Radiation, luminosity, and effective temperature

04 December 2018 14:29

Star is split into multiple sections based on transport process:

- 0-Radius/4 is the core - fusion occurs
- Radius/4 - 0.8*radius - radiation zone, energy transferred by radiation
- Radius/4 - R - convection zone, energy transfered by convection.
- Solar atmosphere = photosphere + chromosphere + corona

How do we find out properties of stars? We look at the spectrum of light - stellar spectroscopy

- Photons travel as packets of energy
- Newton found white light is made up of mix of all colours of photons
- Different type of photos have different wave length:
  - Wavelength around 1m = radio waves
  - Wavelength around 1mm = microwave
  - Wavelength around 1um (10^-6m) = infrared
  - Wavelength about 500nm = visible light
  - Wavelength around 100nm = uv
  - Wavelength around 1nm = xray
  - Wavelength around 10^-3nm = gamma
    - X-ray come from electron interactions i.e hight temp
    - Gamma comes from nucleus - radioactive decay
- X-rays, gamma, and high energy UV blocked by atmosphere. Some infrared and microwave blocked. Radio can penetrate.
- To detect gamma, x-ray, uv, and microwave we use satellites.
- Visible light and radio can be detected by telescopes/dishes on earth.

We treat stars as black body

- Perfect absorber (opaque)
- Perfect emitter
  - Emits all radiation it absorbs
  - Stays constant temperature
- Black body equation found by treating light as photons (from wavelength)

$$\boxed{I(\lambda) = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT} - 1}\right]}$$

- We can also express this equation in terms of frequency

$$\boxed{I(\nu) = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT} - 1}\right]}$$

- It is possible to convert between the equation in terms of wavelength to the equation in terms of frequency. However you cannot simply substitute. These two equations talk about the same thing, so their area must be equal, therefore:

$$\int \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{\frac{hc}{\lambda kT}}-1}\right]d\lambda = \int \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{\frac{hc}{\lambda kT}}-1}\right]d\nu$$

$$c = \lambda\nu$$
$$\lambda = \frac{c}{\nu}$$
$$\frac{d}{d\nu}(\lambda) = -\frac{c}{\nu^2}$$

We take the absolute value

$$\frac{d\lambda}{d\nu} = \frac{c}{\nu^2}$$
$$d\lambda = \frac{c}{\nu^2}d\nu$$

$$I(\nu) = \frac{2hc^2}{(\frac{c}{\nu})^5}\left[\frac{1}{e^{\frac{hc}{\frac{c}{\nu}kT}}-1}\right]\frac{c}{\nu^2}$$

$$I(\nu) = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{\frac{h\nu}{kT}}-1}\right]$$

We can then use Wien's displacement law, which is found by setting the rate of change to 0. This finds a turning point in the curve. It is as such:

$$\boxed{\lambda_{\max} \approx \frac{3\times10^{-3}}{T}}$$

$$\boxed{\nu_{\max} \approx 10^{11}T}$$

We use these equations to find the effective temperature of a star:

The temperature of a perfect blackbody emitting the same light the star does.

The only things we can easily observe from a star are it's distance and brightness. With these we can find:

- Luminosity
- Mass
- Temperature
- Size

We can use the distance and the brightness of a star to find it's luminosity, as brightness decreases with distance.

When we know the luminosity, we can find the stars size.

$$L = flux \bullet Area = \sigma T^4 \bullet 4\pi r^2$$

$$flux = \sigma T^4$$

$\sigma = 5.67\times10^{-8}\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-4}}$

(Stephan's constant)

We can find the size of the star:

We know the luminosity based off the distance and brightness

We can find it's temperature by looking at the peak wavelength

Stellar spectra and classification

04 December 2018 15:30

Spectroscopy

3 types of spectra:

- Continuous: spectrum of all wavelengths.
    - Any hot solid, liquid, or dense gas will produce a thermal spectrum
    - (Kirchhof's 1st law)
- Emission line spectrum:
    - A thin/low density cloud of gas emits light based on it's composition and temperature.
    - Produces spectrum with bright emission lines
    - (Kirchhof's 2nd law)
- Absorption Line Spectrum:
    - A cloud of gas between the observer and a continuous spectra (i.e, a star) absorbs light of specific wavelength
    - (Kirchhof's 3rd law)

