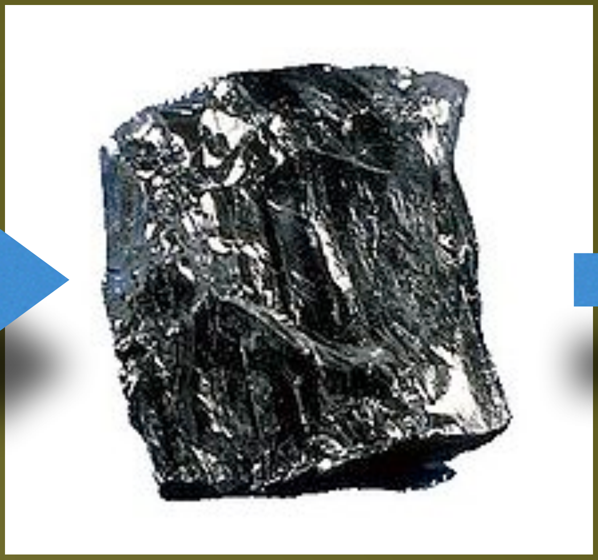
Do Stars Last Forever?

Week 2

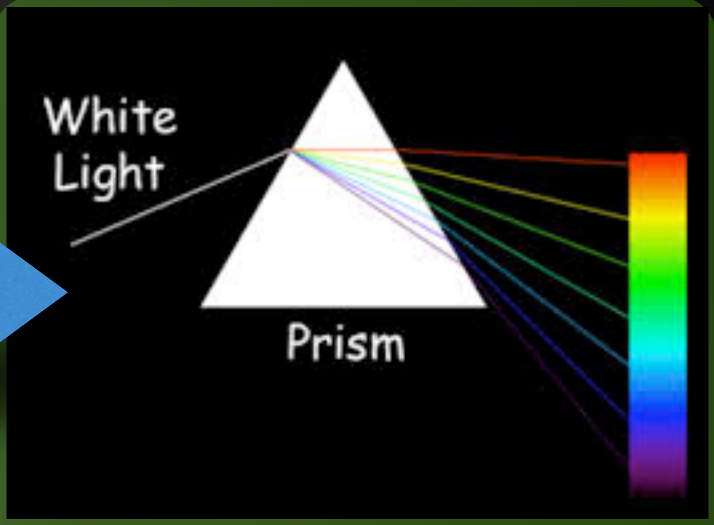
- What do we know about the sun?
- How do we learn about stars?
- What makes stars different?
- How do stars form?
- How do stars evolve?

Ancient Greeks thought the sun was the god Helios, riding his flaming chariot across the sky (most religions viewed the sun as a god)

Anaxagoras (≈500 BCE)
- 1st proposed the sun and stars were the same
- Thought they were burning stones
- Nearly executed for this belief



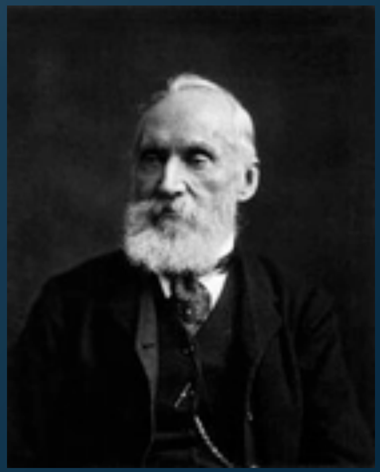
Industrial Revolution:
- The sun is coal!
- Problem: The sun would burn out in a few thousand years (less time than recorded human history)



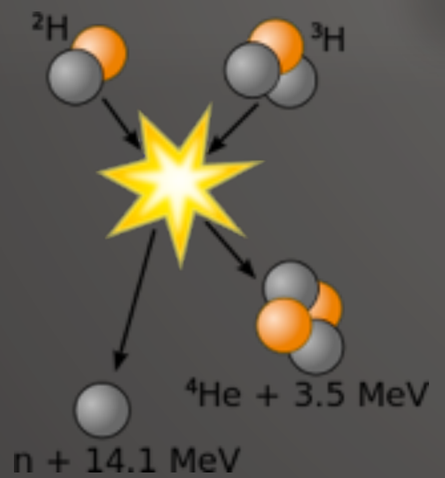
≈1850:Spectroscopy (more on that later this week) showed that the sun is made up of gas

- ≈1870:Thought the sun's energy came from gravitational contraction (remember Jupiter)
- Problem: Sun would only last 20 million years (Earth is older than that)

Hermann von Helmholtz



Lord Kelvin



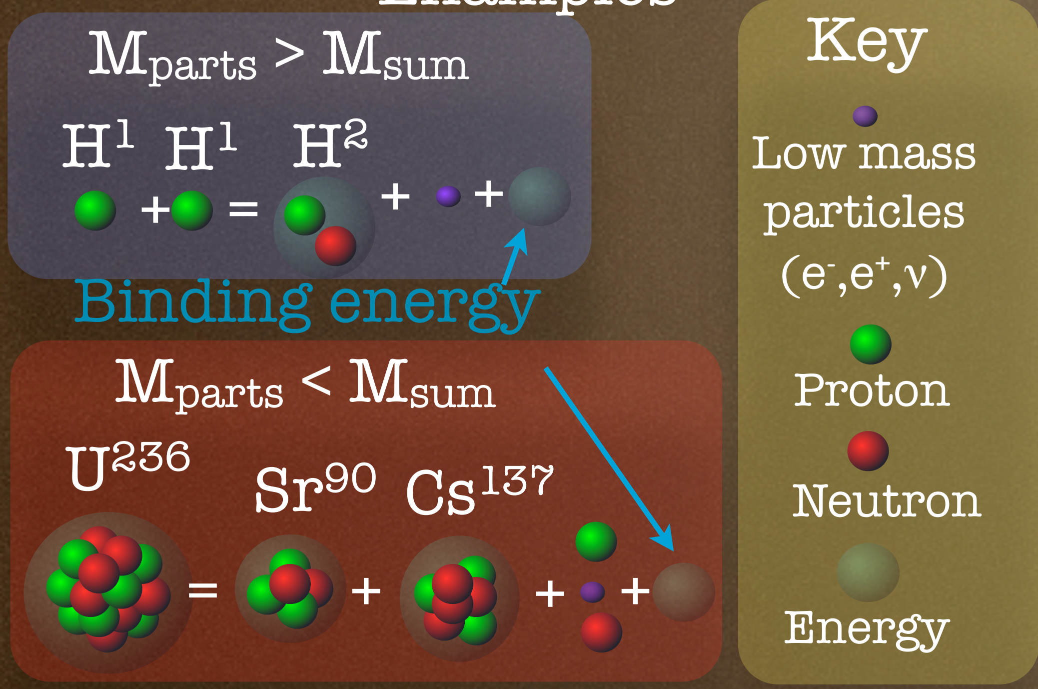
1920's:
Nuclear Fusion!

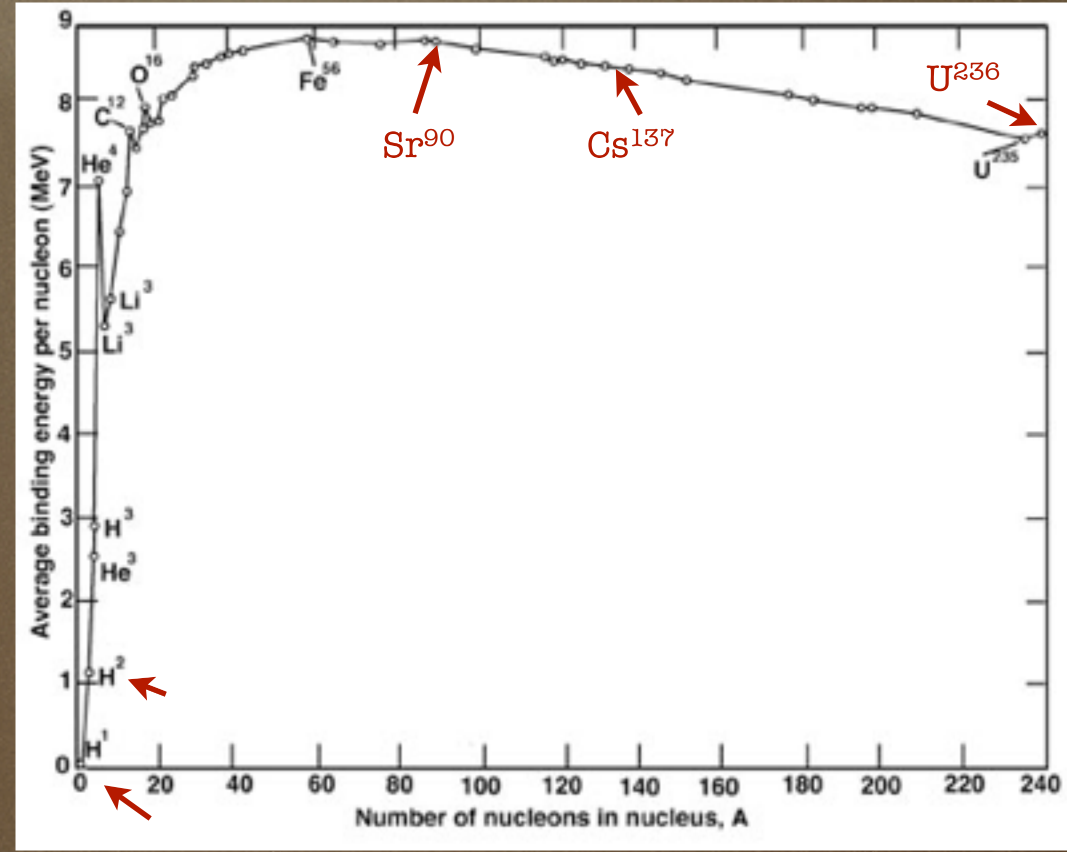
Nuclear Fusion

The Power of the Stars

Binding Energy

Examples





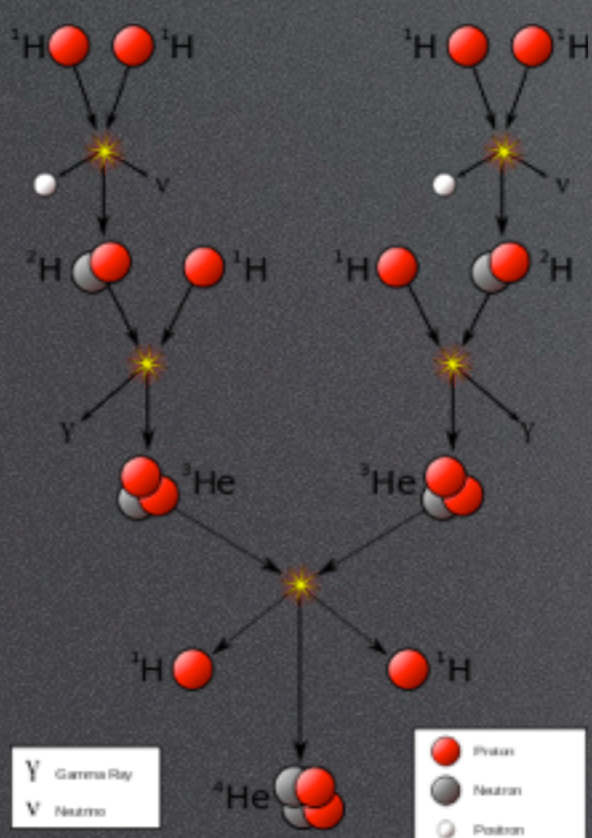
Binding energy per nucleon

Sr=Strontium

Cs=Cesium

- Since $E=mc^2$, a small mass difference is A LOT more energy
- Important later when we talk about high mass stars

