

Module 5

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Cosmology

Structure of the Universe

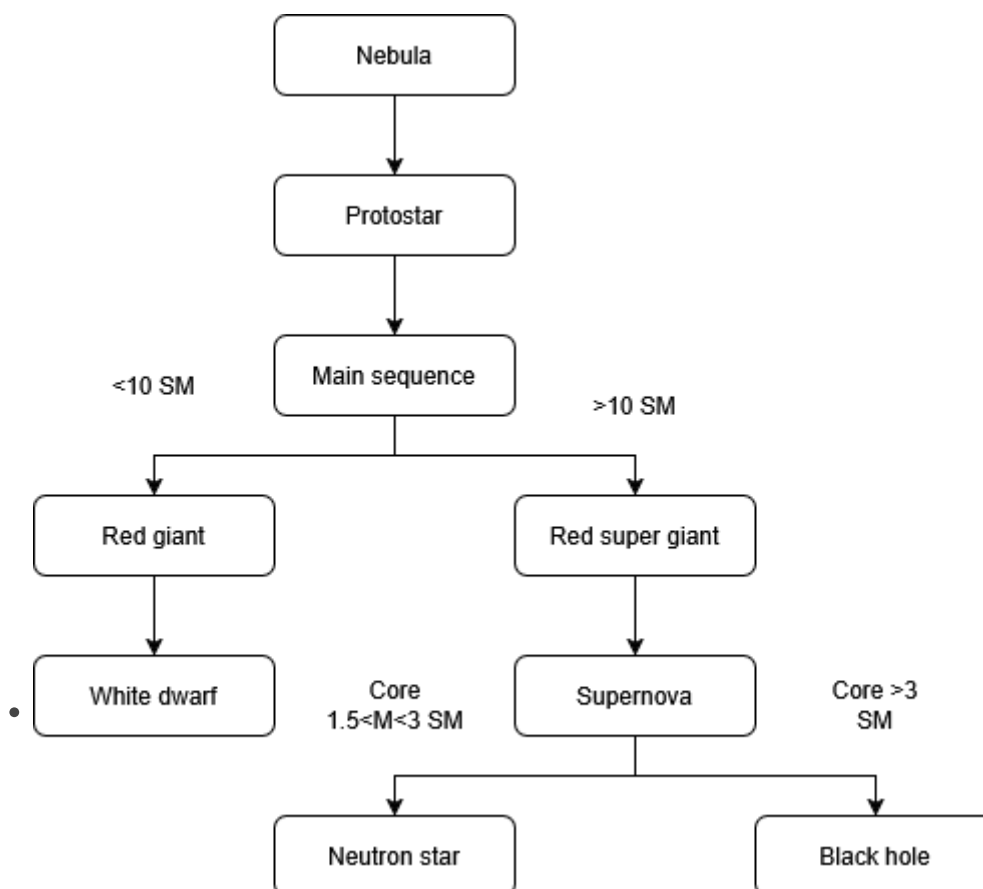
Galaxies are clusters of millions and billions of stars. They are constantly moving due to the expansion of the universe. The further they are - i.e. closer to the edge of the universe - the faster they move.

Stars are spheres of interstellar matter that undergo nuclear fusion.

Planets are bodies that move in elliptical orbits around a star to form a solar system. They are less dense than stars.

Planetary satellites are bodies that move in elliptical orbits around a planet. An example is the moon of Earth.

Star formation and life cycle



Nebula and Protostar

A nebula is a cloud of interstellar matter composed of various elements such as hydrogen and helium. They exert gravitational force on each other, causing a dense sphere to be created from gathered matter.

This sphere is a protostar. A protostar is a small, dense sphere of interstellar matter that does not yet undergo nuclear fusion. As it gets larger, temperature and pressure increases, enabling nuclear fusion to begin. This transitions to the next phase: main sequence.

Main Sequence Star

A main sequence star is a sphere of interstellar matter that undergoes nuclear fusion. It is of a temperature where it primarily fuses hydrogen nuclei (protons) into helium nuclei.

When hydrogen runs out, the star transitions to the next phase: red (super) giant.

Red Giant

A red giant is a sphere of interstellar matter that undergoes nuclear fusion of larger elements like helium, all the way up to, and excluding, iron. This occurs due to gravitational collapse after main sequence - hydrogen is no longer being fused, so the outward pressure caused by fusion decreases, causing the star to succumb to gravitational pressure. At a low volume, the massive density causes temperature and pressure to increase to the point where nuclear fusion of these larger elements can occur.

If the main sequence star after all fuel consumption is less than 10 solar masses, it transitions into a red giant. If greater, it transitions into a red super giant (a larger red giant).