Emission and absorption lines come from electron transitions in atoms:

- Only set values are allowed
- This releases/absorbs photons of only set energy.
- Energy is proportional to wavelength, so set energy = set wavelength

Emission Nebula:

- A star's continuous spectrum hits a nebula.
    - Optically thin nebula, most light passes through
    - Optically thick nebula, light at this wavelength is absorbed then re-emitted in random direction.
    - We can find composition of nebula by seeing what light passes through/what emitted light we see.

Sources of absorption lines:

- Stellar atmospheres
- Interstellar gas
- Intergalactic gas clouds

Doppler effect

Fundamental importance

Wavelength of light is stretched/compressed if object emitting it is travelling away/towards us.

$$\boxed{\frac{(\lambda - \lambda_0)}{\lambda_0} \equiv \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

λ = observed wavelength

λ_0 = 'rest' wavelength

v = source's radial velocity

If V>0, the emitter is moving away (redshift)

If V<0, the emitter is moving towards (blueshift)

Astronomical redshift is defined as z=v/c

We can use doppler effect to find the orbit of a star around it's systems centre of mass

- i.e, prove a planet orbits the star
- Find speed of distance galaxy's relative to us
- Find rotational speed of galaxies.

Stellar Classification

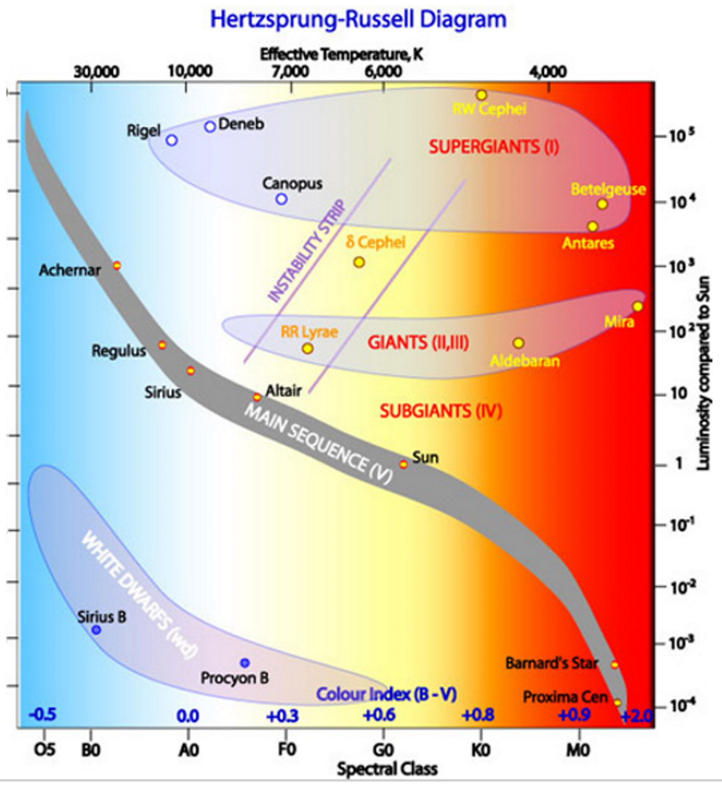
Spectral class	Colour	Surface temp (K)
O	Blue-violet	30000-50000
B	Blue-white	11000-30000
A	White	7500-11000
F	Yellow-white	6000-7500
G	Yellow	5000-6000
K	Orange	4000-5000
M	Red-orange	<4000

We also use a number, 0-9, to state the hottest-coldest stars in each classification: 0 is hottest, 9 is coolest.