p-p Chain



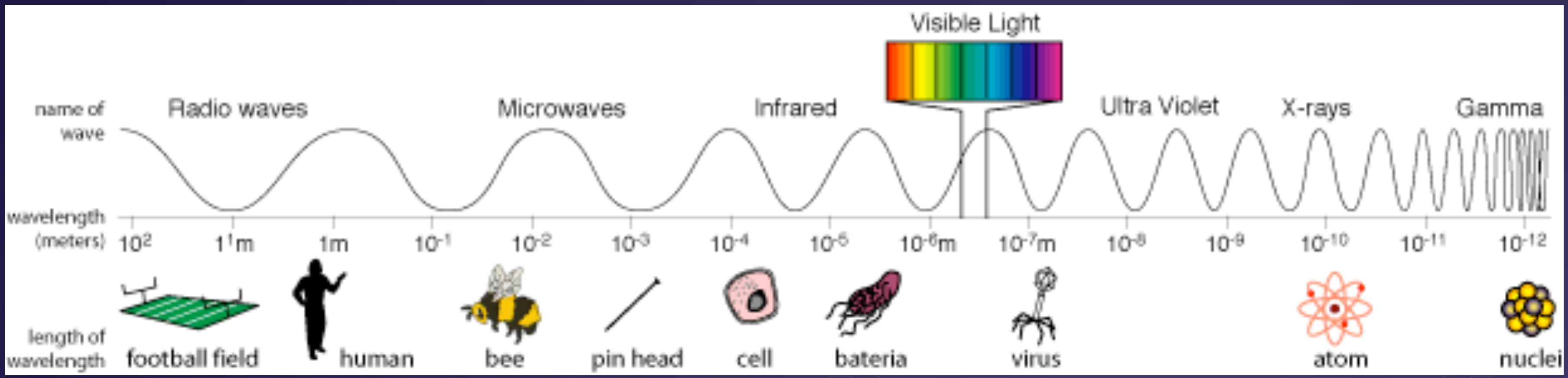
Fusion powers the stars

- Normally protons repel (EM force)
- It takes high temperature and pressure for fusion to occur (the only suitable conditions in the solar system are at the sun's core)
- Evidence that this is correct: Neutrino's! (more on this later)
- Neutrino problem solved as recently as 2002

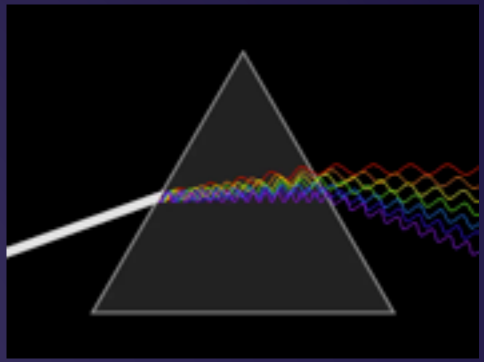
The Nature of Light

Light as a wave

Light is EM radiation



Title graphic from NASA

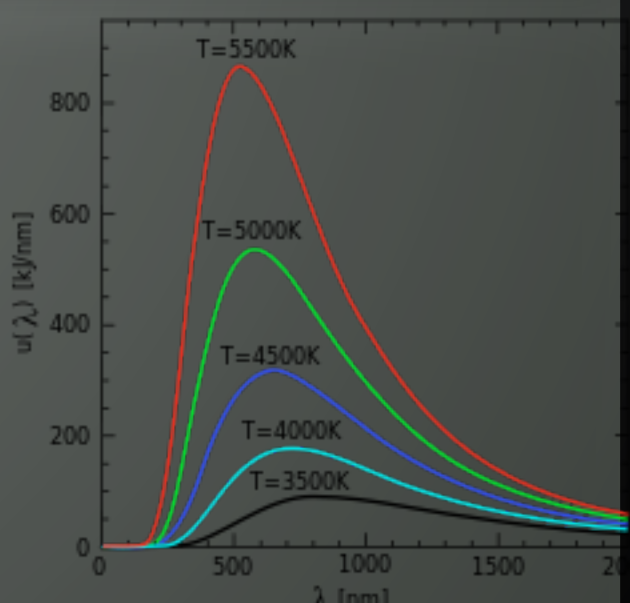


A spectrograph separates different wavelengths of light

- Different "colors" are different frequencies/wavelengths/energies
- Visible light is just a small part of a much larger spectrum
- Prisms take white light and separate it into it's components
- Scientists use spectrographs to do this more precisely

Blackbody Radiation

- Radiation (light) due to the temp of an object
- A star, gold ball, plastic ball, emit the same blackbody radiation at the same temperature: allows us to know the temperature of stars
- Warmer objects emit more radiation at shorter wavelengths (higher energies)



Blackbody curves

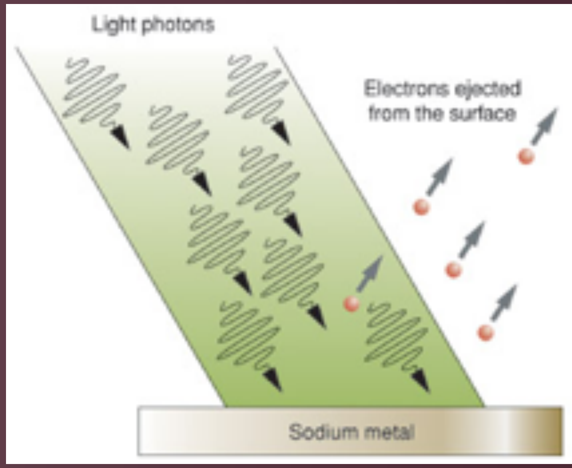
Particle Nature of Light

Blackbody Problem

- A light wave of any frequency would have the same amount of energy
- The blackbody spectrum predicted that an oven would have infinite energy!
- What was missing: light also behaves as a particle
- It was realized that light comes in small packets, whose energy depends on wavelength

Photoelectric Effect

- It was observed that when light was shined on a metal, it could transfer energy to electrons and they would be ejected
- The # if ejected e's was proportional to the intensity
- Consistent with wave nature of light
- The energy of the e's is related to the frequency of the light, and below a certain frequency they are no longer ejected
- Explanation: Light also acts as a particle, the photon
- Light energy only comes in quantized units



Photoelectric Effect

Conclusion: Light is a particle and a Wave!

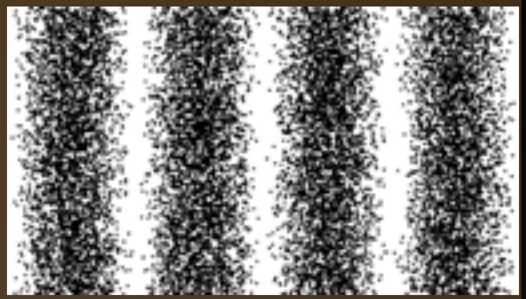
Next Time: More Quantum Physics and the duality of matter

Quantum Physics

Particles as Waves

Double Slit Experiment Revisited

- We saw that light is a particle and a wave, what happens of we shoot individual photons through a thin slit?
- Classically: it should go through one slit or the other, giving us two distinct lines
- No way to know which slit it went through!
- Instead we see that a photon interferes with itself (going through both slits as a super position)
- It lands on the screen at a seemingly random location, but after many photons have been emitted we see that a diffraction pattern appears
- Where it lands is determined by statistics



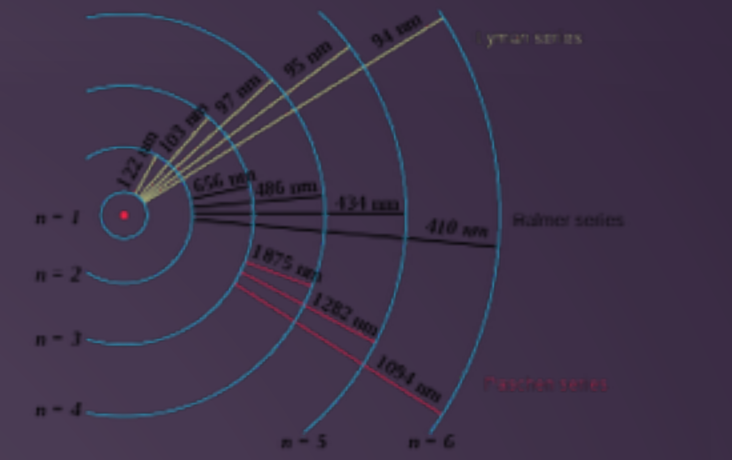
Photons fired individually

Electrons as Matter Waves

- What if instead of photons we send electrons?
- Same thing!
- Small particles like protons, neutrons, and electrons also behave as both particles and waves
- Needed to explain the atomic energy levels and how and why atoms and chemistry work

Atomic Energy Levels

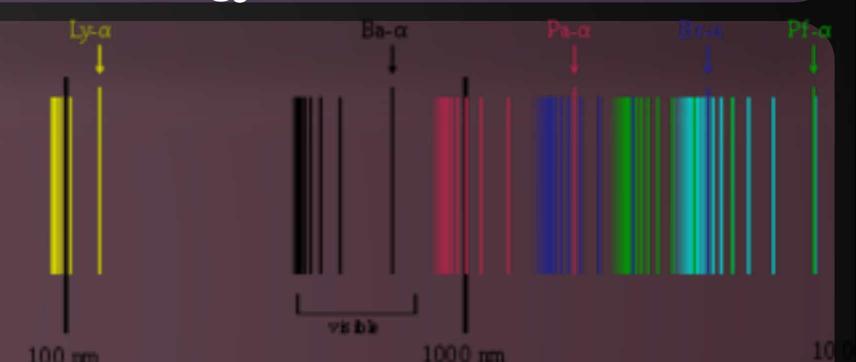
- QM describes precisely how matter waves interact
- Useful in everything from computers to LED lights
- Solving wave equations gives us a quantum description of an atom
- electrons can only exist in discrete energy levels, not in between



- Atoms store energy like small capacitors
- Electrons exist in quantized energy levels

Emission

- e^-'s always want to be in the lowest energy state
- If an e^- is in a higher energy state and a free lower energy level is available, it will jump back down and emit a photon
- Each gap in energy level corresponds to a different energy photon
- Each atom has its own spectrum: act like fingerprints



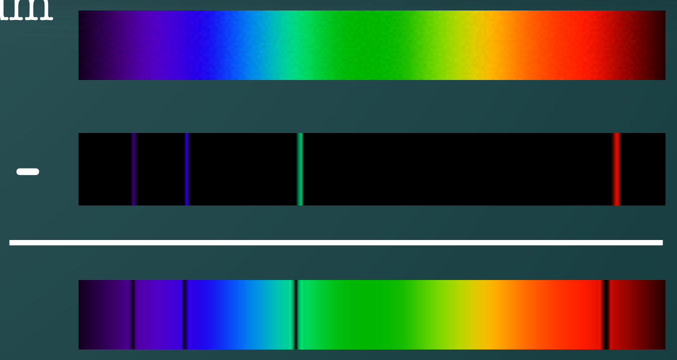
Ex. Spectrum of hydrogen

Ex. Spectrum of mercury

Absorption

- If a photon has the energy to knock the e^- to a higher state it is absorbed
- If white light passes through a gas of a particular atom, it will have absorption lines (opposite emission lines)

