UNIT CONTENTS – SENIOR ASTROPHYSICS

UNIT 10 - FUNDAMENTAL KINEMATICS II & INTRO TO CALCULUS (DIFFERENTIAL & INTEGRAL)5 HOURS (10 WEEKS)

UNIT CONTENT

Conservation of momentum in 1 and 2 dimensions (vector analysis); Definition of angular velocity $\underset{\sim}{\omega} = \frac{d\vartheta}{dt}$, $\underset{\sim}{\omega} = \frac{2\pi}{T}$ and relationship to linear velocity $\underset{\sim}{v} = \underset{\sim}{\omega} r$; Definition of angular acceleration $a_r = \frac{\underset{\sim}{v}^2}{r} = \underset{\sim}{\omega}^2 r$; Recap Newtons universal law of gravitation and escape and critical velocities; Recap centripetal force; Newton's 1st law extended to angular momentum & external torque; recap rotational mechanics; Review of gradients, average and instantaneous rates of change $\frac{\Delta y}{\Delta x}$; Concept of a limit $\lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x}$; Derivative by first principals (limit theory); Application of the derivative principals e.g. $\frac{ds}{dt}$ & $\frac{dv}{dt}$; Rules for differentiation (polynomial & exponential functions) – power functions (product & quotient rules), higher-order derivatives (chain rule); Curvilinear motion (parametric equations); Area under a curve (e.g. velocity-time graph); Relationship between the formula for the area under the curve of a function and the function (i.e. $A = \frac{1}{2}x^2$ and $f(x) = x$); General pattern for integration $\frac{x^{n+1}}{n+1}$; Integrand function as $F(x) = \int f(x)dx$; Application of integration principles e.g. $s = \int v\, dt$ & $v = \int a\, dt$; Concept of a definite integral $\int_a^b f(x)dx = F(b) - F(a)$; Higher-order integrals – substitution methods; Integration by parts; Magnitudes of resolved vectors for displacement, velocity & acceleration; Direction vectors for displacement, velocity and acceleration; Related rates w.r.t. time e.g. $\frac{dF}{dt}$, $\frac{dr}{dt}$; Work done by variable forces $W = \int_a^b f(x)\, dx$; Derivation of gravitational potential energy between two masses (using calculus).

ASSESSMENT

Supervised Written (Examination) – Unit 10 Parts A & B. Duration 2 hrs. 20 mins total.

Unit 11 – The Nature of Stars & Distance Relations

21 hours (6 weeks)

Unit Content

Measuring the distances of stars using stellar parallax (terrestrial & space); Intrinsic brightness (luminosity - *L*) and apparent brightness (*b*) (flux - *F*); Brightness factor $100^{\frac{1}{5}} \approx 2.512$; Using photometry to measure a star's apparent brightness (flux); Relationship between a star's apparent brightness, its luminosity and distance $b = \frac{L}{4\pi d^2}$; Calculating a star's luminosity from its apparent brightness $\frac{L}{L_\odot} = \left(\frac{d}{d_\odot}\right)^2 \frac{b}{b_\odot}$; Magnitude scales - Apparent magnitude (*m*) and Absolute magnitude (*M*); Magnitude difference related to brightness ratio $m_2 - m_1 = 2.5\log\left(\frac{b_1}{b_2}\right)$; Relationship between a star's apparent magnitude and absolute magnitude $m - M = 5\log d - 5$; Relation between a star's colour and temperature (blackbody curves and dominant wavelength); UBV photometry; Absorption line spectra & spectral classes & types – OBAFGKM (spectral) sequence; Strength of absorption lines; Stellar radii, luminosity & surface temperature $L = 4\pi R^2 \sigma T^4$, $\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$; Hertzsprung-Russell (H-R) diagrams; Star varieties - main Sequence (V), sub-giants (IV), giants (III), bright giants, (II), supergiants (Ia & Ib), white & brown dwarfs; Determining a star's size from its spectrum; Luminosity classes; Spectroscopic parallax; Binary star systems - Kepler's 3rd law for binary star systems $M_1 + M_2 = \frac{a^3}{T^2}$; Radial velocity curves for binary systems and light curves of eclipsing binaries; Main-sequence masses & mass-luminosity relation; Total flux of a star $F_{\text{bol}} = \int_0^\infty F_\lambda d\lambda$; Apparent bolometric magnitude $m_{\text{bol}} = C_{\text{bol}} - 2.5\log F_{\text{bol}}$; Relation between absolute bolometric magnitude and luminosity $\frac{L}{L_\odot} = 10^{0.4(4.74 - M_{\text{bol}})}$; Filter systems (e.g. *Johnson-Cousins system*) and Multicolour photometry; Colour indices (e.g. $B - V = m_B - m_V$); Relation between the surface temperature *T* and the colour index $T \approx \frac{9\,000\,K}{(B-V)+0.93}$; Bolometric corrections (e.g. $BC = m_{\text{bol}} - m_V = M_{\text{bol}} - M_V$); Atmospheric extinction (dimming) $m_V(\text{above atmosphere}) \approx m_V - 0.2\sec\text{Z}$.

