Module 5: Newtonian World and Astrophysics

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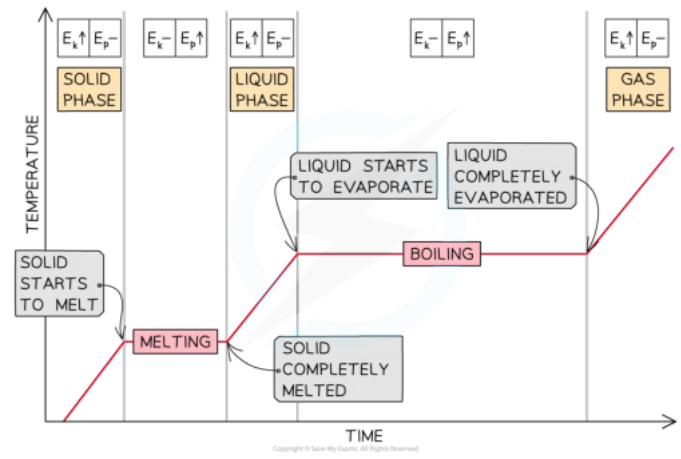
Subject	Physics A2

5.1 Thermal Physics

- **Brownian motion** is the random movement caused by the uneven bombardment and collisions with air molecules
- **Internal energy** is the sun of the RANDOM distribution of kinetic and potential energies of all particles

- Absolute temperature in Kelvin: $T = \theta + 273$
- Specific heat capacity: $E = mc\Delta T$

  Experiment. Use a heater on an insulated substance, $c = \frac{IVt}{mc\Delta\theta}$



- Specific latent heat of fusion/vaporisation: $E = mL$

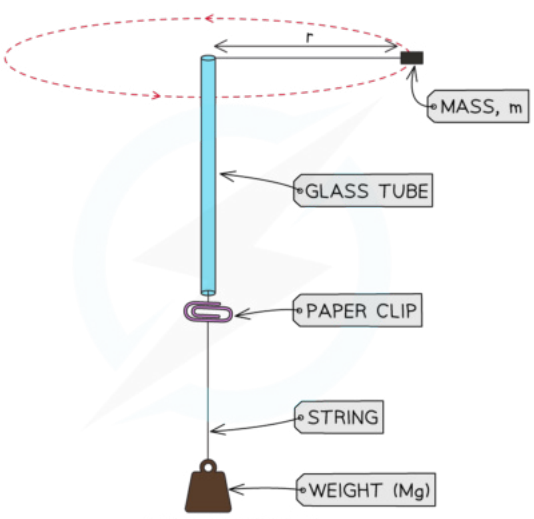
  Experiment. Heat ice and measure mass melted, $L_f = \frac{IVt}{m}$
- PE depends on the state: solids have large negative PE, gases have zero PE

  KE depends on the temperature (independent of the gas used): $E = \frac{3}{2}kT$

- **Ideal gas (kinetic theory of gases)**
  - large number of molecules moving with random speeds in random directions
  - collisions are perfectly elastic
  - time during collisions is negligible compared to time between collisions
  - volume of molecules is negligible compared to volume of the gas
  - no electrostatic interaction between molecules besides collisions
- Combining gas laws: $pV = nRT = NkT$ where $N = n \times N_A$ and Boltzmann constant $k = \frac{R}{N_A}$

- Explaining pressure with Newton’s laws:
  - molecules collides with the wall and exerts a force; according to Newton 3rd the wall exerts an equal force in the opposite direction
  - the collision changes the momentum of the particle, according to Newton 2nd $F \propto \frac{\Delta p}{\Delta t}$
- Root mean squared speed: $pV = \frac{1}{3}Nm\overline{c^2}$

5.2 Circular Motion



- **Centripetal force** $F = \frac{mc^2}{r}$ acting towards the centre is needed to maintain circular motion
  - Velocity is perpendicular to force, hence work done is zero
  - **Experiment.** In the whirling bung experiment, $\text{weight} = \text{tension} = \text{centripetal force}$