Absorption spectrum

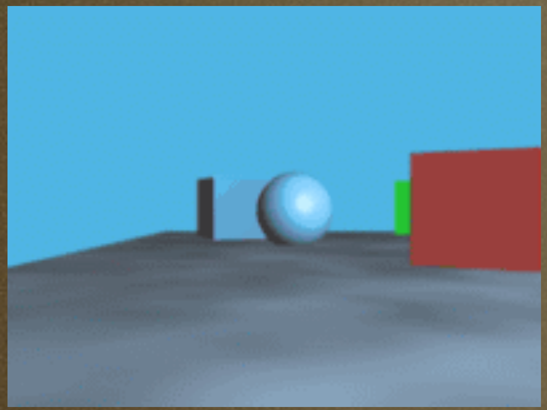


Measuring Stars

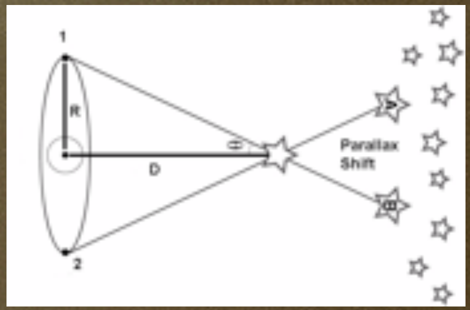
Measuring Properties of Stars

Parallax

Changing our viewpoint makes closer objects move differently than further objects

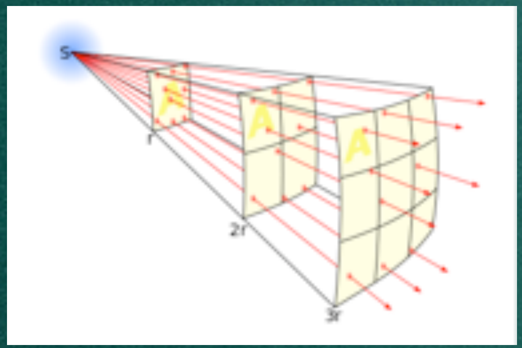


- Have students hold out their finger with a background of stars on the screen



The same works for earth, only our eyes become opposite sides of our orbit

Standard Candles



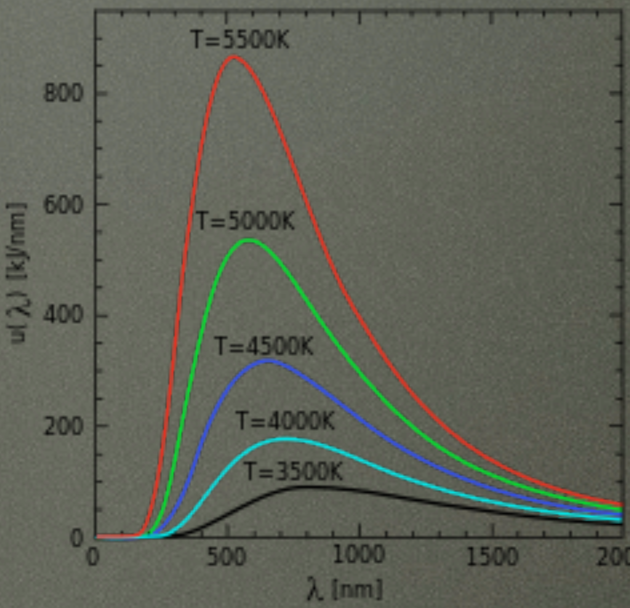
Inverse Square Law describes light observed

- Luminosity (brightness)

$L_{measured}=L_{intrinsic}/d^2$

- For objects where we know $L_{intrinsic}$ we can calculate the distance to the object
- Standard Candle: class of objects that all have roughly the same brightness, allowing us to calculate distance

Measuring Temperature



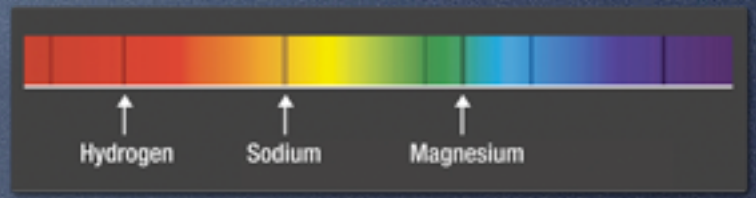
Since stars emit blackbody radiation, measuring the spectrum gives us the temp

Other Indirect Properties

- Size
- Mass
- Composition
- Velocity

Stellar Spectra

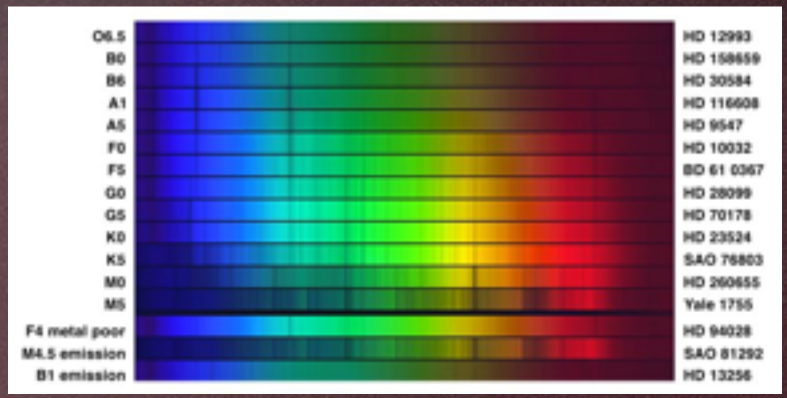
- Stars emit a blackbody spectrum but atoms in their atmospheres absorb some of the spectrum
- Looking at the spectrum tells astronomers what a star's atmosphere is made out of, and how much of that element is present
- Light is the most important tool for an astronomer, almost everything we know about stars comes from studying different aspects of the light they emit/absorb



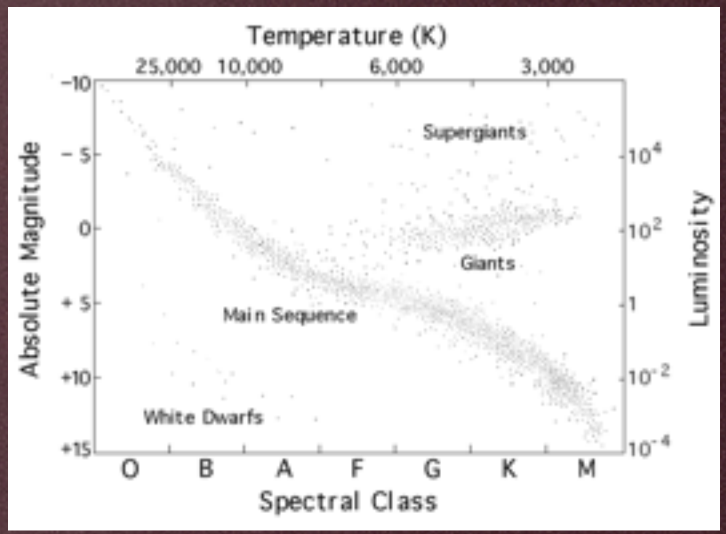
Solar Spectrum

Spectral Class

- Stars are first classified by their spectral type: O,B,A,F,G,K,M
- Plotting spectral class vs luminosity we see a pattern
- The main band is called the main sequence (more on that later)
- The upper right were called giants
- The lower left were called dwarfs
- Also note that there are more M stars, and the multiplicity decreases as we go from M to O
- In the next few videos we will see that both mass and surface temp are related to spectral class, which will define how a particular star evolves



Spectral Class



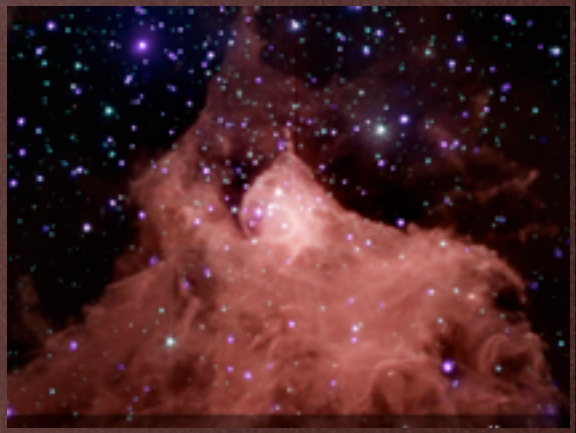
HR Diagram

Forming a Protostar

- Last week we looked at the formation of a star and planets, focusing on the planets and disk
- Today we focus on what was happening to the star

Stellar Nursery's: Molecular Clouds

- Molecular clouds range in size from 1 parsec (roughly the distance to the nearest star or ≈200,000 times the distance from the earth to the sun) to 100 parsecs
- Enough gas to make millions of stars
- Density ranges from 10^6 atoms/cm^3 (roughly a hundred, million, trillion times less dense than Earth's atmosphere) down to just a few
- Composition: molecular H_2 with a smaller percentage of other gases (CO, H_2O, ethanol,etc)
- Dense cores have enough material to form a single star



Molecular Cloud
- violet dots are newly forming stars

Gravitational Collapse

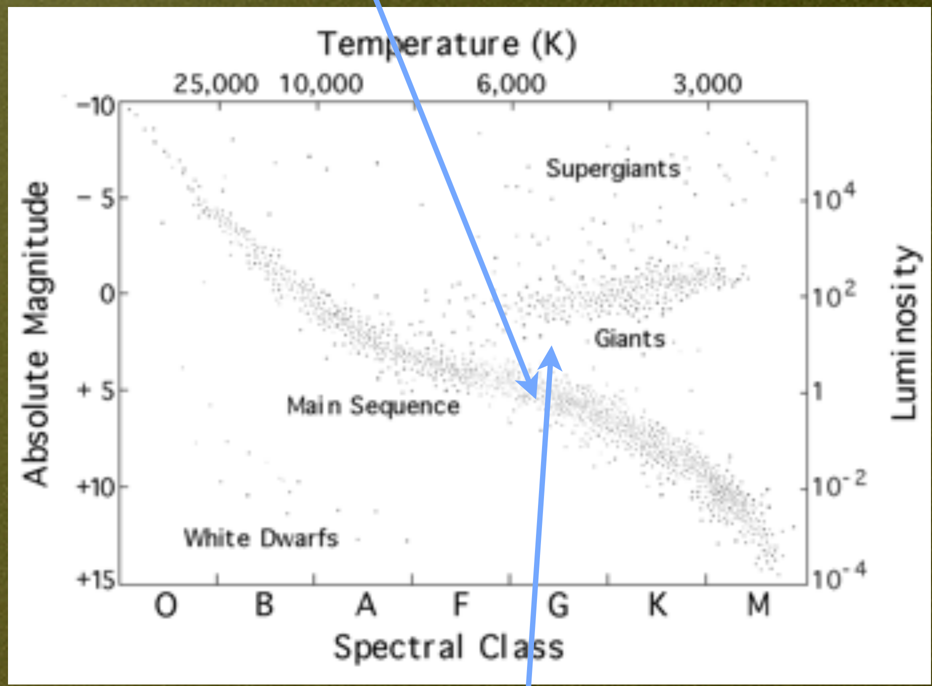
- In a core, eventually self gravity>outward pressure (heat, magnetic fields, turbulence) and the core collapses on itself
- Conservation of energy: contraction→heat(remember last week)
- heat is radiated away
- Free-fall time depends on mass

sun:≈1 million years

Protostar

- Dense gas begins to trap photons and heat
- pressure builds up to slow collapse
- Protostar-when free-fall ends
- Star continues to contract and give off heat (remember gas giants)
- No fusion yet
- Given enough time a (massive enough) star will begin fusion (M>.08Msun)