Assessment

CLEA computer simulation activity "Photoelectric Photometry" and exercise questions.

Additional Assessment Opportunities

- ☼ GHOU "Brightness Vs. Distance" unit
- ☼ GHOU "Spherical Distribution" unit
- ☼ GHOU "Distance, Luminosity Vs. Apparent Brightness" unit

Unit 12 - Birth & Life of Stars

21 hours (6 weeks)

Unit Content

Nebulae & interstellar medium; Emission nebulae – excitation of hydrogen (H II regions); Dark & reflection nebulae (including Bok globules); Interstellar extinction & reddening; Evolution of protostars and pre-main-sequence stars; High & low mass; T Tauri stars (bipolar outflow & Herbig-Haro objects); Accretion disks; Star clusters; Cluster plots on HR diagrams to determine the age of the cluster; Molecular clouds; Supernova remnants and nebulae; Main-sequenced stars (ZAMS) – zero-age main sequence; Evolution of stars between 0.08 and 0.4 $M_{\odot}$ and $M > 0.4 M_{\odot}$; Main-sequence lifetimes; Post-main-sequence evolution; Core helium fusion, helium flash, electron degeneracy & position on H-R diagram; Star clusters – ages & turnoff points; Globular & open clusters; Population I & II stars; Variable stars – Cepheid variability; Cepheids as a measure of distance using $M = m - 5\log(d/10)$; Period-Luminosity relation; Binary stars & mass transfer.

Mathematical base

Star Formation: Density of molecular hydrogen ($\mathrm{H_2}$) clouds $\rho_{mc} \approx 2m_p n_{mc}$; Ratio of final and initial radius of a molecular cloud (one solar mass) $\frac{R_{\odot}}{R_{mc}} = \left(\frac{\rho_{mc}}{\rho_{\odot}}\right)^{\frac{1}{3}}$; Free-fall time $t_{\mathrm{ff}} = \left(\frac{3\pi}{32G\rho_0}\right)^{\frac{1}{2}}$ and pressure gradient time $t_{\mathrm{press}} = \frac{r_0}{c_s}$ where $c_s = \left(\frac{\gamma kT}{\mu m_p}\right)^{\frac{1}{2}}$; Jeans length $r_{\mathrm{J}} = \left(\frac{3\pi\gamma kT}{32G\rho_0\mu m_p}\right)^{\frac{1}{2}}$ or $r_{\mathrm{J}} \approx 2000\ \mathrm{AU} \left(\frac{T}{10\ \mathrm{K}}\right)^{\frac{1}{2}} \left(\frac{\rho_0}{3\times10^{-15}\ \mathrm{kg\ m^{-3}}}\right)^{-\frac{1}{2}}$; Jeans mass $M_{\mathrm{J}} \approx 0.2 M_{\odot} \left(\frac{T}{10\ K}\right)^{\frac{3}{2}} \left(\frac{\rho_0}{3\times10^{-15}\ \mathrm{kg\ m^{-3}}}\right)^{-\frac{1}{2}}$; Rotation speeds $v_f = \left(\frac{r_0}{r_f}\right) v_0$; Radius of disc after collapse $r_f = \frac{v_0^2 r_0^2}{GM}$.

UNIT 12 - BIRTH & LIFE OF STARS (CONT.)

