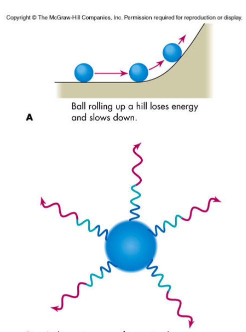
Gravitational Redshift and White Dwarfs

- White dwarfs can induce a ***gravitational redshift*** in their spectra
  - Photons climbing out of the gravitational field of a white dwarf must expend energy to due so
  - Photons cannot change their speed, so they increase their wavelength
  - The amount of redshift depends on the white dwarf's mass and radius

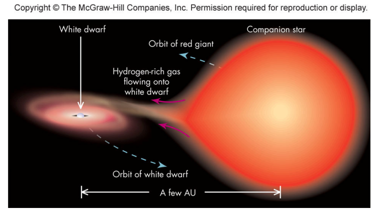


Gravitational Redshift and White Dwarfs

- Knowing a white dwarf's radius (from its luminosity and temperature), the gravitational redshift will give the white dwarf's mass
- Mass determination via the gravitational redshift provides a means to determine a white dwarf's mass in isolation (Kepler's law and a binary pair are not needed)

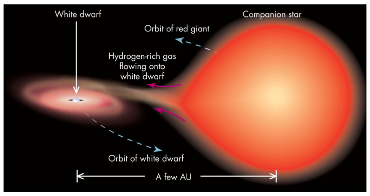


White Dwarfs in Binary Systems



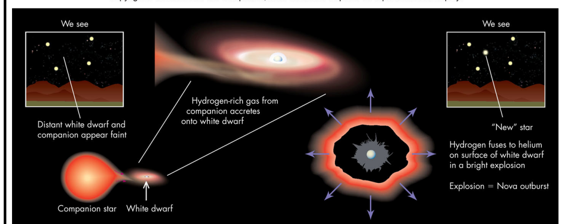
- In a binary system, a white dwarf may gravitationally capture gas expelled from its companion
  - The captured gas will be rich in hydrogen and represent a fuel source to the white dwarf
  - Hydrogen is compressed and heated on the white dwarf's surface

White Dwarfs in Binary Systems

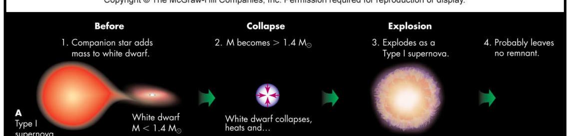


- The gas eventually reaches ignition – a fusion reaction in a degenerate gas results in an explosion: a ***nova***
- Novas may be visible to the eye and may occur repeatedly for the same white dwarf (the explosion does not destroy the white dwarf) as long as the white dwarf never exceeds the Chandrasekhar limit

Novas



Type I Supernova

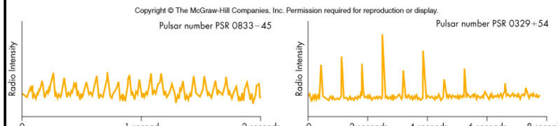


- The result of a white dwarf accreting enough mass to exceed the Chandrasekhar limit
- The white dwarf collapses, igniting carbon and oxygen
- The fusion ignition blows the star apart creating heavy elements in the process (e.g., silicon, nickel, and iron)

Neutron Stars

- A ***neutron star*** is one possible end state of a supernova explosion
- Theoretically derived in the 1930s by Walter Baade and Fritz Zwicky, a neutron star has the following properties:
  - Radius about 10 km
  - Mass between 1 $M_\odot$ and a maximum of about 2-3 $M_\odot$
- Because of its small size, neutron stars were thought to be unobservable

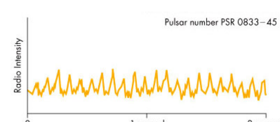
Pulsars



- In 1967, Jocelyn Bell, a graduate student of Anthony Hewish, detected an odd radio signal with a rapid pulse rate of one burst per 1.33 seconds
- Over the next few months, more pulsating radio sources were discovered and eventually were named ***pulsars***

Pulsars

- Ordinary pulsating variables obey a period-density relation where the period is inversely proportional to the square root of its density
  - The long periods of the first pulsars discovered were consistent with their being white dwarfs