Star on the main sequence



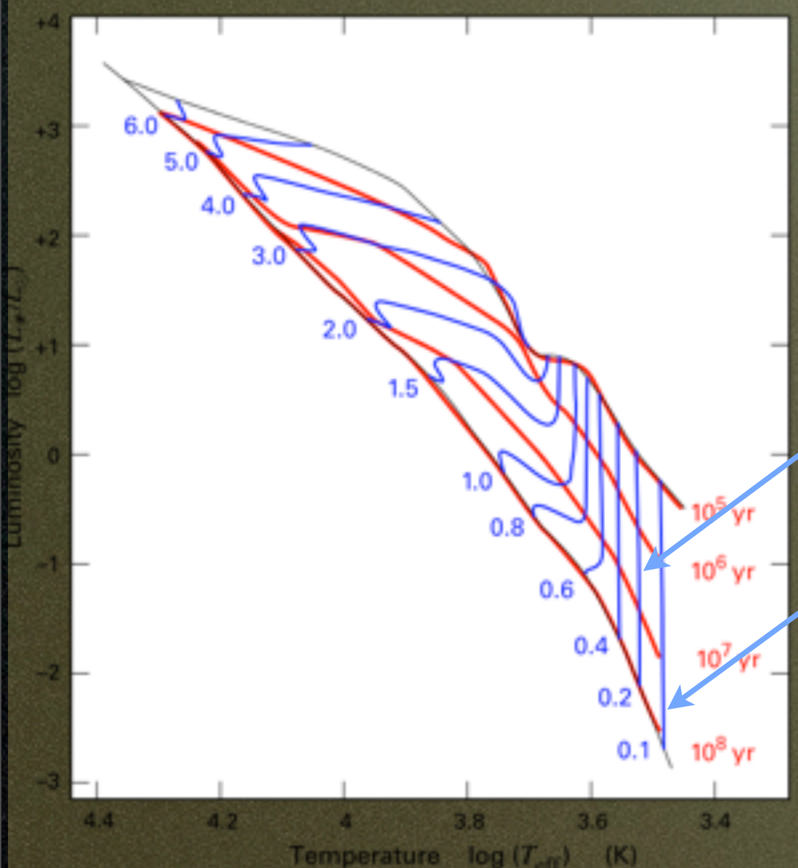
HR Diagram

Approximate location of protostar on the HR diagram

Brown Dwarfs and Very Low Mass Stars

Evolutionary Tracks

- Stellar evolution depends primarily on mass
- Stellar evolution happens on scales of millions or billions of years
- We use computer simulations to model the evolution of stars that MATCHES OBSERVATIONS
- Doesn't work well for very low mass stars (<.1M_{sun})

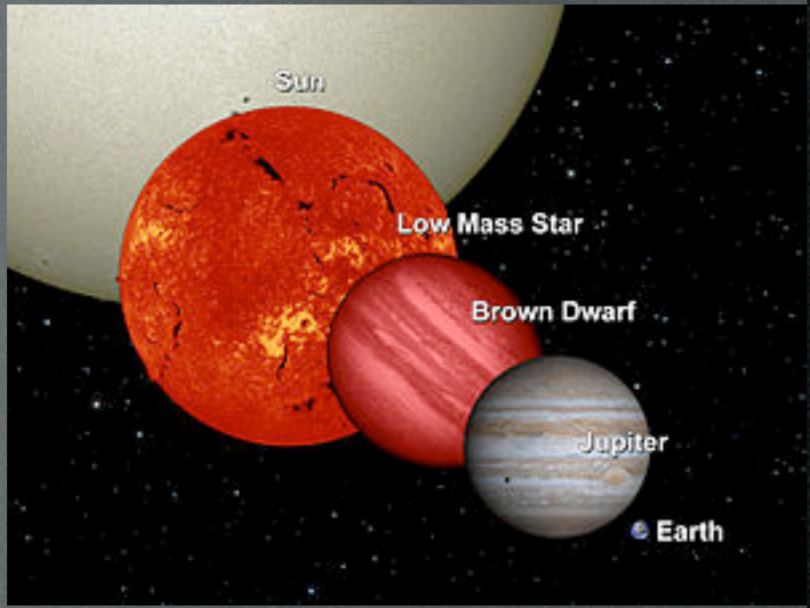


PMS evolution tracks on HR diagram

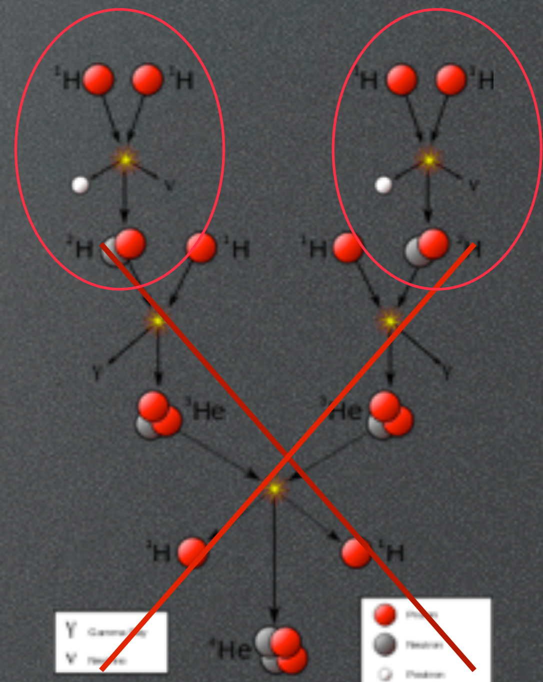
Hayashi Track

- Protostar collapses at roughly const temp before fusion begins
- Notice how different PMS is for different mass stars

Brown Dwarfs



- Anything < .01 M_{sun} lacks the temp and pressure to fuse deuterium and is considered a planet (this line is more fuzzy than it might seem)

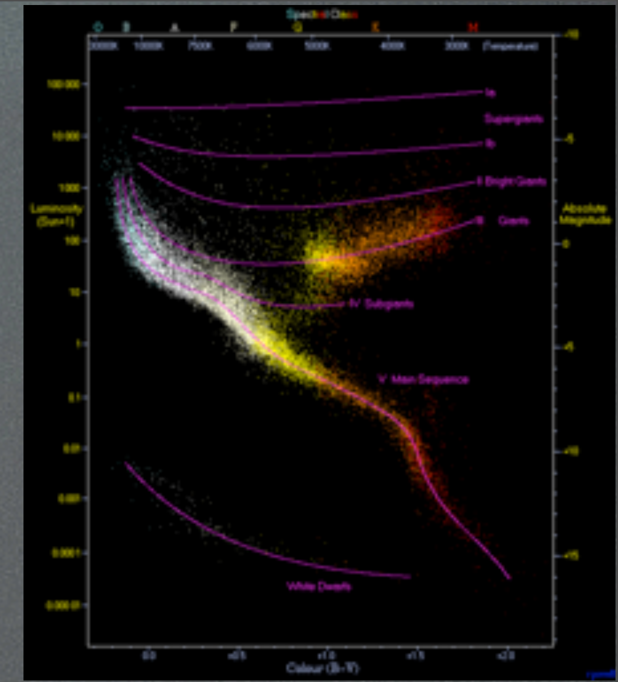


- Brown Dwarf: Stars < .08 M_{sun} that lack the temp and pressure to fuse He

- An estimated 100 billion Brown Dwarfs are in the galaxy (equalling the estimated number of stars)
- Brown Dwarf die as unimpressively as they live, faing slowly over hundreds of millions of years (check)

The Main Sequence

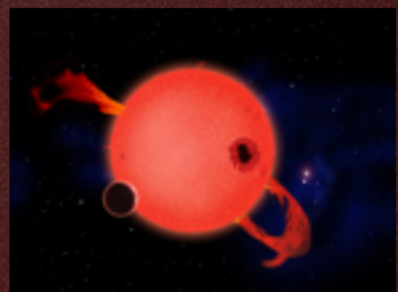
- The only difference between a protostar and a star is time...eventually the temp and pressure in the core are high enough to fuse He and a true star is born
- Main Sequence: H burning phase
- Time on MS depends on mass:
    - O star ≈ a few million years
    - Solar mass stars≈10 billion years
    - Very low mass stars (≈.1 M_{sun}) ≈trillions of years?
- Why the difference: Higher mass stars= higher temp and pressure=burn through fuel faster (like a car moving at 100 mph vs a car at 10mph)



HR Diagram

Very Low Mass Stars (.075 M_{sun}-.25 M_{sun})

- Modeling suggests they are fully convective (i.e. the core is constantly replaced with new H fuel as it is fused into He)
- Roughly 1/10,000 as bright as our sun
- No red dwarfs have ever left the main sequence (so none have ever died)



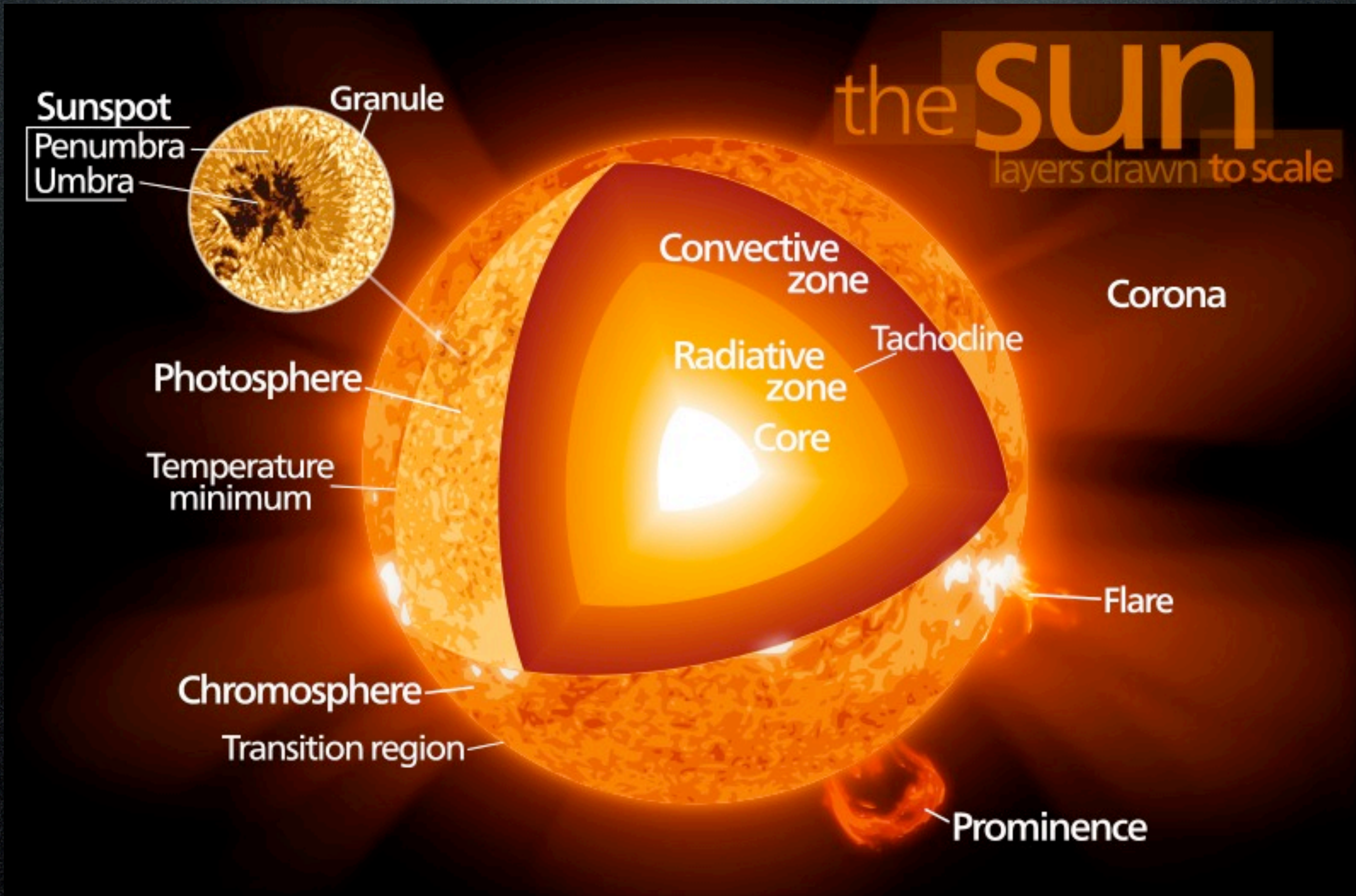
Red Dwarf

Answering This Weeks Question

- We have now answered the question for Brown Dwarfs and very low mass stars: They don't live forever but Red Dwarfs last longer than the current age of the universe. Not bad for the smallest kids on the block