However, a stars temperature isn't the only important this, it's size is too. So we use Luminosity classes to define stars better:

Ia = Most luminous supergiants
Ib = Supergiants
II = Luminous giants
III = Giants
IV = Subgiants
V = Main sequence stars (dwarfs)

Stars exist in stable areas between which they transition. We can use a Hertzsprung-Russel Diagram to show this:



Stellar evolution and life of a star

04 December 2018 15:52

Stars are not eternal

The gravity from the mass of a star pulls everything in.
The pressure from heat from fusion pushes everything out.
This is called Hydrostatic equilibrium
The force from pressure at any radius is balanced with the gravity at that radius.

The pressure comes from the heat generated in the core by fusion
Fusion works by colliding 4 protons to form an He nucleus.
There is a slight difference in mass
E=mc^2 - therefore mass decreases slightly and energy is produced.

In fusion:
Electromagnetic forces keep atoms apart
Thanks to quantum tunnelling they can come close enough to overcome electrostatic repulsion. Strong force then takes over and binds them.

Chance of 4 protons fusion at once is very unlikely, instead:

PPI Chain	PPII Chain	PPIII Chain
1 $p + p \rightarrow d + e^+ + \nu_e$	3' $^3He + {}^4He \rightarrow {}^7Be + \gamma$	4" $^7Be + p \rightarrow {}^8B + \gamma$
2 $d + p \rightarrow {}^3He + \gamma$	4' $^7Be + e^- \rightarrow {}^7Li + \nu_e$	5" $^8B \rightarrow {}^8Be + e^+ + \nu_e$
3 $^3He + {}^3He \rightarrow {}^4He + 2p$	5' $^7Li + p \rightarrow {}^4He + {}^4He$	6" $^8Be \rightarrow 2{}^4He$

PP1 is most dominant

Neutrinos don't interact with matter, so pass directly out of star
Only a small amount of energy is lost to neutrinos
There are 3 flavours of neutrinos.
Sun only produces electron neutrinos
Solar Neutrino problem:
When these calculations were made, we found that there was 1/3 times the amount of electron neutrinos reaching earth as expected.
Turns out, neutrinos switch between each flavour - neutrino oscillations.

Heavy element production

When the temperature is high enough (larger stars or death of star) heavier elements can fuse:

$$^4He + {}^4He \rightarrow {}^8Be$$
$$^8Be + {}^4He \rightarrow {}^{12}C + \gamma$$

$$\begin{aligned} {}^{12}C + {}^{12}C &\rightarrow {}^{24}Mg + \gamma \\ &\rightarrow {}^{23}Mg + n \\ &\rightarrow {}^{23}Na + p \\ &\rightarrow {}^{20}Ne + \alpha \\ &\rightarrow {}^{16}O + 2\alpha \end{aligned}$$

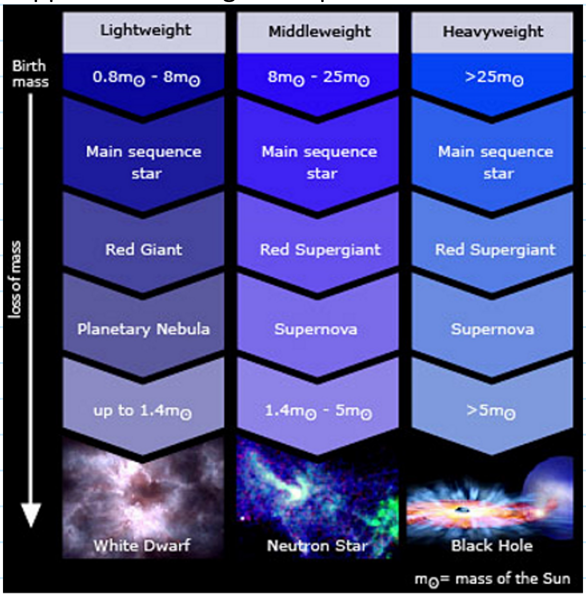
$$\begin{aligned} {}^{16}O + {}^{16}O &\rightarrow {}^{32}S + \gamma \\ &\rightarrow {}^{31}S + n \\ &\rightarrow {}^{31}P + p \\ &\rightarrow {}^{28}Si + \alpha \\ &\rightarrow {}^{24}Mg + 2\alpha \end{aligned}$$