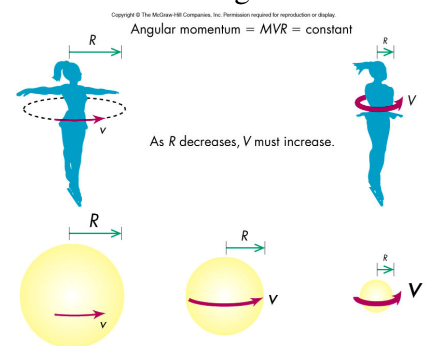


- Later pulsar discoveries had much shorter periods – the theoretical neutron star was dusted off for consideration, although at first, it appeared neutron stars would pulsate too fast

Pulsars Explained

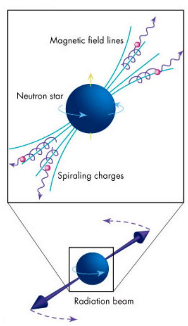
- The key to explaining pulsars turned out to be a rotating neutron star, not a pulsating one
  - By ***conservation of angular momentum,*** an object as big as the Sun with a one-month rotation period will rotate more than 1000 times a second if squeezed down to the size of a neutron star
  - Such a size reduction is exactly what is expected of a collapsing massive star's iron core

Conservation of Angular Momentum



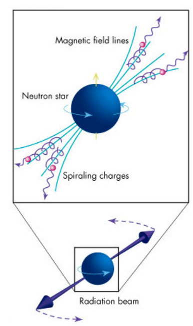
A Pulsar's Emission

- A collapsing massive star is expected to retain its magnetic field endowing the neutron star with an extremely powerful magnet field
- The powerful magnetic field is such that it beams radiation energy in two opposing directions
- The beamed radiation together with the rapid spin gives the pulsar its observed characteristics



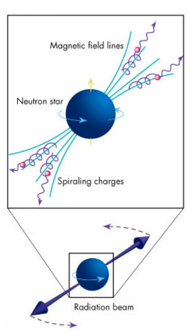
A Pulsar's Emission

- Like dynamos on Earth, the spin of a neutron star's magnetic field (not necessarily aligned with the physical spin axis) creates an electric field
  - This electric field is intense and rips charged particles from the surface and channels them into two narrow beams at the magnetic poles

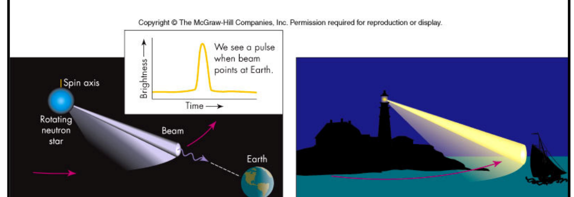


A Pulsar's Emission

- The charged particles accelerate to speeds close to that of light and in so doing produce radio emissions along the polar axes (visible light and gamma rays may be produced in very young pulsars)
- Radiation produced in this manner is called ***nonthermal radiation*** or ***synchrotron radiation***



A Pulsar's Emission



- The pulsation of a pulsar is the result of one of the radio beams sweeping across the Earth

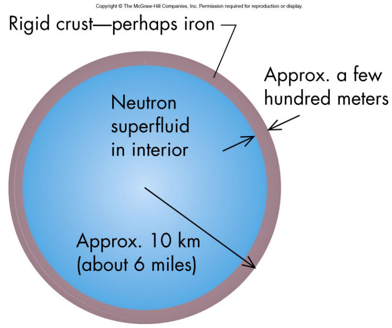
Emissions from a Neutron Star

- Electric/magnetic fields of a rotating pulsar exert forces on charged particles in its vicinity, speeding them up
  - The charged particles in turn exert a reaction force on the neutron star
  - Consequently, neutron stars should slow down with age – this is what is observed

Internal Structure of Neutron Stars

- Neutron stars occasionally speed up
  - Jumps in a neutron star's rotation are called ***glitches***
  - Neutron stars have three layers: a millimeter thick atmosphere, an iron crust of a few hundred meters, and a neutron core with ***superfluidity*** properties (having virtually no friction or magnetic fields)
  - The core and crust spin independently
  - Occasionally though, the slowing crust will reach a critical value and the core will shed some of its rotational energy to the crust, speeding it up – a glitch