The Structure of the Nearest G2 Main Sequence Star

Solar Structure



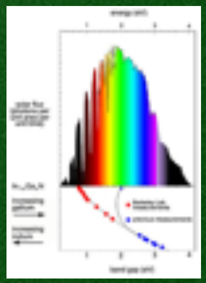
Layer	Thickness	Density	Temperature
Core	150,000 km	160 g/cm^3	Up to 16 million K
Radiative Zone	350,000 km	20 g/cm^3-.2 g/cm^3	7 million - 2 million K
Convective Zone	196,000 km	.2 g/cm^3	2 million - 5700 K
Photosphere	100 km	.37 density at sea level	5700 K
Chromosphere	2000 km	10^{-8} Earths atmosphere	41000 K
Corona	5 million km	10^{-12} Earths atm	1 million K

Core

- Nuclear furnace with ionized H and He

Photosphere

- Where the blackbody spectrum of the sun is emitted



Solar spectrum

Chromosphere

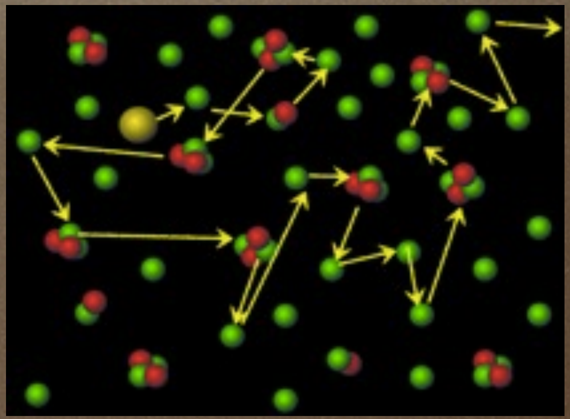
- Lower layer of solar atmosphere

Corona

- Outer layer of solar atmosphere

Radiative Zone

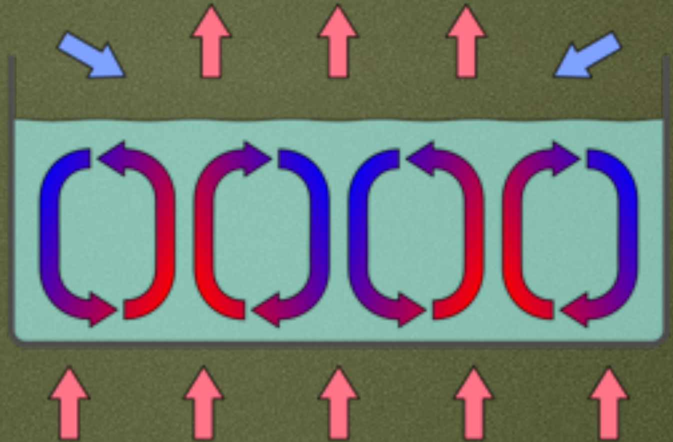
- Radiative energy transport
- Photons scatter off densely packed plasma interior: takes 10's of thousands to 10's of millions of years to exit radiative zone
- Photons also lose energy and multiply as they exit



Random Walk

Convective Zone

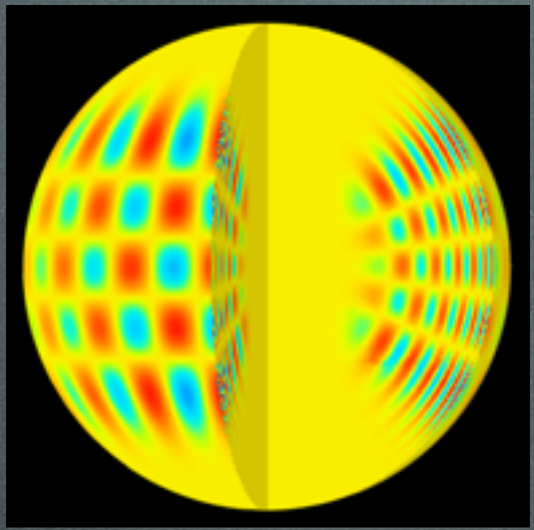
- Convective energy transport (like boiling water)
- Photons absorbed by the H and He atoms
- Causes the gas to move around



Convection currents

Solar Granulation shows us convection (click for video)

How do we know about the inner layers?



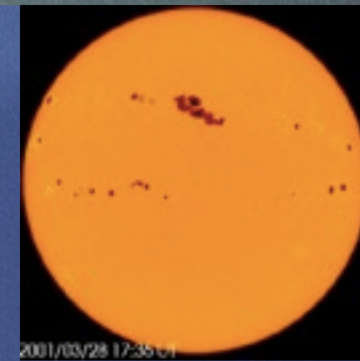
Helioseismology helps us understand the internal structure of the sun

Solar Magnetic Features

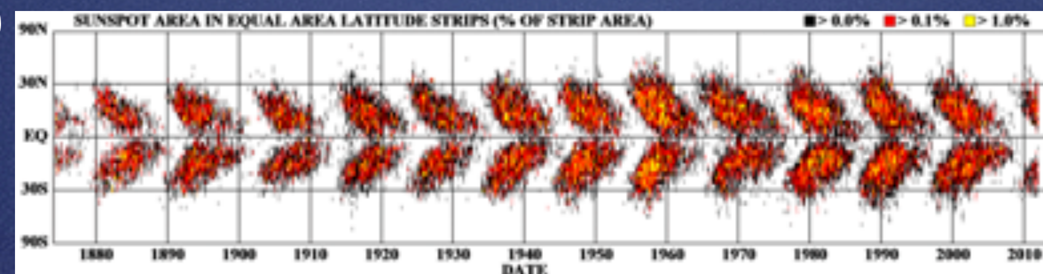
Click for lots of good solar videos

Sun Spots

- Dark, planet sized regions (typically twice Earth's radius
- Darkness due to cool gas in umbra
- Caused by giant columns of magnetic field
- The number and location of sun spots varies (11 year sunspot cycle)



Sunspots
(click for video)

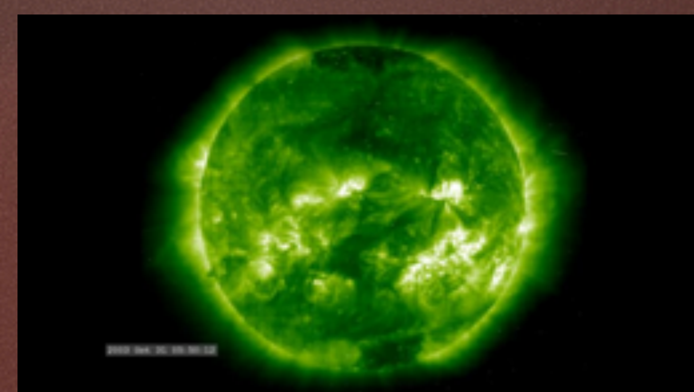


Solar cycle

Prominences

- Giant arcs of magnetism anchored in the photosphere

- Charged particles and plasma travel through the arcs

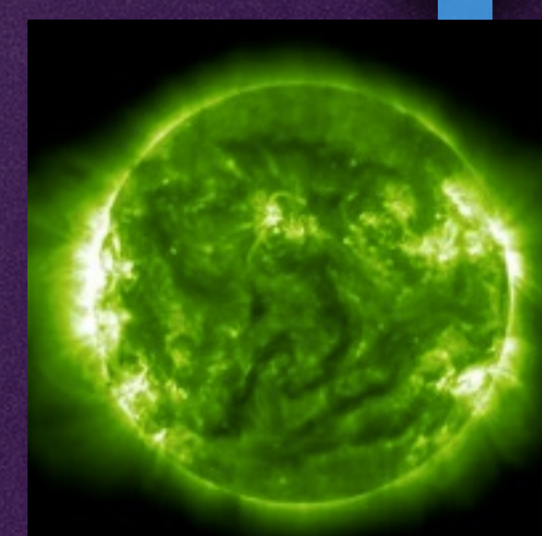


Prominence (click for video)

Solar Flares

- Due to magnetic reconnection
- Energy: 1 million times more powerful than a volcanic eruption
- Energy spans a wide range of wavelengths including UV and X-ray

This video shows an animation of reconnection and a close up of an actual event



Flares video

Coronal Mass Ejections

- Very powerful flares

- typical: 10 billion kg plasma ejected

- energy of 220 aircraft carriers moving at 500 km/s

CME

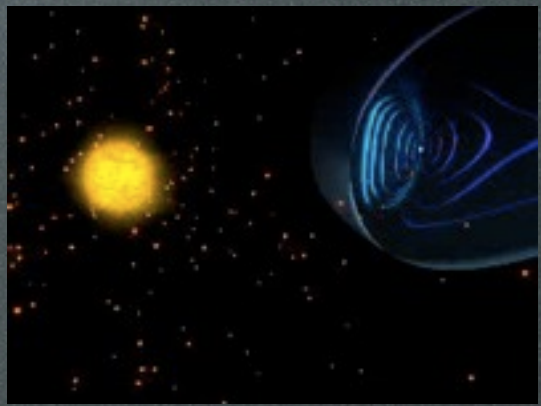
Solar Dynamo

- Magnetic field caused by circulating plasma
- Differential rotation causes twisting, poles reverse much more quickly
- Explains why sunspots in the north are matched with those in the south
- Eventually shorts itself out... leading to the solar cycle

Twisting magnetic field video

Solar Wind

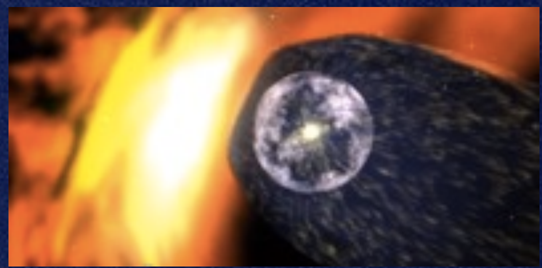
- A continuous stream of 1 million tons of particles are thrown into space every second
- Speeds 200 to 500 km/s (≈1 million miles per hour)
- Due to magnetic field
- 6 particles per cm^3