After these elements run out again, the star transitions into the next stage depending on the mass of the **core** of what is left.

White Dwarf

A red giant will always transition into a white dwarf. The Chandrasekhar limit states that the maximum mass for a white dwarf is 1.44 solar masses.

Supernova

The outer layers of the super red giant collapse into the core and bounce off, resulting in a blast that sends the material of these outer layers into space. The scattered material can form part of nebulae, being part of the birth of a new star.

What happens next depends on the mass of the remaining core of the super red giant.

Neutron Star

If the mass of the core is between 1.5 and 3 solar masses, it collapses into a neutron star. This is due to the gravitational pressure bringing atoms closer together, to the point where electrons collide with protons to form neutrons.

Black Hole

If the mass of the core is greater than 3 solar masses, it continues collapsing into itself, creating a black hole. This has a gravitational force so strong, even light cannot escape it.

EM radiation from stars

Electrons occupy certain orbits in atoms, and these orbits are associated with definite energies and are known as energy levels. When electrons gain energy, they move up a level. When they go down a level, lost energy is emitted as a photon with an energy equal to the difference in energy of the energy levels. The frequency of this photon is dictated by $E=hf$.

1. Emission line spectra are produced in cooling hot gas of an element, when an excited electron moves down an energy level and emits a photon. The energies and frequencies of these photons, along with abundances, are plotted on a spectrum in lines on a dark background. The spacing between these lines is proportional to the spacing between energy levels. Since the spacing of energy levels is unique to each element, each element has its own emission spectrum.
2. Absorption line spectra are produced in firing EM radiation into cold gas of an element, when photons of certain energies are absorbed by atoms of this element, causing electrons to move up an energy level. Thus, these absorbed photons do not pass through. Instead of a black background, this is presented as black lines on a rainbow background where photons of that frequency (as per $E=hf$) have been absorbed.

Outputs of the above two methods are passed through a diffraction grating to display the spectrum on a screen. The wavelength of the light source can be calculated using:

$$n\lambda = d\sin\theta$$

... where n is the order of the maximum, λ is the wavelength, d is the distance between diffraction grating lines, and θ is the angle between the output beam and the grating.

Wien's law

Wien's displacement law states that:

$$\lambda_{max} \propto \frac{1}{T}$$

... where λ_{max} is peak emitted wavelength, and T is temperature. It is used to estimate the peak surface temperature of a star from the wavelength at which the star's brightness is maximum. However, the Earth's atmosphere can block certain wavelengths, reducing their intensity, and pollution can block EM radiation. Thus, telescopes are placed at high altitudes and even in Earth's orbit. Also, some detectors may be less responsive to certain wavelengths.

Stefan's law states that:

$$L = 4\pi r^2 \sigma T^4$$

... where L is luminosity, r is distance to the object, sigma is Stefan's constant 5.67×10^{-8} , and T is temperature.

Stefan's law

Astronomical distances

The astronomical unit (AU) is the distance between the centre of the Earth and the centre of the Sun.

One light year is the amount of distance travelled by light in one year. About 9.5×10^{15} m.

One parsec is the distance of a star from Earth when the angle of parallax subtended by the radius of the Earth's orbit is 1 arc second ($1/3600$ th of a degree). This is about 3.1×10^{16} m.

Stellar parallax is the apparent shifting in position of a star viewed in a background of distant stars when viewed from different positions on the Earth

[Diagram of parallax setup to view a star]

