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Gravitation

- Newton's law of gravitation : Newton in 1665 formulated that the force of attraction between two masses m_1 and m_2 as

$$F = \frac{Gm_1 m_2}{r^2}$$

where $G = 6.67 \times 10^{-11} \text{ Nm}^{-2}$ and is called universal gravitational constant.

- Gravitational field Intensity : Gravitational force per unit mass placed at a point is called gravitational field intensity at that point. Gravitational field intensity of earth is 'g'

$$I = \frac{F}{m} \text{ where test mass } m \text{ is very very small.}$$

- Gravitational potential (V_g) : Gravitational potential at a point is the amount of work done to bring a unit mass from infinity to that point under the influence of gravitational field of a given mass M, $V_g = -\frac{GM}{r}$
- Gravitational potential and field due to system of discrete mass distribution.

$$V = V_1 + V_2 + V_3 + \dots \quad \text{i.e. } V = \sum_{i=1}^N V_i$$

$$I = I_1 + I_2 + I_3 + \dots \quad \text{i.e. } I = \sum_{i=1}^N I_i$$

- Gravitational potential and field due to system of continuous mass distribution.

$$V = \int dV \text{ where } dV \text{ is potential due to elementary mass } dM.$$

$$I = \int dI \text{ where } dI \text{ is field intensity due to elementary mass } dM.$$

- Gravitational potential energy of two mass system is the amount of work done to bring a mass m from infinity to the point P under the influence of gravitational field of a given mass M. $U_g = -\frac{GMm}{r}$

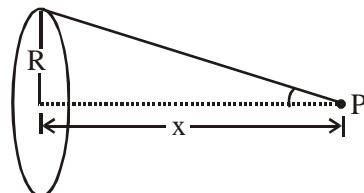
where, U_g is G.P.E. of two mass system.

Note that $U_g = mV_g$



- In general, gravitational potential energy of a system is work done against gravitational force in assembling the system from its reference configuration. Infinite mutual separation is reference configuration for mass-system.
- Gravitational field intensity due to a ring of radius R, mass M at any point on the axial line at a distance x from the centre of the ring is

$$E_g = \frac{GMx}{(R^2 + x^2)^{3/2}}$$



The field is directed towards the centre. At the centre of the ring E_g is minimum ($= 0$) and E_g is maximum at

$$x = \frac{R}{\sqrt{2}}$$

- Relation between Field and potential : $\mathbf{I} = \frac{-dV}{dr} \Rightarrow \mathbf{F} = \frac{\partial V}{\partial x} \hat{i} - \frac{\partial V}{\partial y} \hat{j} - \frac{\partial V}{\partial z} \hat{k}$
 $dV = -\mathbf{I} \cdot d\mathbf{r}$
- Work done against gravitational force in changing the configuration of a system
 $= P.E. \text{ in final configuration} - P.E. \text{ in initial configuration.}$
i.e. Work done $= U_2 - U_1 = W_{\text{Against gravitational force}} = -W_{\text{by gravitational force}}$
- Variation of g with height

$$g' = \frac{g}{\left(1 + \frac{h}{R}\right)^2} \text{ if } h > \frac{R}{10}$$

$$g' = g \left(1 - \frac{2h}{R}\right) \text{ if } h < \frac{R}{10}$$

Note g never becomes zero with height, that is, $g \rightarrow 0$ if $h \rightarrow \infty$

- Variation of g with depth (d)

$$g' = g \left(1 - \frac{d}{R}\right); \quad \text{where } g \text{ is acceleration due to gravity at earth surface.}$$

- Variation of g with rotation of earth / latitude

$$g' = g \left(1 - \frac{R\omega^2}{g} \cos^2 \lambda\right)$$

that is, g is maximum at the poles and minimum at the equator

- Escape velocity $v_e = \sqrt{\frac{2GM}{R}}$;

Escape velocity is the minimum velocity required to escape a mass from the surface of the earth/ planet from its gravitational. If velocity provided is greater than or equal to escape velocity, the mass will never come back to the earth/planet.

- Planetary motion

$$\text{Orbit velocity } v_o = \sqrt{\frac{GM}{r}} \text{ from the fact } \frac{GMm}{r^2} = \frac{mV^2}{r} = \text{Required Centripetal force}$$

where v_o is speed with which a planet or a satellite moves in its orbit and r is the radius of the orbit.

$$\text{Time period } T = \frac{2\pi r}{v_o} \text{ or } T^2 = \frac{4\pi^2 r^3}{GM}; \quad \text{where } v_0 = \text{orbital velocity} = \sqrt{\frac{GM}{r}}$$

$$\text{Kinetic Energy } KE = \frac{1}{2}mv_o^2 = \frac{GMm}{2r}, \quad \text{Potential Energy } PE = -\frac{GMm}{r}$$

$$\text{Net energy } E = KE + PE = -\frac{GMm}{2r}$$

- Kepler's Laws

First Law : The planets revolve around the sun in the elliptical orbits with sun at one of the focus.