Solar Winds Video

Heliosphere

- Bubble created by the suns magnetic field and solar winds, protecting us from some interstellar particles
- Voyager 1 + 2, launched in the 1970's reached the heliopause in the early 2000's



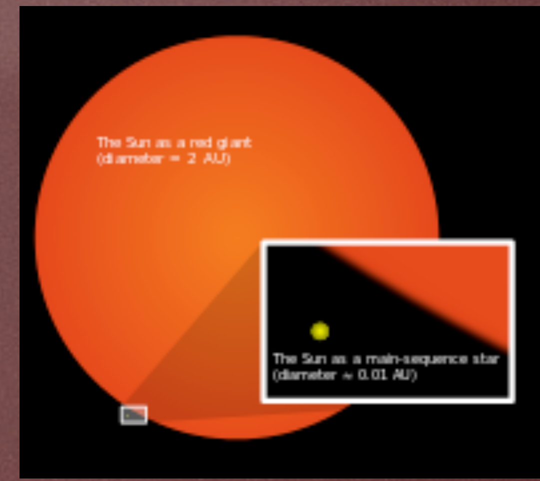
Heliosphere video

Red Giants and Planetary Nebulae

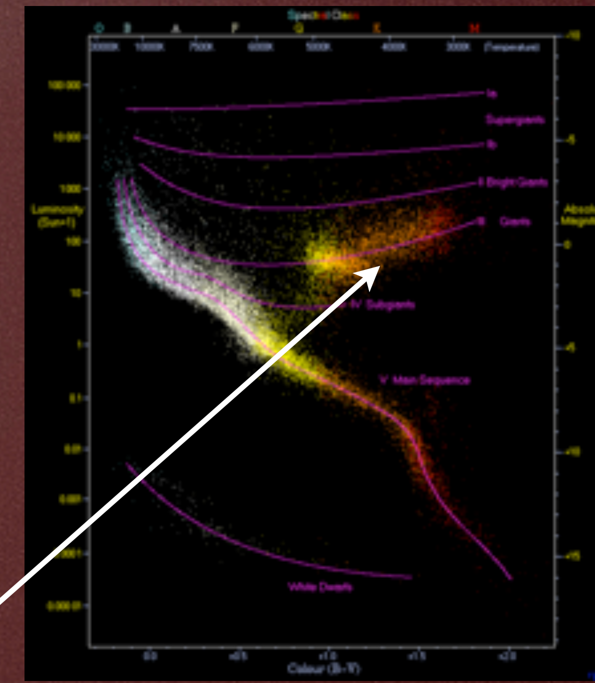
The beginning of the Post Main Sequence

Red Giant Phase

- Eventually a large enough star ($M>.25M_{sun}$) will burn most of the H in its core
- Still has H shell surrounding the (now) He core
- The inner region of the star contracts, creating heat that drives fusion in the H shell
- As the core contracts, the outer layers swell, the surface temp decreases and the luminosity increases
- This phase lasts 100's millions to billions of yr



The sun as a red giant


Giant Stars

HR Diagram

Helium Flash (.8-2.25 M_{sun})

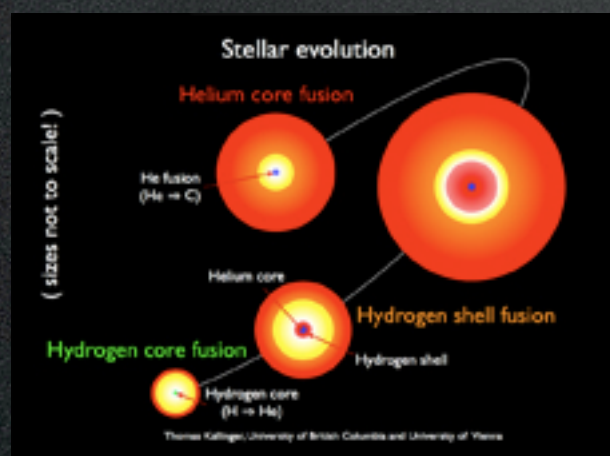
- The core of the star collapses again, igniting He fusion in the core
- Higher mass stars begin to burn He while H shell is still fusing

Helium Burning

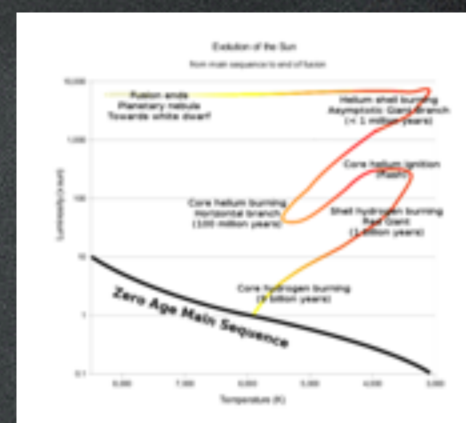
- Second stable phase
- Lasts millions to 10's millions of yr
- Fusion of 3 He's into C
- Much of the C in the universe formed inside stars

Helium Shell Burning

- Star is left with a C core and He shell
- Contraction allows He shell to burn and size of the star increases (again)



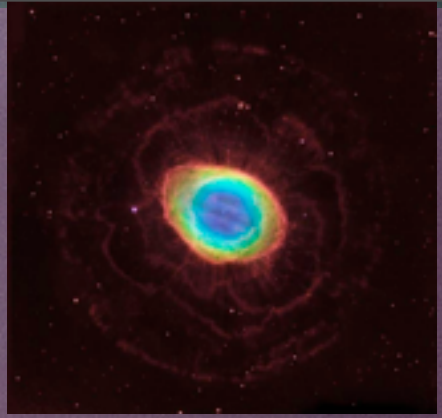
Post MS



Post MS track

Planetary Nebulae

- Outer atmosphere of red giants are very thin
- Excessive solar winds due to shell burning in RG and AGB phases blows atmosphere into ISM
- Our sun will lose up to 1/2 M_{sun} in these phases
- Includes higher elements biproducts (C, N, O) that will mix with next generation of stars
- Result: Planetary Nebula
- Exact creation method unknown:
  - Shock Waves Theory
  - Accretion Disk Theory



Ring Nebula

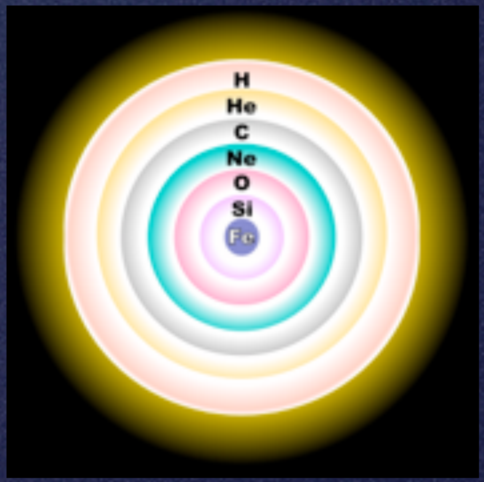
Butterfly Nebula

Bow-Tie Nebula

Cat's Eye Nebula

Massive Stars ($M>25M_{sun}$)

- Stars with $M<8M_{sun}$ cannot fuse C, but...
- Stars can have masses greater than 100 M_{sun}
- Lifetime measured in millions (not tens of billions) of yr
- After H is gone, He burning lasts only 100k yr
- Swells to a red super giant
- Has enough temp+press to fuse C into Ne
- Then Ne to O, O to Si
- Burns Si to Fe core for less than a day
- Star has an onion like structure
- Fe is most bound structure, fusion stops here



Not to scale

White Dwarfs

The corpses of long dead stars

A Little More Quantum Mechanics

Heisenberg Uncertainty Principle

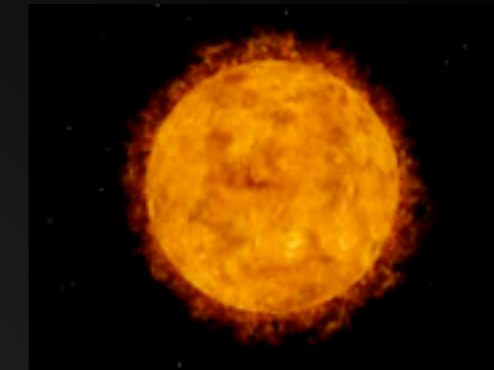
- One of the strange results of Qm
- $\Delta x \Delta P = \hbar/2$
- One consequence: Confining particles to increasingly smaller spaces means they can have greater ranges in velocity

Pauli Exclusion Principle

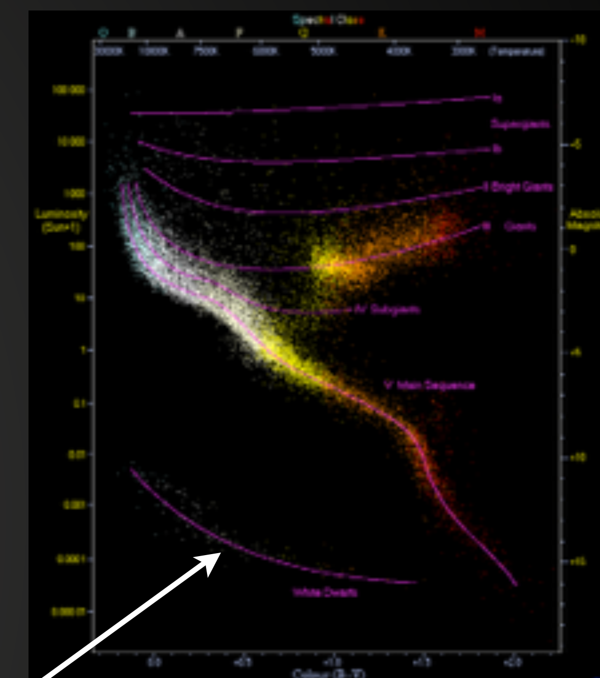
- QM describes 2 classes of particles: fermions and bosons
- fermions: quarks (more on this in week 4), protons, neutrons, electrons, etc.
- bosons: photons, gravitons, certain bound states of fermions
- Pauli Exclusion: 2 fermions cannot be in the same state in the same place at the same time
- Seems obvious but consider photons:
    - two beams of light crossing each other pass through one another without interacting at all!
    - we can have as many photons in the same place at the exact same time as we want
    - the same is true for bound fermions in states that are Bosons (this has to do with quantum spin, which is beyond the scope of this class)!