Life of stars

Life span depends on mass:
A high mass star has stronger gravity.
Therefore needs more pressure to keep stable.
Therefore higher internal temperature
More rapid fusion

Greater luminosity
Shorter life span.
Life span relative to ratio between available fuel and luminosity
Stellar evolution:
Proto-star
Large gas cloud and dust, starts to collapse on self
Not dense enough for any pressure, particles in free fall
Pre-Main sequence (PMS)
Density of cloud increases
Starts to become opaque
Collisions produce heat which is trapped
Trapped heat creates pressure, slows down collapse
Hydrostatic equilibrium from heat from friction
Main sequence (MS)
Core gets hot enough that it starts to fuse Hydrogen.
Now in hydrostatic equilibrium
This phase lasts as long as the core burns.
Post-Main sequence
After hydrogen in core is used up, it shrinks.
Increases the temperature of star
Outer shells start to burn, causing star to expand
This causes surface temperature to drop.
This creates red giant

What happens after red giant depends on size:



If the mass is low, it forms a white dwarf. A small hot ball.
If the mass of the white dwarf is more than 1.4 times the mass of the sun, we get a neutron star:
Gravity pulls matter in really close.
When close together, average speed of atoms increases, and so they exert force on each other preventing collapse
ICalled electron degeneracy pressure
When gravity is too large, electrons bind with protons to form neutrons
This is when mass > 1.44 solar masses
Chandrasekhar limit
Occurs in massive stars and Type II supernova
Type II supernova occur in stars of mass 8-25 solar masses
Stars this size fuse till Iron. Iron cannot fuse.
Iron core grows, electron degeneracy pressure supports it

Iron core reaches Chandrasekhar limit
Core contracts and gets hotter
This causes a supernova (core collapse supernova)
When the core stops collapsing, it rebounds forming a shockwave
This shockwave blows off stars outer layers.
A neutron star is very dense, and has an escape velocity of around 0.8c
Sometimes the neutron star becomes a pulsar (rotating fast enough, pointing right direction, strong enough magnetic field)
As it spins, magnetic field creates a huge electric field.
This rips electrons off the surface and accelerates them along field
If aligned with earth, we see these as bursts of radiation.
Pulsars rotational energy is radiated away, so they must spin down.

Question for lecturer: core collapse to black hole:
Does this mean the bounce back doesn't occur? If so how is there a supernova?
What's the time scale.

If mass of neutron star > 3 solar masses (star of size 25-50 solar masses) we get a black hole
Black hole is when the escape velocity is larger than speed of light.
A radius, called Schwarzschild radius, exists
If a mass M is compressed to this size, the escape velocity is above the speed of light.
We can find this radius by equating Gravitational potential and kinetic energy

$$\frac{GMm}{r} = \frac{1}{2}mv^2$$

$$v = c$$

$$R_{sch} = \frac{2GM}{c^2}$$

We cannot observe black holes directly, we can only detect their influence:
Matter falling into a black hole heats up, and produces radiation
X-rays if hot enough
Seen easily in binary systems.
Accretion disk forms, sending off x-rays
Their gravity on other objects
We can see stars near our galactic core orbiting something very quickly.
Implies unseen large mass
Black hole mass approx 4 million solar masses
Gravitational waves
Colliding black holes produced gravitational waves
Detected by LIGO

LIGO detected merging neutron stars at first
This is where all heavy elements in the universe are created

Galaxies and large-scale structure in the Universe

04 December 2018 17:17

Galaxy classification

We classify galaxies based on their shape (and size):

- Elliptical (and dwarf elliptical)
    - Large bulge, no disk
    - Further classified by ratios of major and minor axis
        - E0 is round
        - E6 is elongated
        - 10(a-b)/a

    - Very little to no rotation
    - Star orbits are very eccentric
    - Very little star formation (older galaxies)

- Spiral (and Barred spirals)
    - Have a central bulge and a disk
    - Named based on size of bulge:
        - Sa, Sb, Sc
        - Sa is largest bulge, Sc is smallest
    - Barred spiral are named similarly:
        - Sba, SBb, SBc
    - Stars are formed in disks, so larger disk = more star formation

    - In spiral galaxies, stars orbit ore in circular disk
    - Start formation is ongoing
    - Stars mostly form in spirals

- Irregular
    - Odd shapes, normally formed from colliding galaxies.