MATHEMATICAL BASE

Stellar Interiors - Equations of Stellar Structure: Derivation of the equation of hydrostatic equilibrium $\frac{dP}{dr} = -\frac{GM_r\rho_r}{r^2}$; Deriving an equation to estimate the central pressure of a star $P_c \approx 2\frac{GM_\odot\rho_\odot}{R_\odot} \approx \frac{8\pi}{3}G\rho_\odot^2 R_\odot^2$; Equation of mass continuity $\frac{dM}{dr} = 4\pi r^2\rho(r)$; Relating pressure to density using the equation of state $P(r) = \frac{\rho(r)kT(r)}{\mu m_p}$; Radiation pressure exerted by photons $P_{\text{rad}}(r) = \frac{a}{3}[T(r)]^4$; Estimation of the central temperature of a star using the ideal gas law as the equation of state $T_c \approx P_c\frac{\mu_\odot m_p}{\rho_\odot k} \approx \frac{2GM_\odot\mu_\odot m_p}{R_\odot k}$; Central temperature for sphere of ideal gas in hydrostatic equilibrium $T_c \propto \frac{M_\mu}{R}$.

Energy Generation in Stars: The equation of energy generation $\frac{dL}{dr} = 4\pi r^2\rho(r)\epsilon(r)$; Derive the gravitational potential energy of a mass shell $dU = -\frac{GM_r}{r}dm$ and $U = -\frac{3}{5}\frac{GM^2}{R}$; Gravitational potential energy of the Sun as $U_\odot = -q\frac{GM_\odot^2}{R_\odot}$; Kelvin-Helmholtz time $t_{KH} \equiv \frac{|U_\odot|}{L_\odot}$; Mass deficit and Einstein's mass energy equation $\Delta E = (\Delta m)c^2$; Energy release from fusion $E_{\text{fus}} = \frac{N_{\text{H}}}{4}\Delta E$ and fusion timescale $t_{\text{fus}} = \frac{E_{\text{fus}}}{L_\odot}$; Potential energy of two protons separated by a distance r $U = \frac{e^2}{4\pi\epsilon_0}\frac{1}{r}$; Typical kinetic energy of a proton at the centre of the $\langle E\rangle = \frac{3kT_c}{2}$; de Broglie wavelength for a proton $\lambda_{dB} = h(2m_pE)^{-\frac{1}{2}}$; Minimum kinetic energy at which tunnelling has a significant probability $E \approx \left(\frac{e^2}{4\pi\epsilon_0}\right)^2\frac{2m_p}{h^2}$; The net result of the PP chain being $4\text{p} \rightarrow {}^{4}\text{He} + 2\text{e}^+ + 2\nu_\text{e} + 2\gamma$; The net result of the CNO cycle being $4\text{p} \rightarrow {}^{4}\text{He} + 2\text{e}^+ + 2\nu_\text{e} + 3\gamma$; Triple alpha process ${}^{4}\text{He} + {}^{4}\text{He} \rightarrow {}^{8}\text{Be} + \gamma$ and ${}^{4}\text{He} + {}^{8}\text{Be} \rightarrow {}^{12}\text{C} + \gamma$.

ADDITIONAL ASSESSMENT OPPORTUNITIES

- ☼ GHOU "Cepheid Variable Stars" unit
- ☼ GHOU "The Science of Cepheids" unit

UNIT 13 – STELLAR REMNANTS

21 hours (6 weeks)

UNIT CONTENT

Old low-mass stars becoming Supergiants (0.4 – 4 $M_\odot$); Horizontal branch stages of red giant stars; Asymptotic giant branch (AGB) stars – structure; Planetary nebulae; White dwarfs; Properties; Mass-radius relation; Intermediate-Mass and High Mass stars; Heavy element fusion reactions; Supernova explosions; Supernovae types (Ia, Ib, Ic, II); Decay of supernova; Remnants of supernovae - neutron stars and pulsar.

