

Radiation, luminosity, and effective temperature

04 December 2018

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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 transferred 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 photons have different wave length:

Wavelength around 1m = radiowaves

Wavelength around 1mm = microwave

Wavelength around 1μm (10^{-6} m) = infrared

Wavelength about 500nm = visible light

Wavelength around 100nm = uv

Wavelength around 1nm = xray

Wavelength around 10^{-3} nm = gamma

X-ray come from electron interactions i.e high 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)

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

We can also express this equation in terms of frequency

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

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

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

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

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

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

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:

$$\lambda_{\max} \approx \frac{3 \times 10^{-3}}{T}$$

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

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.

$$L = \text{flux} \cdot \text{Area} = \sigma T^4 \cdot 4\pi r^2$$

$$\text{flux} = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$$

(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

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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.

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

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 star's temperature isn't the only important thing, its size is too. So we use Luminosity classes to define stars better:

Ia = Most luminous supergiants

Ib = Supergiants

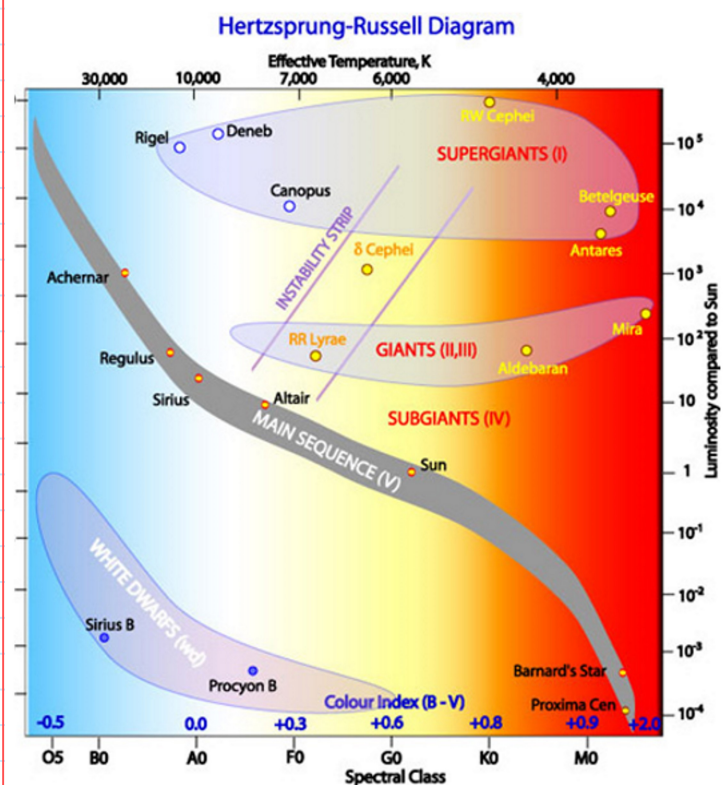
II = Luminous giants

III = Giants

IV = Subgiants

V = Main sequence stars (dwarfs)

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



Stellar evolution and life of a star

04 December 2018

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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' ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	4'' ${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$
2 $d + p \rightarrow {}^3\text{He} + \gamma$	4' ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	5'' ${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$
3 ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$	5' ${}^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$	6'' ${}^8\text{Be} \rightarrow 2{}^4\text{He}$

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

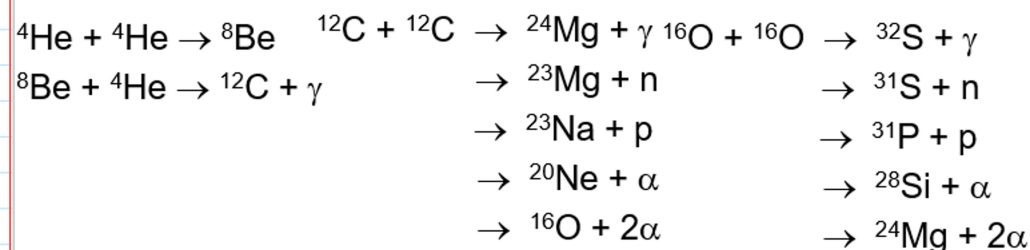
Solar Neutrino problem:

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:



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.

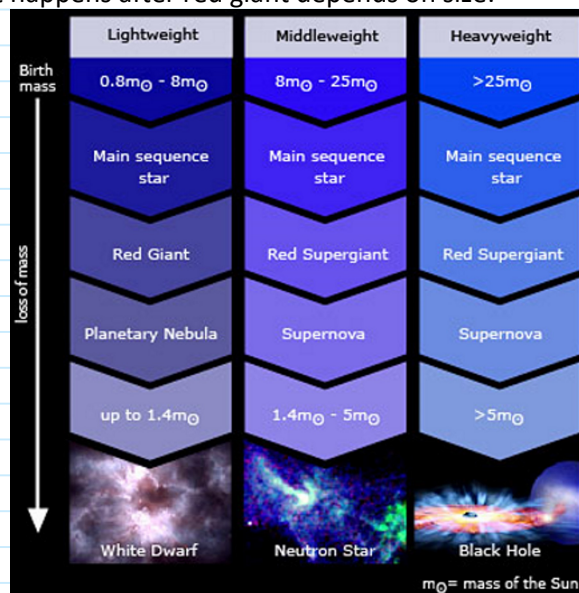
Increases the temperature of star

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

Called 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

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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 in circular disk

Star 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

Tilted 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

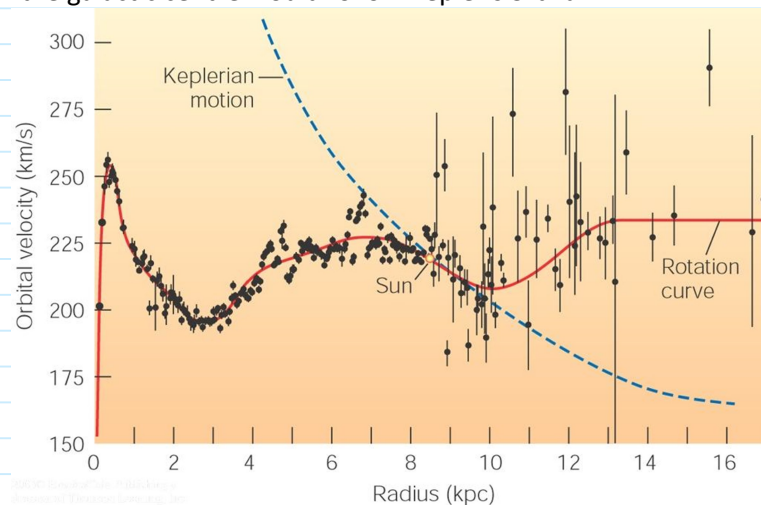
We can detect rotation speed of a galaxy using the doppler effect:

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

$$\sin(i) = (\text{observed velocity})/(\text{actual velocity})$$

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 centripetal 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 orbiting 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.

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

It turns out 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

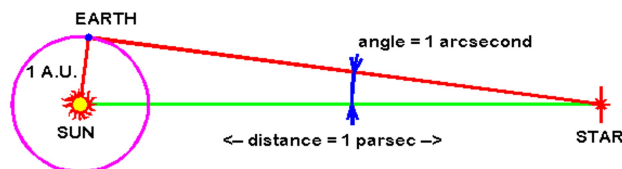
10^2 light years:

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