No significant star formation outside of galaxies.

Galaxy structure

Spiral structure in spiral galaxies aren't just from rotation of arms, as they would wind tightly and not be visible

- Instead, the arms don't move, and occur due to density waves
- Stars moving around centre bunch together in some areas, making arms appear

Disks in galaxies contain mostly population I stars:

- Lots of metal
- Young and brighter/hotter (blue)
- Circular orbits

Stars in the bulge and halo are population II stars:

- Metal poor
- Old and red
- Titled and elliptical orbits

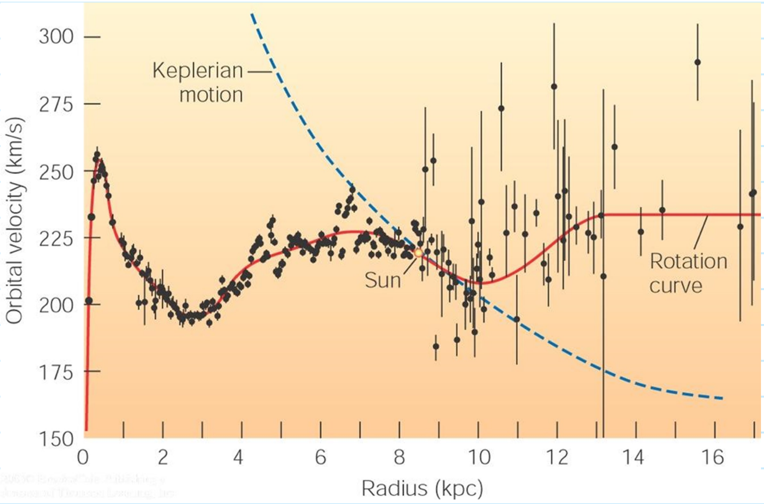
Galaxies normally exist in clusters

- Vary in size from a few dozen (groups)
- To thousands (clusters/super clusters)

- Giant elliptical galaxies at the centre of clusters appear to have consumed a number of smaller galaxies

Masses of galaxies - Dark matter

- Most of the stars in a spiral galaxy are in line with the galactic plane
  - Some stars exist in more elliptical and eccentric orbits
  - This is the buldge
  - These are called halo stars
- The masses of galaxies don't seem to add up
  - We can detect rotation speed of a galaxy using the doppler effect:
    - If we define the angle, *i,* between us and a galaxy (with i=90 meaning it appears completely circular to us) we can find the speed of stars in the galaxy with respect to galactic centre
      - Sin(i) = (observed velocity)/(actual velocity)
    - We can therefore find rotational speed of galaxy by looking at relative shift of arm travelling towards vs away from us
    - If all the mass of a galaxy was concentrated in centre, the velocity of a star at a distance r from the galactic centre would follow Kepler's 3rd law



- As we can see from this figure, the velocity of the stars at their measured radii do not follow what we expect. This occurs in many galaxies we observe
  - The best way to explain this is that we do still have circular motion, but that there is more mass in the centre of the galaxy than we can observe:

We can equate centripital force at a radius R with the force by gravity at a radius R:

$$\frac{mv(R)^2}{R} = \frac{GM(R)m}{R^2}$$

$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

We know velocity of a star orbitting the galactic core, and we know its distance from the galactic core. We can therefore find what M(R) must be. It turns out that we need a lot of extra mass near the galactic core, this extra mass is called dark matter.

$$v(R) = \sqrt{\frac{G[M_{vis}(R) + M_{dark}(R)]}{R}}$$

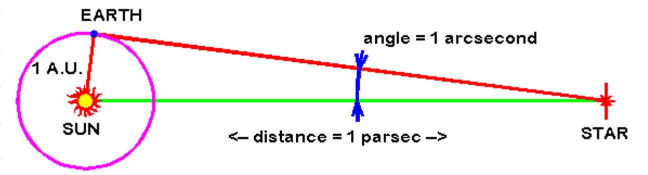
  - It turns our that the total mass is roughly 10 times the amount of visible mass.
  - The extra mass is largely situated in the halo