Interior Structure of a Neutron Star

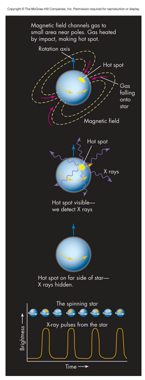


Internal Structure of Neutron Stars

- Neutron stars occasionally speed up
  - When a neutron star is born, the very hot crust may shrink and suddenly crack making the star's radius smaller
  - Conservation of angular momentum then requires the neutron star to speed up – another glitch
- Neutron stars are eventually expected to slow to the point that their emissions become undetectable – the pulsar "dies"

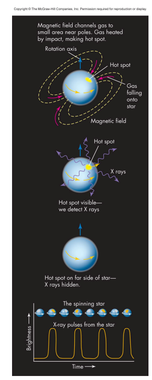
X-Ray Binary Stars

- Neutron stars in binary systems sometimes emit intense X-rays – such stars are called ***X-ray binaries***
- There are several types of X-ray binaries
  - X-ray bursters
    - Intense bursts of X-rays emitted at irregular time intervals
    - Thought to be caused by gas falling on and exploding off a neutron star's surface (akin to a nova)



X-Ray Binary Stars

- X-ray pulsars
  - Rapid, regular pulse of X-rays like a regular pulsar
  - Thought to be caused by "hot spots" near the magnetic poles where gas from companion falls
- Millisecond pulsars
  - Extremely rapid rotation of 1000 times per second
  - Thought to be caused by "spinning up" as a result of acquiring mass from its companion via an ***accretion disk***



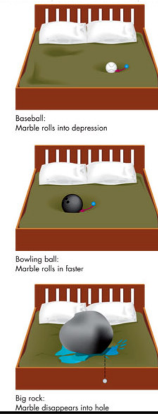
Black Holes

- Massive stars greater than 10 $M_{\odot}$ upon collapse compress their cores so much that no pressure is capable of supporting it – a ***black hole*** results
- A black hole is an "object" (region of space) that has an escape velocity that exceeds the speed of light – hence the name
  - Using the equation for the ***escape velocity*** at an object's surface, equating it to the speed of light c, and solving for radius *R*:

$$R = 2GM/c^2$$

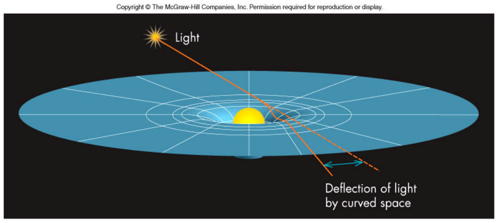
  - where *M* is the object's mass
  - For the Sun, *R* is about 3 km – if the mass of the Sun could be compressed into a radius of 3 km it would become a black hole

Black Holes



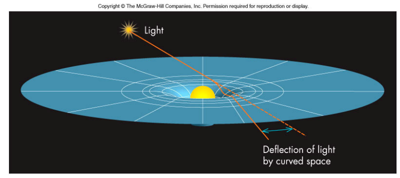
- Einstein's general theory of relativity gave a mathematical and physical picture to black holes
  - Gravity is related to the ***curvature of space***
  - A black hole is a place where the curvature of space is so extreme that a hole forms
  - Typical analogy – imagine a water bed with a heavier and heavier object placed on it
  - This analogy is only approximate and a mathematical treatment is very difficult

The Schwarzschild Radius



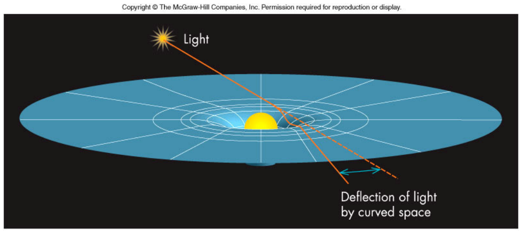
- Karl Schwarzschild did find a simple expression for the size of a black hole – its ***Schwarzschild radius*** – and it was exactly the same as the radius derived by the escape velocity approach

The Event Horizon



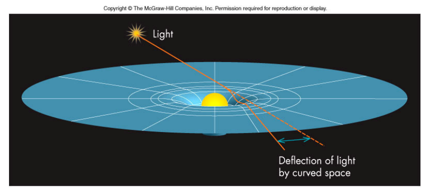
- The spherical surface that encompasses the black hole is called the ***event horizon***
  - This name expresses the fact that everything within the black hole (any events) are beyond our ability to see (like a ship beyond the horizon)
  - We are only capable of knowing a black hole's mass, electric charge, and spin (a spinning black hole will not have a spherical event horizon)