White Dwarfs

- Fusion is finished. The atmosphere has been blown away. A core of mostly C remains. Now what?
- Gravity will continue to contract star but forever…
- No, we need QM to explain why
- Electron degeneracy Pressure:
  - Since e^- cannot be in the same state or the same place, they push back against the force of gravity
- Only true for stars with cores $M<1.4M_{sun}$ (core mass $M<8M_{sun}$)
- Our sun will have ≈ 1/2 M_{sun} and will be about the size of Earth!
- Initial surface temp ≈100,000K
- Over billions of yr the star cools and ceases to emit radiation
- Becomes a black dwarf, the cinders of a low-mid mass star



The sun as a white dwarf



white dwarfs

HR Diagram

Answering the Question

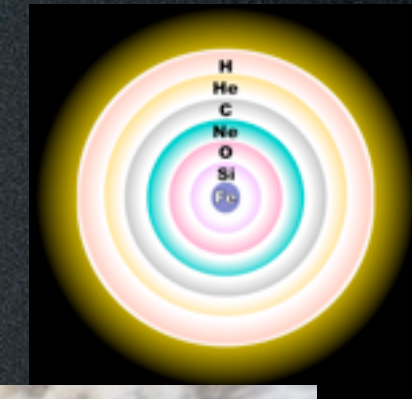
- We have now seen that low-mid mass stars do not live forever, and in fact have an unexpected end that couldn't be explained without QM
- For high mass stars, the end becomes even stranger

Supernova and Neutron Stars

Where we left off

- When we last left our massive star it had an Fe core with shells of increasingly smaller atoms and a single day of Si fusion
- At this point an $8M_{sun}$ star is left with $\approx 1.5M_{sun}$ Fe core

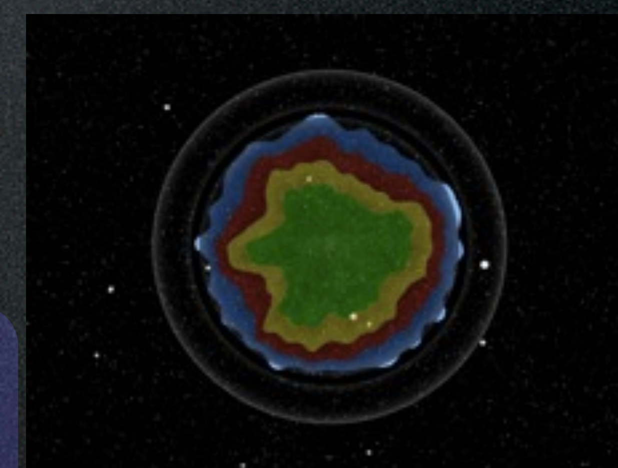
Star



Core Collapse

- Instead of millions of years, the star now evolves in milli-seconds
- Core collapses at 1/3 c and radiates very low mass non-interacting particles called neutrinos (more on those later in the course)
- Neutrino radiation exceeds the radiation from the rest of the observable universe
- In time<1s the Fe core collapses until nuclear forces prevent further collapse

Supernova video



Supernova video

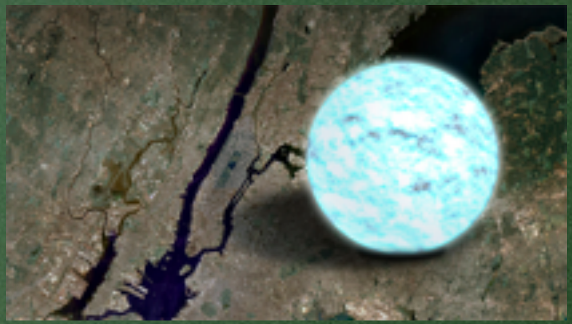
Supernova

- The collapsing star crashes into the impenetrable core until a shock wave is blasted away from the core
- Still uncertain as to exactly how this happens
- Material blown away at 10,000 km/s
- Shockwaves leave behind a supernova remnant of gas 100 light years or more
- Every element larger than Fe in the universe was created by supernovas

Supernova Remnant

Neutron Star (core 1.5 M_{sun}<M<2.1 M_{sun})

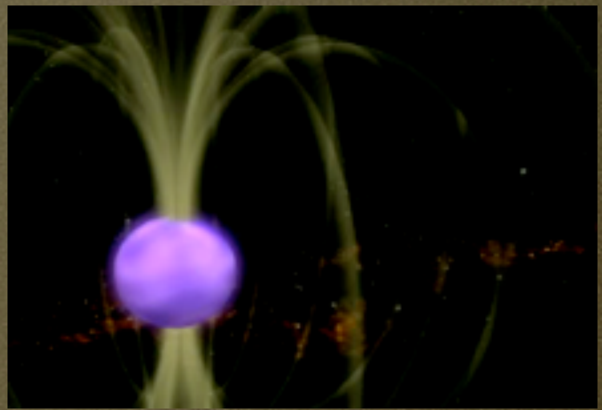
- Once again mass determines what will happen in the next phase of the stars life
- During the supernova protons and electrons are squeezed together into neutrons
- Gravity causes the remnant of the star to collapse, with only the neutron degeneracy pressure to stop it
- The core is now the density of the nucleus of an atom
- A tsp of neutron star is more than 1 billion tons!



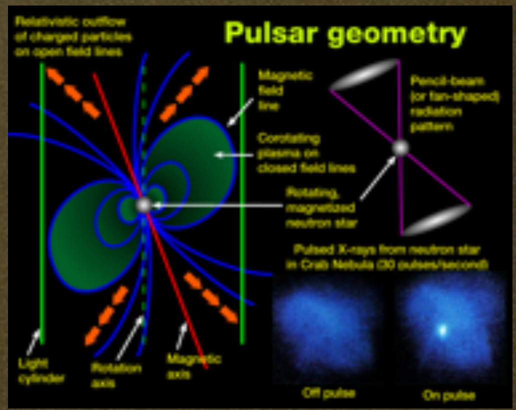
A 1/2 million M_{earth} neutron star would be about 12 miles wide

Pulsar

- Even a slowly rotating MS star will be rapidly rotating by the time it shrinks to the size of a neutron star
- Neutron star 20 km in size (M_{sun}) will rotate 100 times per second!
- Causes tremendous magnetic (1 trillion times Earth's) fields and detectable signals when the magnetic axis and rotation axis are different



Pulsar magnetic field

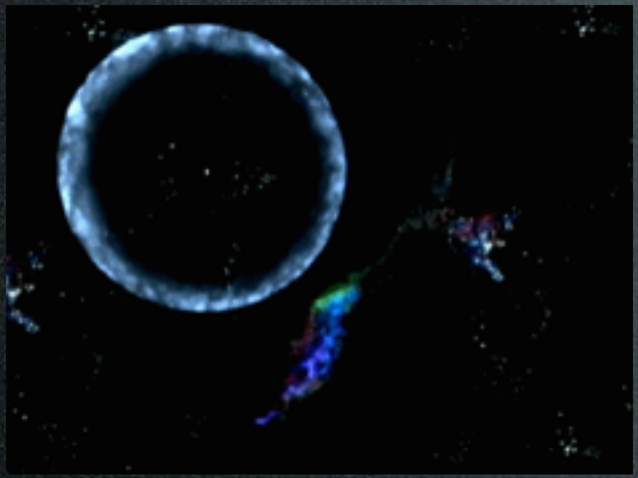


Pulsar Geometry

Next Time

- We have now seen the end of massive stars, but what about VERY massive stars (perhaps 30 M_{sun}) or more?
- Before we answer that, we must learn about one of the most famous theories in all of physics: relativity

More Supernova videos

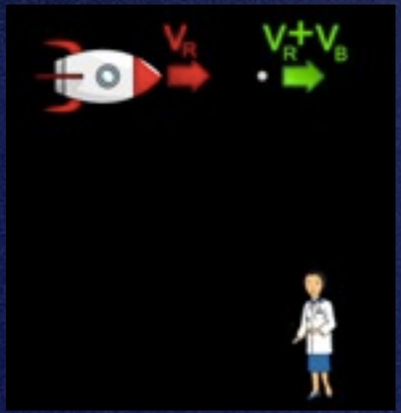


Supernova lighting
Earths atmosphere

Frames of Reference

Frames of Reference

- Imagine a rocket traveling through space with a speed v_R
- To an observer on the rocket, the ship isn't moving at all (pause to let viewer think about this)
- But a person at rest on the ground would seem to move toward the rocket observer with a speed v_R
- If the rocket launches a pellet, the observer on the rocket will see the pellet traveling with a speed v_B



- From the perspective of a person at rest on the ground, the rocket is moving with a speed v_R
- When the rocket launches a pellet, the observer on the ground sees the pellet moving with a speed $v_R + v_B$

- This is a general rule about frames of reference
- Observers see themselves at rest and see everything is moving relative to them
- Two observers in different frames of reference will disagree on the speed of an object due to the difference in the motions of the reference frames
- For now assume that each frame of reference is an "inertial" frame, meaning that it is moving at a constant speed with no change in direction

Special Relativity

Einstein's Postulates

1. The laws of physics are the same in all inertial frames of reference

- This means that if you are on a rocket in space moving with a constant speed and direction, there is no experiment that you can perform to know that you are moving
- In other words, every inertial observer can argue he/she is at rest while every other observer is in motion, and they are all correct

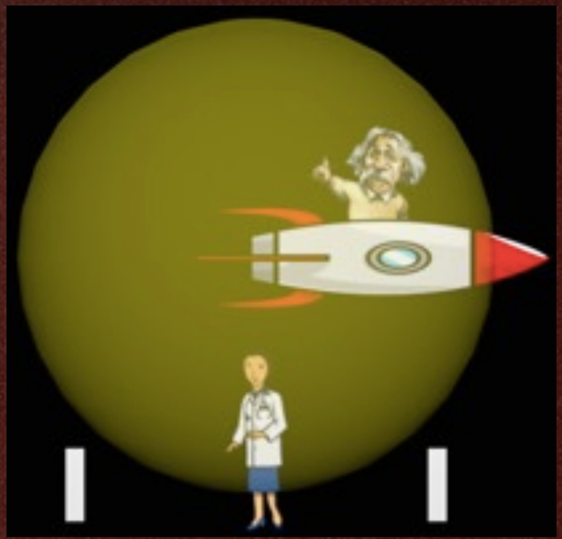
2. The speed of light is the same for all observers

- Unlike the speeds of particles, which we saw move at different speeds depending on the frame of reference, all observers see light moving at the same speed

Example

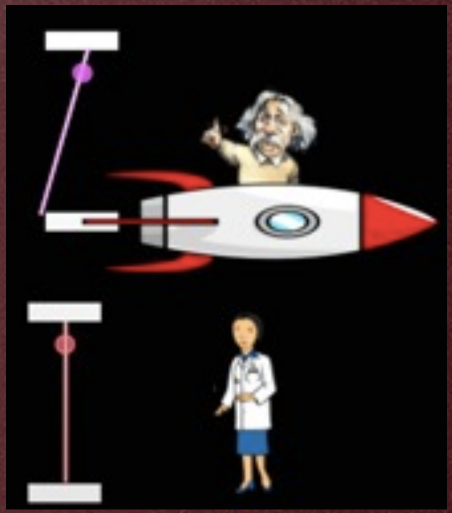
- If a rocket is flying by an observer and emits a pulse of light in all directions, the observer on the rocket will see a spherical pulse moving away at the speed of light c in all directions

- Similarly, the observer at rest on the ground will see the sphere of light expanding from the point it was emitted at the same speed of light
- If the light followed the rocket then the photons on the right would be moving faster than the ones on the left (which was known to be false in the 19th century both from theory and experiment)



Time Dilation

- Think of a simple clock that bounces a pulse of light of a mirror
- To an observer at rest, the light pulse in the rocket clock travels a further distance because it is moving
- Since speed=distance/time=c is the same for both pulses of light, the time must also increase

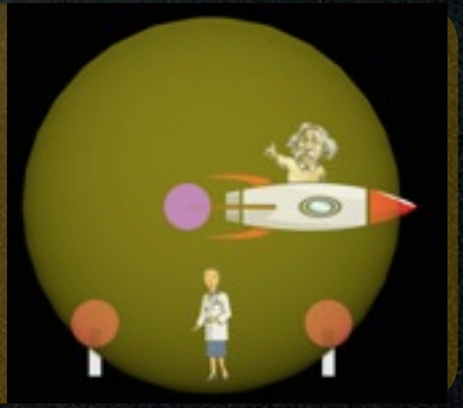


- This means the observer at rest would think the rockets clock is ticking more slowly
- For example: if you travel near the speed of light outside the solar system and back, only a few years might pass for you, but on everyone on earth would age hundreds of years
- Time travel is possible… into the future, you just can’t come back (you would have to travel faster than the speed of light, which violates the known laws of physics)

- The observer on the rocket sees the opposite: in his frame the clock on the ground is moving slower

Simultaneity

- Let’s say the observer on the rocket and the one on the ground have detectors that measure when the light reaches them
- From the rockets point of view, the light hits both of his detectors at the same time, then at a later time hits one ground detector, and at a later time hits another ground detector
- In other words, both detectors in his frame were simultaneous, but both ground detections occurred at different times



- In the rest frame, the observer sees one rocket detector hit, then both of her detectors at the same time, then the other rocket detector hit
- In other words, both of her detectors went off at the same time but both rocket detectors went off at different times

So two observers in different frames of reference will disagree on whether or not two events occurred at the same time!