- Because of dark matter, there is a huge gravitational force in large galactic clusters.
  - These areas of large gravity bend light, magnifying and distorting things behind them.
  - We can use this magnification to study very distant galaxies
- We can also see evidence for dark matter outside of galaxies
  - Intergalactic gas clouds emit x-rays
    - We can therefore measure their temperature
    - From which we can estimate the gas pressure and the gravitational attraction
    - Again, we see more mass than expected -> dark matter present
- What is dark matter?
  - Computer models tell us dark matter is 'cold'
    - This means it is moving at non-relativistic speeds
    - This rules out neutrinos

Extragalactic distances

We use multiple methods to find distances in our universe. Each method relies on the previous to calibrate it

- 10^{-4} light years:
  - Within our solar system we can use radar ranging
- 10^2 light years:
  - Used to find nearby stars
  - We use the parallax between earth, sun, and the star.
  - 1 parsec is defined as the distance when the earth, sun, and star make an angle of 1 arcsecond (1/3600 of a degree)
  - 1 parsec = 3.26 light years



- 10^5 light years:
  - Find distances in our galaxy
  - We look at clusters of stars
    - Stars in clusters came from same gas cloud - same age
  - We can find their brightness's and temperatures from looking at amount of light and their spectra
  - Fit into Hertzsprung-Russel diagram
    - Where luminosity fits
  - With known brightness and estimated luminosity we can find distance
- 10^7 light years:
  - Near galaxies
  - We look at Cepheids
    - Brightness changes over time, follows period
    - Period is related to luminosity
    - Can calculate distance
- 10^{10} light years:
  - Galactic clusters
  - White dwarf supernova
  - White dwarf in binary system, matter falls onto white dwarf
    - Eventually surpasses Chandrasekhar limit
    - Consequence is thermonuclear explosion
    - All type Ia supernova have approx. same luminosity
    - Therefore distance can be found by measuring brightness and comparing to estimated luminosity
- Further distances:
  - We use Hubble's law
  - $V = dH_0$
  - The recession velocity of a distant object is proportional to its distance
  - Due to expansion of universe
  - H_0 approx. 70km/s/Mpc (Megaparsec)

Hubble's law was discovered by looking at redshift of distant galaxies. Hubble noticed that the further the galaxy, the faster they were moving away.

- His initial value for H_0 was hugely wrong
- We now know it is about 70km/s/Mpc (between 68-73, currently debated)
- $1/H_0$ is the approximate age of the universe

Cosmology

07 December 2018 14:51

Big Bang

The universe started with the big bang

Big bang timeline:

- T=0 Big Bang, inflation begins
- T=10^-32s, inflation ends
- T = 100s, formation of simplest elements
- T=1 month CMB fixed
- T=10,000 years, Radiation = Matter Energy
- T=380,000 years, CMB last scattering

4 main pieces of evidence for big bang

- Expansion of universe
  - We can see that the universe is expanding (see Hubble's law)
  - If universe is expanding it must have started from a small point
  - Using Hubble's law we estimate the age of the universe is roughly 14billion years
- Evolution of universe

- Cosmic microwave background radiation (CMBR)
  - If the universe started from the big bang, we should be able to see radiation from this time
  - This was detected in 1960
  - Shows the universe is a blackbody with temperature of 2.73K
  - Radiation comes from "last scattering" time of universe
  - When temperature after big bang dropped below 3000K, electrons bound with protons
    - This meant photons could travel through space
    - Before this the universe was opaque

- Abundances of lightest chemical elements
  - 20 minutes after big bang, temperature is too low for new elements to be formed
    - Not enough high energy photons to destroy existing elements
  - This is why universe is largely H and He
  - Our calculations match the true abundances in the universe very well
    - Major strong point for Big Bang model
  - To make the values match we get important clues about dark matter

The Cosmological Principle

On the largest scales of the universe, we make some assumptions:

- Homogeneity
  - On large scales, the universe has the same physical properties
    - Same mass density, same expansion rate, same ratio of visible to dark matter
- Isotropy
  - Same large scale structure in any direction
- Universality
  - Laws of physics are the same everywhere in the universe

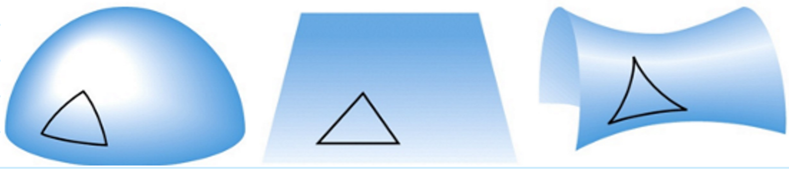
Dynamics of the Universe

Shape of the universe

- Friedmann equation describes state of universe:

$$\dot{R}^2(t) = \frac{8\pi G\rho R^2(t)}{3} - kc^2 + \frac{\Lambda}{3}R^2(t)$$

  - R is 'scale factor'
  - Λ Is the 'cosmological constant'
  - K is curvature, describes shape of universe



K=-1, spherical space: parallel light beams converge
K=0, Flat space, parallel light beams remain parallel
K=1, Hyperbolic space, Parallel light beams diverge
K is thought to be 0

Deceleration of the Universe:
- Expansion of universe should slow down due to gravity
- Fate of universe depends on matter density
- We can define critical density, the density at which expansion stops at infinity.
- Critical mass can be found by:

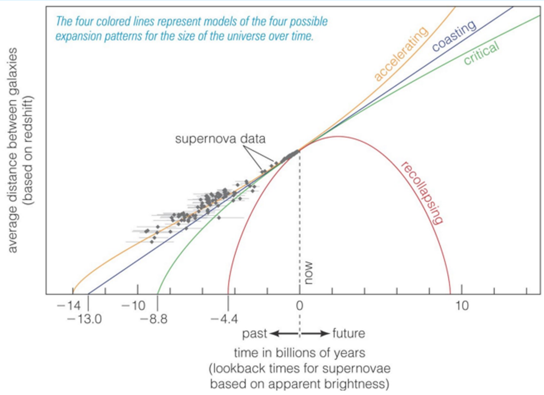
$$\rho_{\text{crit}} = \frac{3H_0^{\,2}}{8\pi G}$$

- When looking at our universe, we define:

$$\Omega = \rho \big/ \rho_{\text{crit}}$$

- If density > critical density, matter will slow expansion after a finite time
  - Universe collapse on itself
  - Big Crunch
- If density < critical density, universe will never stop expanding
  - 'Open universe'
- If density = critical density $\Omega = 1$, Critical universe
  - Universe will stop expanding at t=infinity

- By looking at type Ia supernova, we can measure distances and recession speeds, and so find rate of expansion
  - We expected to find the expansion of the universe decelerating
  - Instead we found it's accelerating



  - What is driving this acceleration?

The cosmological constant:
- Vacuum of universe is not perfectly empty
  - Quantum physics predicts vacuum full of particles that pop into existence and then annihilate
  - Therefore universe has a constant energy density
- We can explain acceleration using Cosmological constant
  - Cosmological constant is the Λ In Friedman equation from earlier
  - Used to believe it was 0

Energy corresponding to it can account for the mass ($E=mc^2$) needed to produce a flat space-time
- This energy is what we call dark energy

From knowing geometry of universe, we can tell that the universe is the sum of visible, dark matter, and dark energy
- Visible ~ 4%
- Dark matter ~ 22%
- Dark energy ~ 74%

Cosmic Microwave Background

The CMB is quite smooth, but has some fluctuations
- Galaxy formation is highly dependant on these fluctuations
- Looking at CMB also tells use universe has flat geometry
- This likely comes from inflation
  - Period of rapid expansion in moments after big bang
    - Occurred when strong and electroweak forces became separate
  - Rapid expansion during start of universe may have smoothed out ripples in space time
  - Results in smooth CMB and flat geometry