MATHEMATICAL BASE

Average density is a white dwarf as a ratio to solar density $\rho_{\text{wd}} = \frac{M_{\text{wd}}}{M_\odot}\left(\frac{R_\odot}{R_{\text{wd}}}\right)^3 \rho_\odot$; Derivation of central pressure as a ratio to central solar pressure $P_c \sim \left(\frac{M_{\text{wd}}}{M_\odot}\right)^2 \left(\frac{R_\odot}{R_{\text{wd}}}\right)^4 P_{c,\odot}$; Electron degeneracy pressure; Quantum states of an electron in a hydrogen atom (principle n), (orbital m_l), (orbital magnetic *l*) and (orbital magnetic m_s); Pauli exclusion principle; Heisenberg uncertainty principle $\Delta x \Delta \boldsymbol{p} \geq \hbar$; number density (of degenerate electrons) n_e; Uncertainty of a degenerates electron's location as $\Delta x \sim V^{\frac{1}{3}} \sim n_e^{-\frac{1}{3}}$; Uncertainty of a degenerate electron's momentum as $\Delta \boldsymbol{p} \sim \frac{\hbar}{\Delta x} \sim \hbar n_e^{\frac{1}{3}}$; Velocity (Heisenberg speeds) of nonrelativistic degenerate electrons as $\Delta v = \frac{\Delta \boldsymbol{p}}{m_e} \sim \frac{\hbar n_e^{\frac{1}{3}}}{m_e}$; Velocity of electrons due to thermal motion $v_{\text{th}} \sim \left(\frac{kT}{m_e}\right)^{\frac{1}{2}}$; Pressure contributed by thermal pressure as $P_{\text{th}} = n_e kT \sim n_e m_e v_{\text{th}}^2$; Pressure contributed by degenerate electrons $P_{\text{degen}} \sim n_e m_e (\Delta\, v)^2 \sim n_e m_e \left(\frac{\hbar n_e^{\frac{1}{3}}}{m_e}\right)^2 \sim \hbar^2 \frac{n_e^{\frac{5}{3}}}{m_e}$; Mass-radius relationship - $R \sim \frac{\hbar^2}{G m_e m_p^2}\left(\frac{M}{m_p}\right)^{-\frac{1}{3}}$; Increasing average density rapidly with mass - $\langle\rho\rangle \sim \frac{M}{R^3} \sim \frac{G^3 m_e^3 m_p^5}{\hbar^6} M^2$; Number & critical mass density of relativistic degenerate electrons $n_e \sim \left(\frac{c m_e}{\hbar}\right)^3$ and $\rho \sim \frac{2c^3 m_e^3 m_p}{\hbar^3}$; Mass when degenerate electrons becomes relativistic $M \sim \left(\frac{\hbar^3 c^3}{G^3 m_p^4}\right)^{\frac{1}{2}}$; Energy and energy density of relativistic electrons $E_{\text{rel}} \sim (\Delta p) c \sim \hbar n_e^{\frac{1}{3}} c$ and $u_{\text{rel}} \sim \hbar c n_e^{\frac{4}{3}}$.

UNIT 13 – STELLAR REMNANTS (CONT.)

MATHEMATICAL BASE

Pressure contributed by highly relativistic degenerate electrons $P_{\text{rel}} \sim \frac{\hbar c}{3} n_e^{\frac{4}{3}}$; Central pressure of a white dwarf $P_{\text{c,rel}} \sim \frac{\hbar c}{m_p^{\frac{4}{3}}} \frac{M^{\frac{4}{3}}}{R^4}$; Chandrasekhar mass for a carbon/oxygen white dwarf as $M_{ch} \sim 1.4 M_{\odot}$; The main sequence lifetime of a massive star $\tau \approx 30\text{Myr} \left(\frac{M}{7M_{\odot}}\right)^{-3}$; Degenerate non-relativistic neutron pressure $P_n \sim \hbar^2 \frac{n_n^{\frac{5}{3}}}{m_n}$; Neutron star radius $R \sim \frac{\hbar^2}{G m_n m_p^2} \left(\frac{M}{m_p}\right)^{-\frac{1}{3}}$; Ratio of neutron star to white dwarf radius/mass relation $\sim \frac{1}{1839} \left(\frac{M_{\text{wd}}}{M_{\text{ns}}}\right)^{-\frac{1}{3}}$ yielding $R_{\text{ns}} \sim 3\ km \left(\frac{M_{\text{ns}}}{1.4 M_{\odot}}\right)^{-\frac{1}{3}}$, and accounting for strong force $R_{\text{ns}} \approx 11\ km \left(\frac{M_{\text{ns}}}{1.4 M_{\odot}}\right)^{-\frac{1}{3}}$; Escape speed from a neutron star (Newtonian formula) $v_{\text{esc}} = \left(\frac{2GM_{\text{ns}}}{R_{\text{ns}}}\right)^{\frac{1}{2}}$; Escape speed from a neutron star as a significant fraction of the speed of light $\frac{v_{\text{esc}}}{c} \approx 0.6 \left(\frac{M_{\text{ns}}}{1.4 M_{\odot}}\right)^{\frac{2}{3}}$.