This has been proven both mathematically and experimentally

General Relativity

General Relativity

Equivalence Principle

- Since gravity causes an object to accelerate, the physics in an accelerating frame is the same as the physics in a gravitational field
- In other words, if you are in a room with no windows then there's no way to know if you are on a rocket accelerating at 9.8 m/s^2 or on the surface of the earth

Consequences

- Imagine a rocket traveling past a beam of light

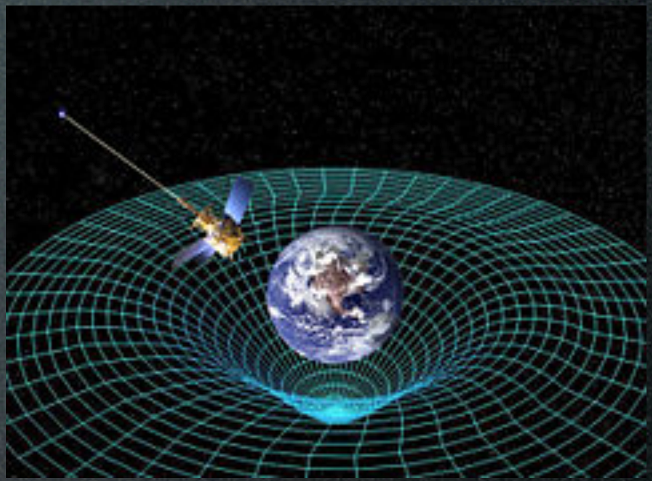
- From the rockets frame, the rocket is stationary but the light is curved

- The equivalence principle tells us that this means a beam of light should curve near the surface of the earth... and it does!
- First experimental evidence was in 1919 during a solar eclipse

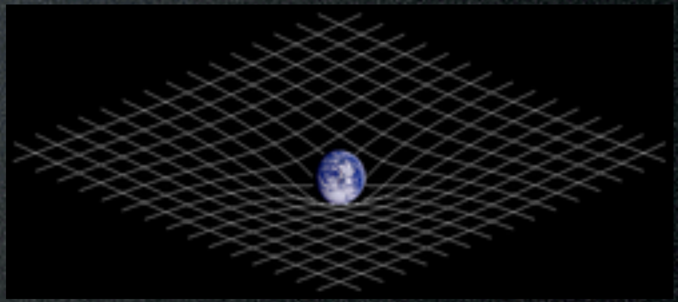
- Clocks tick slower near the surface of a gravitational body than they do further away
- GPS needs to correct for this in order to work properly

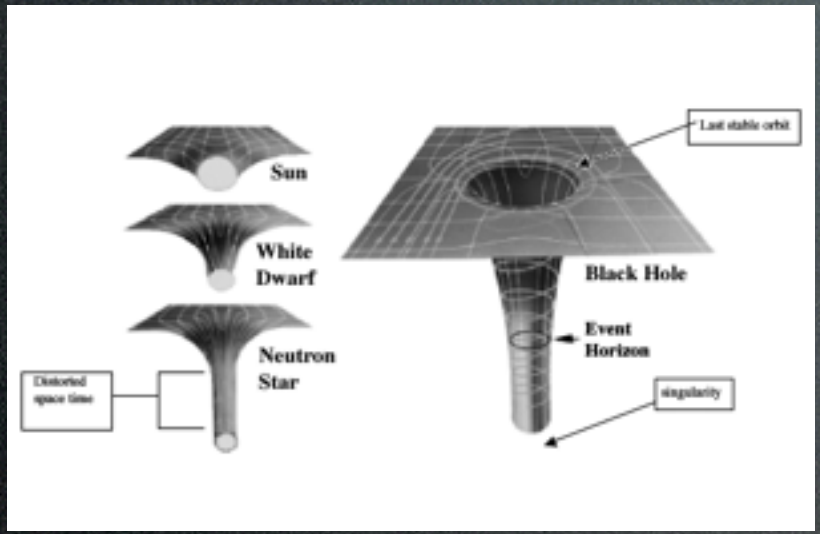
Gravity as Space-Time

- Einstein combined space and time together into one fabric of space-time
- Light travels in straight paths in space time
- This means space-time is warped by objects with gravity
- Heavier objects warp space-time more
- Not a single experiment has ever proven GR wrong



Space-time warped by the earth





space-tme warped by larger objects
(note:don't show BH half in this video, save it for next lecture)

Escape Velocity

Need to create animations for this video.

What is escape velocity?

- Suppose you want to launch something into space
- How fast does it need to be moving to escape the gravity of the earth, or the sun, or any other massive object without falling back?
- Using conservation of energy we find $v_{esc}=\sqrt{2GM/r}$
- In other words: depends on mass and distance to the center of the larger object
- If $v<v_{esc}$, the projectile will fall back to Earth
- If $v=v_{esc}$, the projectile will be in orbit
- If $v>v_{esc}$, the projectile will fly into space forever

Next time: We introduce black holes and see that their escape velocity has some very interesting properties

Black Holes

I need to create more images and animations for this video

Creation

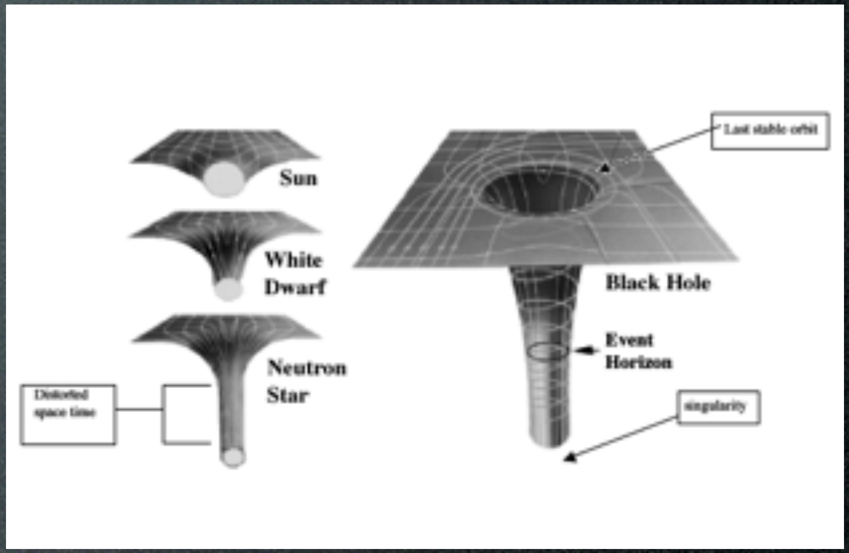
- We saw that $M<8M_{sun}$ stars become white dwarfs and $8M_{sun}<M<20M_{sun}$ stars become neutron stars
- At some (unknown exactly) limit neutron degeneracy can no longer stop gravitational collapse
- A singularity is created at the center

Singularity

- GR: perfectly describes very massive things
- QM: perfectly describes very small things
- Black Hole: very small and very massive...
- GR and QM do not mix: no theory of quantum gravity
- Result: A Black hole appears to be a single point that can store an infinite amount of energy
- More research is needed to fix this problem

Event Horizon

- Distance from the singularity where the escape velocity is greater than the speed of light
- Nothing inside the event horizon can escape the black hole
- For a BH the mass of the sun, R_s=3km (R_{sun} ≈700,000 km)



Space-time around a black hole

Journey into a Black Hole

Need to create videos and images for this lecture

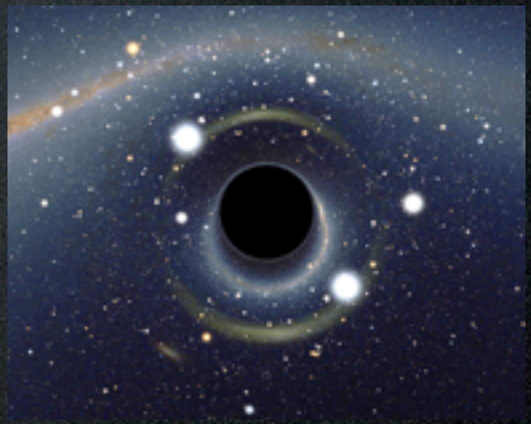
What if we shrink the sun down to R=3km, so it becomes a black hole

What doesn't change?

- At a significant distance from R_s (about $3R_S$), gravity acts on the planets and other solar objects the same
- In other words: NOTHING IS SUCKED INTO THE BLACK HOLE
- The Earth still has the exact same orbit

What does change?

- Besides the obvious (no light, heat, solar winds, or other affects due to fusion, which is no longer happening)
- Anything passing inside about $3R_s$ will have a warped path with no stable orbits possible
- Anything passing inside R_s will be gone from this universe forever
- Space-time is bent so much that we can see objects directly behind the black hole



Warped space

Journey into a Black hole

Scenario

- You begin sufficiently far from a black hole, firing your rockets to keep you at a constant distance
- You have a radio that allows you to communicate with Earth
- You begin to turn down your rockets and drift closer to the BH

What you see

- 1. Gravitational time dilation: observer outside sees your clock moving more slowly
- 2. Gravitational redshift: your radio frequencies are red-shifted
- 3. Until you reach ≈ $3R_s$ you can reverse your boosters to speed up and escape the black hole, after that...
- 4. You are too close to be in a stable orbit
- 5. Tidal forces different from your head to your feet
- 6. You and your ship are pulled into strings of spaghetti
- 7. Time is running so slowly your friend sees you stop at the event horizon (it takes an infinite time for you to get there to the outside world) even thought time moves normally for you
- 8. Inside the event horizon: you are pulled directly into the singularity
- 9. After that: new physics: No one knows

Do Stars Last Forever?

Answering the Question

We saw that the fate of a star depends on its initial mass:

Very Low mass stars:
- Hard to find and not well studied
- Predicted to live trillions of years (at least 100 times longer than the age of the universe)
- They will die, but none have died yet!

Low-mid mass stars (including our sun):
- After puffing out perhaps as far as the Earths orbit, gravitational contraction crushes the star into a white dwarf, with only electron degeneracy balancing gravity

Massive stars
- After fusing elements all the way up to Fe, they explode in a supernova and are left with a compact neutron star, where only neutron degeneracy pressure balances gravity

Very massive stars
- Same as massive stars, only not even neutron degeneracy can stop gravitational collapse and they are crushed into black holes, one of the most exotic known objects in the cosmos