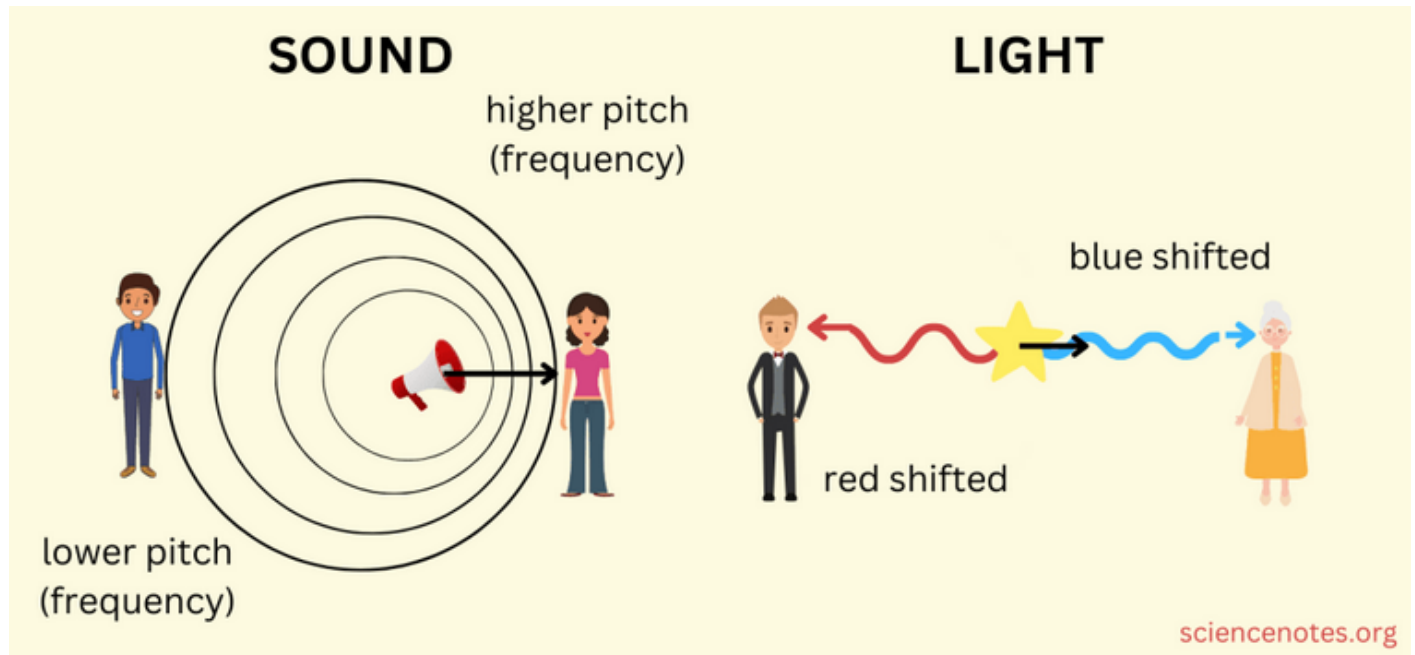
Scientists take an image of the star from one observation point in January, then another 6 months later in June. Since 6 months pass, the Earth travelled 2AU about the sun. This is a base of a triangle used in this calculation. The angle $2p$ is determined with telescopic imaging. This is divided by 2 to get an angle p . This is used in the equation:

$$d = \frac{1}{p}$$

... where d is distance to the star in parsecs.

The Doppler effect

The Doppler effect is the apparent change in wavelength caused by the relative motion between the wave source and an observer.



When the moving object moves towards the object, the observed frequency is greater. When away, it's observed as lower.

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} = \frac{v}{c}$$

... where v is the velocity of the galaxy relative to Earth. For distances from galaxies, the difference in wavelength/frequency is taken between the known hydrogen line spectrum and that of the observed galaxies.

The Doppler effect was observed by Edwin Hubble in 1929. He noticed the differences in hydrogen line spectra from different galaxies compared to the known hydrogen line spectrum and concluded that galaxies are constantly moving - not only that, but the largest majority of them are moving away from us. He also noticed that galaxies further from us moved faster than those closer to us. This is expressed in his equation:

$$v = H_0 D$$

... where v is velocity, D is distance to a galaxy, and H_0 is Hubble's constant, which is estimated to be $2.27 \times 10^{-18} \text{ s}^{-1}$. The reciprocal of Hubble's constant corresponds to the age of the universe.

The observation evidences the universe's expansion - specifically, the expansion of space between galaxies. Like drawing dots on a deflated balloon and inflating it: the space between dots expands, but the dots aren't technically moving. This leads onto dark matter and dark energy.

Dark matter and dark energy

When calculating the universe's density, we use two methods to estimate their mass: luminosity of distant galaxies; or speed of their rotation. However, values from both of these methods have massive discrepancies, with the latter method showing far more mass. This suggests that there is an invisible form of matter that accounts for the missing mass. This is hypothesised to be dark matter, which accounts for approximately 27% of the universe. It is responsible for providing the gravitational force required to form galaxies and keep them from flying apart.

Dark energy is a material with a gravitationally repulsive effect that causes negative pressure, causing the acceleration of the universe's expansion. This is why the majority of galaxies are moving away from us - the force from dark energy is greater than the gravitational pull between the Milky Way and the other galaxies. The rare exceptions, such as the Andromeda galaxy, are due to the gravitational force between us and them being greater than the force provided by dark matter.

[For dark energy, unsure if "force" is the correct word to be used.]

CMBR and the cosmological principle

The cosmological principle states that on a large scale the universe is isotropic and homogeneous, and the laws of physics apply everywhere.

- Isotropic: The same in all directions.
- Homogeneous: Of uniform density throughout.