5.3 Oscillations

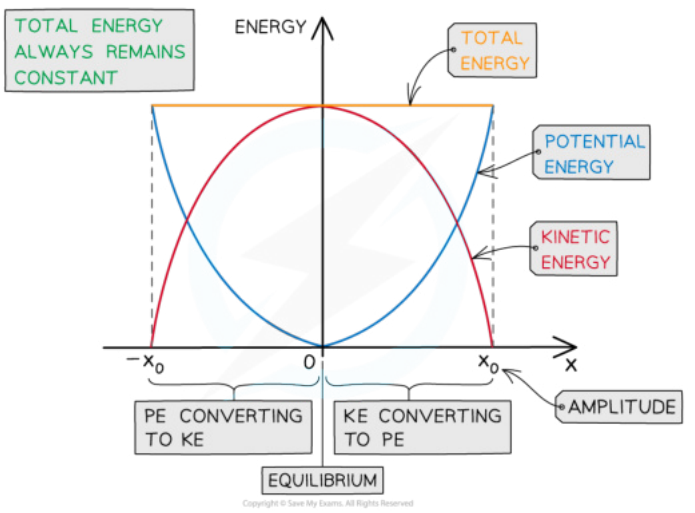
- **Simple Harmonic Motion** is defined by $a = -\omega^2 x$:
  - acceleration is proportional to the displacement from the equilibrium position
  - acceleration acts in the opposite direction of the displacement

- Pendulum (small $\angle$)

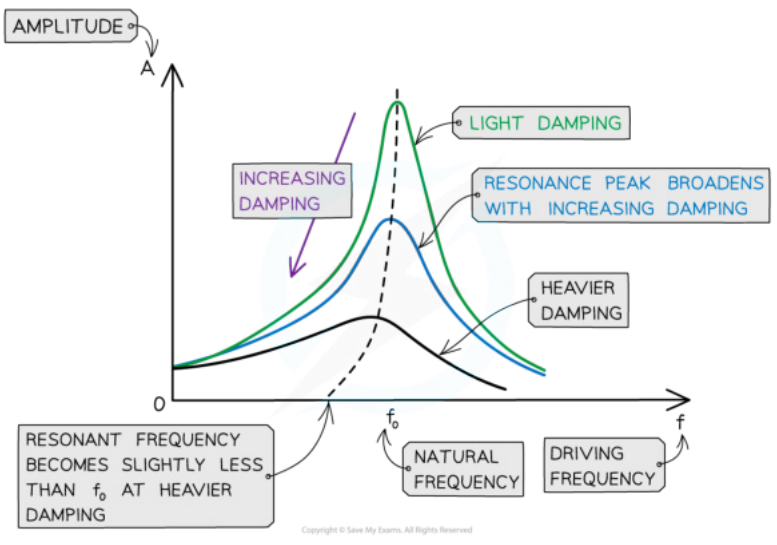
$$T = 2\pi\sqrt{\frac{L}{g}}$$

- Mass-spring system:

$$T = 2\pi\sqrt{\frac{m}{k}}$$



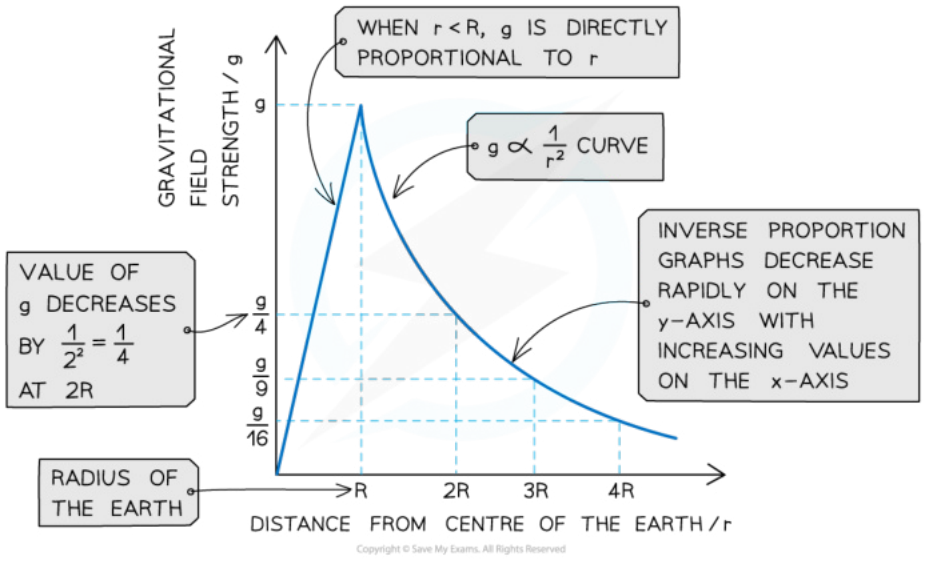
- **Damping** decreases amplitude
  - in light damping, frequency and period is unchanged
  - in critical damping, the oscillations stop the most quickly (or no oscillations performed)
  - in heavy damping, period increases
- **Resonance** happens when driving frequency is equal to natural frequency