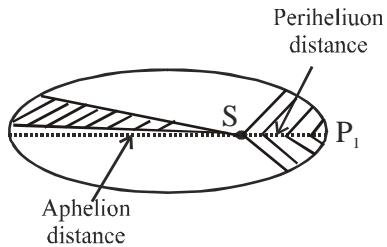


Second Law : The radial line sweeps out equal area in equal interval of time. This law may be derived from law of conservation of angular momentum.

$$\text{Areal velocity } = \frac{dA}{dt} = \frac{L}{2m} = \text{constant}$$

Q Torque about axis of rotation is zero so angular

moment is constant i.e. $I_1\omega_1 = I_2\omega_2$



$$\Rightarrow (mr_1)(v_1) = (mr_2)(v_2) \Rightarrow \frac{v_1}{v_2} = \frac{r_2}{r_1}$$

Thus $\frac{v_1}{v_2} = \frac{r_2}{r_1}$ or $\frac{v_{\text{perihelion}}}{v_{\text{aphelion}}} = \frac{r_{\text{aphelion}}}{r_{\text{perihelion}}}$ that is, when the planet is closer to the sun it moves fast.

Third Law: The square of the time period of a planet is proportional to the cube of a semimajor axis

$$T^2 \propto a^3 \text{ or } T^2 \propto r^3$$

$$\text{If eccentricity of the orbit is } e \text{ then } \frac{r_{\text{aphelion}}}{r_{\text{perihelion}}} = \frac{r_{\max}}{r_{\min}} = \frac{a + ae}{a - ae} = \frac{1+e}{1-e}$$

- Weightlessness in a satellite :

$$\text{Net force towards centre} = F_c = ma_c \Rightarrow \left(\frac{GMm}{r^2} - N \right) = m \frac{V^2}{r} \text{ where } N \text{ is contact force by the surface}$$

$$\Rightarrow \frac{GMm}{r^2} - N = m \left(\frac{GM}{r^2} \right) \text{ or } N = 0 \text{ that is, the surface of satellite does not exert any force on the body and hence its apparent weight is zero.}$$

- Gravitational potential due to a ring at any point on its axis, assuming mass of the ring is uniformly or nonuniformly distributed is

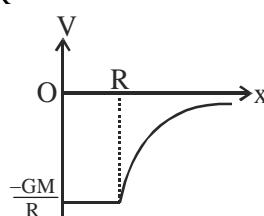
$$V = \frac{-GM}{\sqrt{R^2 + x^2}} ; \text{ potential at the centre is } \frac{-GM}{R}$$

- Gravitational potential due to a shell

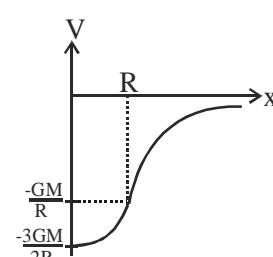
$$V_{\text{in}} = V_{\text{sur}} = \frac{-GM}{R}; \quad V_{\text{out}} = \frac{-GM}{x}$$

- Gravitational potential due to a solid sphere of radius R

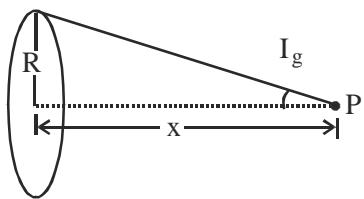
$$V_{\text{in}} = \frac{-GM}{2R^3} (3R^2 - x^2) \quad \text{for } 0 \leq x \leq R$$



$$V_{\text{sur}} = -\frac{GM}{R} \text{ for } x = R; \quad V_{\text{out}} = \frac{-GM}{x} \text{ for } x > R$$



- Gravitational field intensity due to a disc

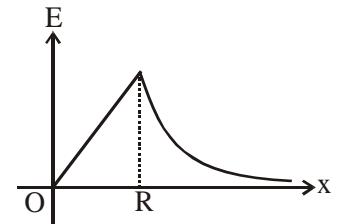


$$E = \frac{2GM}{R^2} \left[1 - \frac{x}{\sqrt{x^2 + R^2}} \right] = \frac{2GM}{R^2} [1 - \cos \theta]$$

- Gravitational field intensity due to a solid sphere

$$E_{in} = \frac{GMx}{R^3} \text{ for } x < R$$

$$E_{sur} = \frac{GM}{R^2}, E_{out} = \frac{GM}{x^2} \quad x \geq R$$

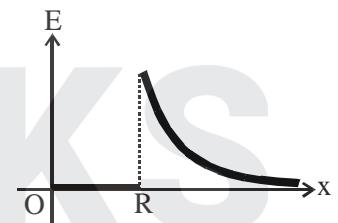


- Gravitational field intensity due to a hollow sphere

$$E_{in} = 0 ; x < R$$

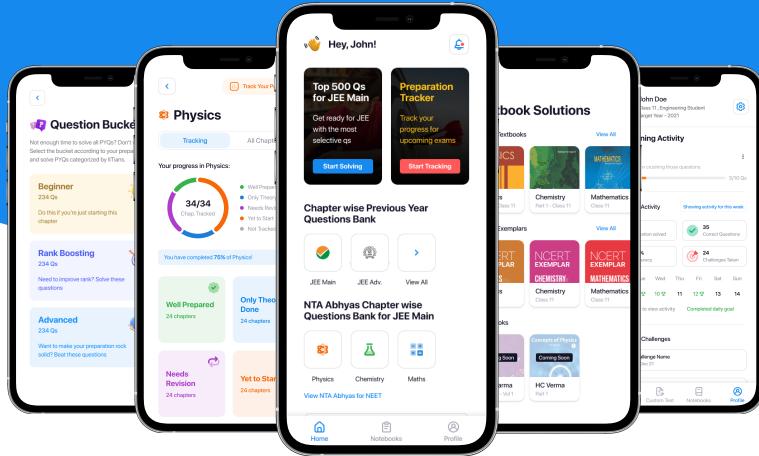
$$E_{surface} = \frac{GM}{R^2} ; x = R$$

$$E_{out} = \frac{GM}{x^2} ; x > R$$





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