Cosmic microwave background radiation (CMBR) is radiation that was released at the time of the Big Bang. Over billions of years as the universe expanded, the radiation expanded. The increase in wavelength puts CMBR in the microwave part of the EM spectrum, and its intensity is equal everywhere in the universe.

Evolution of the universe

1. The universe was contained in a singularity of incredible pressure and temperature of 10^{32} K.

For an unknown reason, this singularity began to expand in a period known as inflation. During and after inflation, matter and antimatter (in an uneven ratio of abundance) formed from the energy in the form of quarks, leptons, all their antimatter variants, and photons. Hadrons and baryons still couldn't form from the quarks since the temperatures were still far too large. Matter and antimatter annihilated, and still do, resulting in the production of multiple high-energy photons.

After this, the universe cooled down to 10^{12} K, so quarks could join to produce hadrons,

but these hadrons could not combine to create atoms yet, as temperatures were still too high.

2. **100 seconds after inflation**, the universe cooled to 10^9K , low enough for protons (hydrogen nuclei) to form to fuse into helium and lithium nuclei. All matter was in plasma form - i.e. protons and electrons are not bound to one another due to high temperature. The composition of the universe was majority hydrogen at this point.
3. **250,000 years after inflation**, the universe cooled to $10,000\text{K}$, low enough for a process called decoupling to occur, whereby radiation and matter could decouple. This enabled electrons to bind with nuclei to form atoms - specifically, hydrogen, helium, and lithium atoms. Since photons could now move more freely, the universe became transparent. The radiation here became the CMBR we observe today.
4. **10^6 years after inflation**, the temperature cooled to 6000K . This is when galaxies started to form.
5. **10^9 years after inflation**, the universe cooled to 17K . Stars that underwent gravitational collapse formed heavy elements.
6. **13.7×10^9 years after inflation (now)**, the universe cooled to 2.7K . This is present day.

Thermal Physics

Temperature

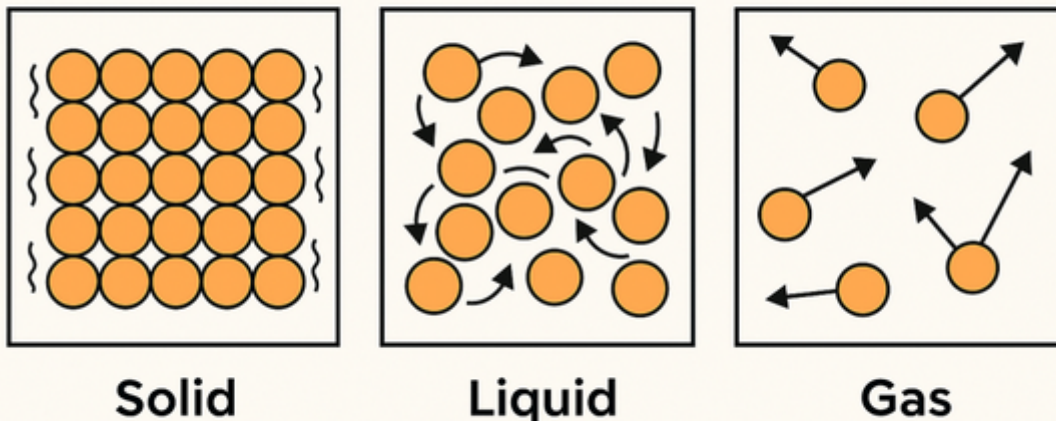
Thermal equilibrium describes the equal transfer of thermal energy in and out of a system.

The absolute scale of temperature is Kelvin. You convert from Celsius to Kelvin by adding 273 to the Celsius number. This is because -273 Celsius (0K) is absolute zero, which is the theoretical lowest possible temperature at which particles have an internal energy of 0J, causing zero movement and zero pressure.

Solids, Liquids, and Gases

Property	Solid	Liquid	Gas
Shape	Definite shape.	Indefinite shape (depends on container).	Indefinite shape (depends on container).
Volume	Definite volume.	Definite volume.	Indefinite volume (depends on container).
Particle arrangement	Particles are fixed close together in a regular lattice. (Edge case exceptions like glass, where they are arranged in an irregular lattice.)	Particles are close together, but not in a regular lattice - rather, in a random arrangement.	Particles are very far apart in a random arrangement.
Particle movement	Particles vibrate in place.	Particles are constantly moving close to each other, flowing over other particles.	Particles are constantly moving in straight lines in directions influenced by collisions with other particles.
Intermolecular forces	Strong.	Moderate.	Weak, often negligible.
Compressibility	Almost incompressible.	Almost incompressible.	Highly compressible.
Fluidity	Cannot flow.	Flows easily.	Flows easily.
Density	Generally high.	Generally moderate.	Generally very low.