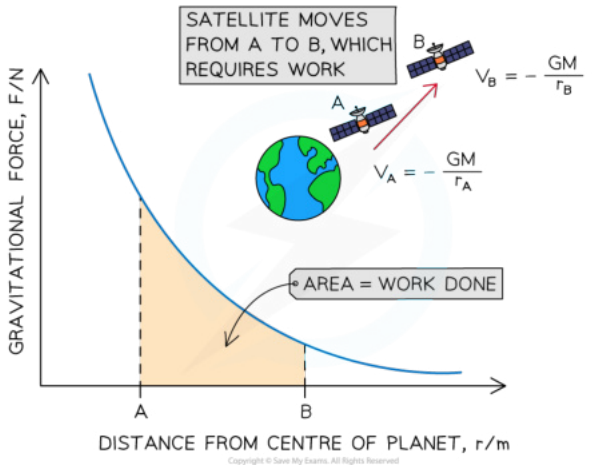


5.4 Gravitational Fields

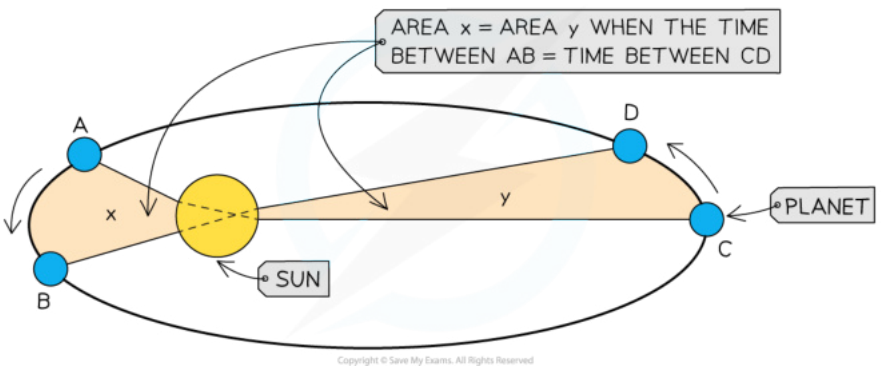
- A gravitational field has infinite range, and affects anything with mass

Vectors	gravitational field strength (g=F/m); acceleration	gravitational force (F=-GMm/r^2)
Scalars	gravitational potential (V=-GM/r)	gravitational potential energy (E=-GMm/r)





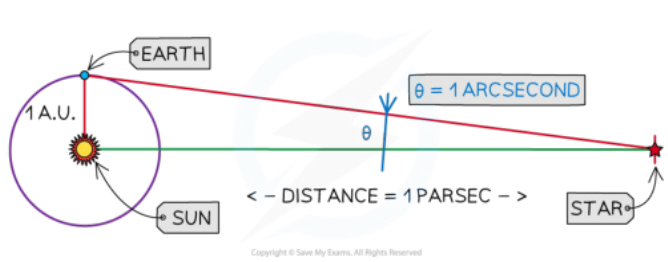
- **Gravitational potential** V_g is the work done <u>per unit mass</u> to move an object from infinity to a point
  - it <u>takes energy</u> to move objects apart, hence the negative sign
  - gravitational potential is <u>ZERO AT INFINITY</u>
  - total $V_g = \sum V_g$ from each mass
- **Escape velocity** removes a mass from a field: $E_k + E_g = 0 \implies v = \sqrt{\frac{2GM}{r}}$
- **Geostationary orbit** is above the equator with a period of 24h
  Polar orbit covers the entire Earth
- **Kepler's laws:**
  1. The orbit of a planet is an <u>ellipse</u> with the Sun as one of the foci
  2. The line joining the Sun and the planet sweeps out the same area in the same amount of time
  3. $T^2 \propto r^3$, in circular orbits $T^2 = \frac{4\pi^2}{GM} r^3$



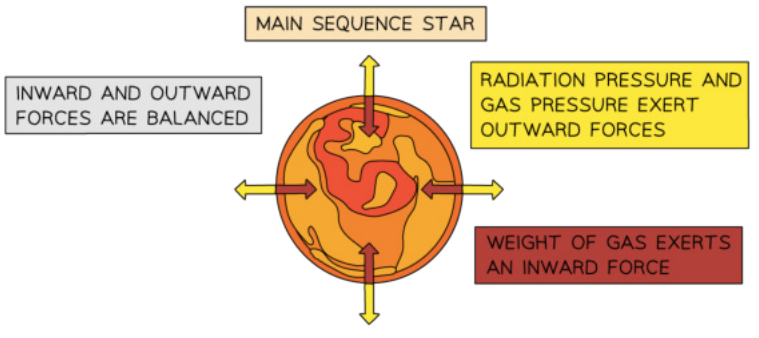
5.5 Astrophysics and Cosmology

- **Parsec** corresponds to a parallax angle of 1 arcsecond (1/3600°) as Earth moves through 1 AU