The Event Horizon



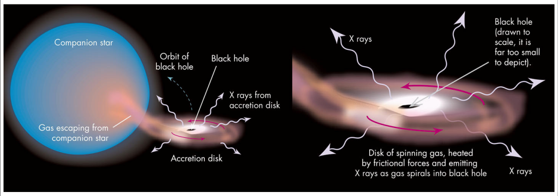
- A black hole's gravitational field is no different than any other object with the same mass (except for their interiors)
- The curvature of space will bend light and this is indeed observed

Formation of Black Holes



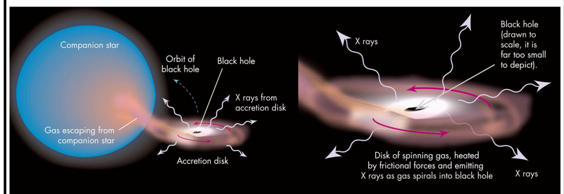
- Not all astronomers are convinced of the existence of black holes
- Astronomers are virtually convinced that supernova explosions create neutron holes, and it is only a "small" extrapolation to create black holes
- However, it remains to be demonstrated by <u>observation</u> that black holes exist

Observing a Black Hole



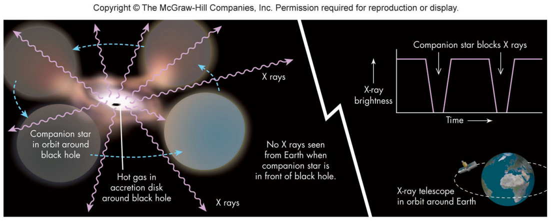
- General approach to "observing" black holes is an indirect approach – look for an effect on an object that can be uniquely attributed to an interaction with a black hole

Observing a Black Hole



- A black hole in a close binary system
  - An accretion disk may form around the black hole as it draws in material from its companion
  - Material swirling around at or near the speed of light at the black hole's event horizon will emit X-rays due to the extreme temperatures

Observing a Black Hole



- If the black hole is eclipsed by the companion, an x-ray telescope will observe the periodic disappearance of the x-ray signal
- From the periodicity of the X-rays and the known mass of the companion, the mass of the invisible black hole can be found

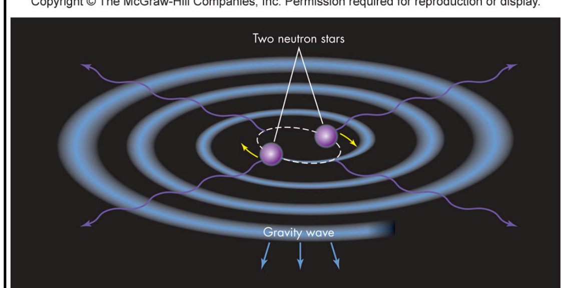
Observing a Black Hole

- If this mass exceeds the maximum allowed for a neutron star (Cygnus X-1 and A0620-00 are two examples), a black hole is currently the only known object that can have high mass and not be visible (and yet its companion is)

Gravitational Waves

- If a compact object orbits a companion or even if two typical stars rapidly orbit each other, these systems should generate ***gravitational waves*** – much like twirling your finger in a pond will propagate water waves
  - Gravitational waves are theoretically very weak – none have been detected to date
- Indirectly though, gravitational waves should cause a binary system to lose energy, making the star move together
  - Two neutron stars orbiting each other appear to be losing energy at just the rate predicted

Gravitational Waves



Hawking Radiation

- In 1974, Steven Hawking predicted that black holes should radiate a blackbody spectrum – ***Hawking radiation***
- Maximum radiation is at a wavelength 16 times the Schwarzschild radius
- Using Wien's law, a solar mass black hole will radiate with a temperature of 6×10^{-8} K
- Although this level of radiation is too small to detect, it does imply that black holes are not truly black
- The basis of Hawking radiation is a quantum process that allows energy to escape the black hole despite its intense gravity
- The net result: If left alone, a black hole, whose only source of energy is its mass, will eventually "evaporate", albeit with a very large time scale (10^{67} years!)