Particle Arrangements in Solids, Liquids, and Gases



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Internal energy is defined as the sum of the random distribution of kinetic and potential energies of all molecules in a system.

Potential energy is defined as the energy stored within a system due to the relative positions and intermolecular forces between molecules in a system.

When the temperature around a material increases, there is a positive temperature gradient, so thermal energy from the surroundings transfers to the kinetic energy stores of its particles, increasing its internal energy. This enables it to change state from solid to liquid (melting) to gas (evaporating).

Conversely, reduction of temperature causes a negative temperature gradient, so the opposite happens, causing a change in state from gas to liquid (condensing) to solid (freezing).

During a change in state, the temperature of the material remains constant, so kinetic energy doesn't change. However, due to the increased spacing between particles, potential energy becomes less negative, so internal energy increases regardless.

Specific Heat Capacity

Specific heat capacity is the amount of energy to increase the temperature of 1 unit mass of a substance by 1 unit of temperature. It is calculated with:

$$\Delta Q = mc\Delta T$$

... where delta Q is the change in energy, m is the mass, c is the specific heat capacity, and delta T is the change in temperature.

Specific Latent Heat

Specific latent heat is the amount of energy required to change the state of 1 unit mass of a substance. It is calculated with:

$$Q = mL$$

... where Q is energy, m is mass, and L is specific latent heat.

Brownian Motion

Brownian motion describes the observed random motion of particles suspended in a fluid due to the bombardment of smaller particles.

Amount of Substance

The mole is a unit used to measure the amount of a substance. Each mole of a substance contains 6.02×10^{23} atoms. From this, mass and mass/mol can be calculated using the formula:

$$n = \frac{m}{M_r}$$

... where n is amount of substance, m is mass, and M_r is mass per unit amount.

The Kinetic Theory

The kinetic model of matter dictates the motion of particles in an ideal gas. Real gases behave similarly to an ideal gas in low pressures and high temperatures significantly above their boiling points. The behavior of an ideal gas has multiple assumptions:

- The gas contains a large number of molecules.
- Particles move randomly and rapidly.
- All collisions are perfectly elastic (kinetic energy is perfectly conserved).
- The forces between particles are negligible, apart from collisions. As such, the internal energy is equal to the random distribution of kinetic energies of all particles in the gas, as it is assumed that potential energy is negligible.
- The time for a collision to happen is negligible to the time between collisions.
- Particles have a negligible volume compared to the volume of the container they're in.

With all these assumptions, an equation can be made for an ideal gas in a container:

$$PV = nRT, R = 8.31 JK^{-1}mol^{-1}$$

... where P is pressure, V is volume, n is amount of gas, R is the ideal gas constant, and T is temperature.

The root mean square speed of a gas, c_{rms} , is the square root of the mean of the squares of all velocities of particles in an ideal gas:

$$\sqrt{c^2} = c_{rms} = \sqrt{\frac{v_1^2 + v_2^2 + v_3^2 + \dots}{N}}$$

It is known that:

$$pV = \frac{1}{3}Nm\bar{c}^2$$

... where p is pressure, V is volume, N is the number of particles, m is mass of a particle, and $\bar{c}$ squared is the mean square speed.

Investigating Gases

Boyle's law states that the product of the pressure and volume of an ideal gas in a container is constant regardless of how pressure and volume are modified.

$$P_1V_1 = P_2V_2$$

... where bases of 1 and 2 represent values of pressure and volume before and after modification of one of the variables.

The pressure-temperature law is similar, but states that the ratio of pressure to temperature is constant regardless of how pressure and temperature are modified.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

On a graph of pressure against temperature, the x-intercept marks the value of absolute zero, as a temperature of 0K means that particles have no energy, so they don't move, so no pressure is exerted.

Charles' law is also similar, but relates to the ratio of volume to temperature:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Combining this gives:

$$\frac{PV}{T} = \text{constant}$$

... where PV/T is directly proportional to the amount of gas molecules n in the container of ideal gas. If you plot PV/T against n, you will obtain R - the ideal gas constant - from the gradient of the

straight line through the origin.

The Boltzmann Constant

The Boltzmann constant k is a constant used when relating the temperature of a gas to the mean translational kinetic energy of particles in the gas.

$$PV = \frac{1}{3}Nm\bar{c}^2 = NkT \implies \frac{1}{2}m\bar{c}^2 = \frac{3}{2}kT$$

You use $PV = nRT$ when you're dealing with amount of substance, and you use $PV = NkT$ when dealing with numbers of molecules.