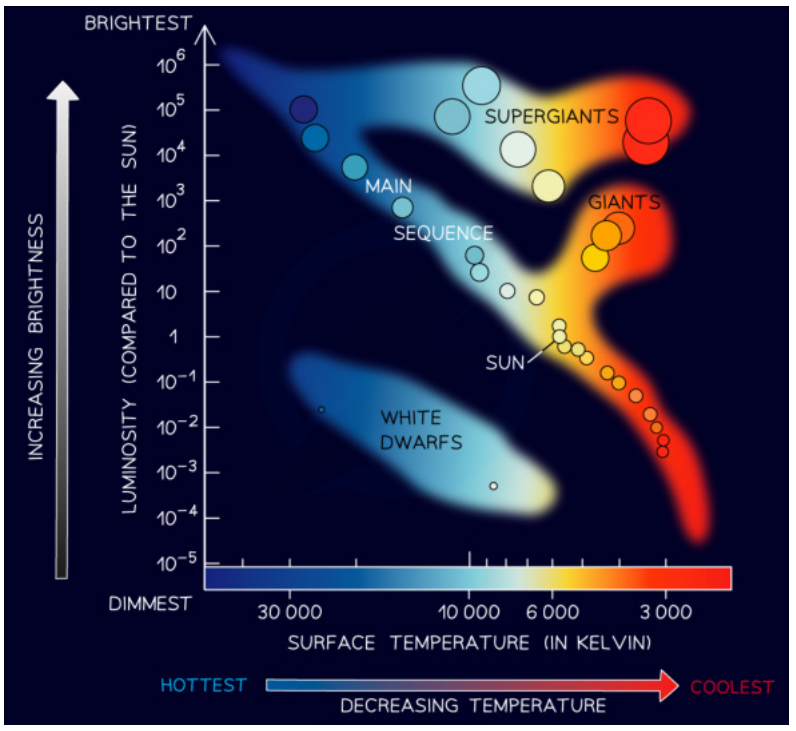
$$\tan\theta = \frac{1}{d} \approx \theta$$



- **Cosmic parallax** is the <u>apparent shift</u> in position of a relatively close star against the distant backdrop as Earth orbits the Sun.
- **Life cycle of stars**
  1. <u>Nebula from supernovae</u> → <u>Protostar</u> → <u>Main sequence star</u>
     volume ↓, temperature ↑, pressure ↑; nuclear fusion begins
  2. When core H_2 is used up, the core collapses under gravity and increased pressure enables shell hydrogen burning. More massive stars carry out nuclear fusion up till Fe.



3. Stars < $10M_\odot$ Red giant → White dwarf + Planetary nebula
   Electron degeneracy pressure prevents the white dwarf from further collapse when the core mass is under the **Chandrasekhar limit** of $1.44M_\odot$
4. Stars > $10M_\odot$ Red supergiant → Supernova
   a. Core < $3M_\odot$ Neutron star
   b. Core > $3M_\odot$ Black hole



- **Hertzsprung-Russell Diagram** uses logarithmic scale
  Supergiant's temperature decreases throughout its life

- **Emission & Absorption Spectra**
  $n = \infty$ has zero energy; $n = 1$ (ground state) is the most negative
- **Diffraction grating** $d \sin\theta = n\lambda$
- **Black body** absorbs all EM radiation that shines onto it and emits a characteristic distribution of EM radiation at a specific temperature
  Wien's displacement law: peak wavelength $\lambda_{\max} \propto \frac{1}{T}$
  Stefan's law calculates the luminosity (total power output) $L = 4\pi r^2 \sigma T^4$
- **Doppler's effect:** red shift moves away, blue shift moves towards $\frac{\Delta f}{f} \approx \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$
  For a given star, $\Delta\lambda \approx \frac{v}{c}\lambda \implies \Delta\lambda \propto \lambda$
- **The Big Bang Theory**
  - **Hubble's law:** expansion of the Universe $v = H_0 d$
  - **Microwave background radiation:** gamma photons are stretched into microwave (average temperature of the Universe is 2.7K, see Wien's)
- **Timeline:** age of the Universe is 13.7 billion years
  1. Universe started with infinitely hot and dense singularity
  2. Expands rapidly with only γ photons, INFLATION
  3. Order of formation (PAIR PRODUCTION): Quarks & Leptons → Hadrons → H-2 and He nuclei
  4. Atoms capture electrons, RECOMBINATION
  5. The Sun and the Earth is about 4.6B years old
- **Cosmological principle** states that on a large scale, the Universe is homogeneous (every part is identical), isotropic (looks the same from every direction) and the laws of physics are universal
- 5% baryonic matter, 25% dark matter which speeds up stars on the edges of galaxies, 70% dark energy that accelerates the expansion of the Universe