ASSESSMENT

Unsupervised Individual Written (Assignment Questions – Open Book) – Units 12 & 13

ADDITIONAL ASSESSMENT OPPORTUNITIES

- ☼ CLEA computer simulation and work-booklet “Dying Stars & the Birth of the Elements”
- ☼ CLEA computer simulation and work-booklet “Pulsars”
- ☼ GHOU “Searching & Discovering a Supernova” unit
- ☼ GHOU “Supernova Light Curves” unit

UNIT 14 - CONIC SECTIONS

18 hours (5 weeks)

UNIT CONTENT

Description of Conic Sections; Orbits – open (parabolic & hyperbolic), closed (circular and elliptical); Cartesian & Polar coordinate systems; Distance formula $r=\sqrt{(x_1,y_1)^2+(x_2,y_2{}^2)^2}$; Cartesian circle $x^2+y^2=r^2,(x-h)^2+(y-k)^2=r$; Cartesian parabola $x^2=4py$, $(x-h)^2=4p(y-k)$; Cartesian ellipse $\frac{(x-h)^2}{a^2}+\frac{y^2}{b^2}=1$; Ellipses – Properties and construction of (foci, perihelion, aphelion), perigee & apogee.

Derivation (from first principals of kinematics) of: Eccentricity as $e=\frac{c}{a}$, $e=\frac{F_a-F_p}{ap}$ & $e=\frac{A-P}{A+P}$; Velocities at perigee & apogee $\hat{v}_P=\sqrt{\frac{GM}{P}(1+e)}$ & $\hat{v}_A=\sqrt{\frac{GM}{A}(1-e)}$; Velocities at points in elliptical orbits $\hat{v}=\sqrt{GM\left(\frac{2}{r}-\frac{1}{a}\right)}$; Period of elliptical orbits $T=2\pi\sqrt{\frac{a^3}{GM}}$; definition of eccentricity using loci, foci and directrix; Introduction to orbital parameters - apogee and perigee (elliptical orbits); Introduction to Polar coordinates (r, ϑ); Recap Sine & Cosine rules - $\frac{a}{\sin A}=\frac{b}{\sin B}=\frac{c}{\sin C}$, $a^2=b^2+c^2-2bcCosA$; Recap unit circle - $x=r\cos\vartheta, y=r\sin\vartheta, \tan\vartheta=\frac{y}{x}$ functions; Converting between Cartesian & Polar coordinate equations; Polar equations for conic sections, $r=\frac{ep}{1-e\cos\vartheta}$ at e = 1, ½, & 2; $r=\frac{a(1-e^2)}{1-e\cos\vartheta}$ (ellipse); $r=\frac{p}{2-\cos\vartheta}$ (parabola); $r=\frac{2p}{1-2\cos\vartheta}$ (hyperbola).

ASSESSMENT

Supervised Written (Examination) – 2 hours total

UNIT 15 – COSMOLOGY

24hours (7 weeks)

UNIT CONTENT

General relativity & the expanding Universe; Red-shifts & expansion; Hubble constant & the age of the Universe; Detection of the cosmic microwave background & spectrum; Symmetry of the Universe; Strong & weak forces; Quarks; Superstring theories; Evolution of the Universe – Planck time, GUT theory, inflationary epoch, confinement period; Matter & antimatter, pair production & annihilation; Primordial fireball & era of recombination; Cosmic light horizon; Structure of the early universe; Period of the dark ages & star formation – initial galaxy structures; Cosmic timeline & fate of the Universe; Dark matter & dark energy; Overall space time; Closed & open Universe; Possible geometries of the Universe; Curvature of space fabrics; The effects of dark energy; Special theory of relativity - time dilation and length contraction $T = \frac{T_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$ and $L = L_0\sqrt{1-\left(\frac{v}{c}\right)^2}$; Space-time continuum – Gravitational Redshift; Using general relativity to predict black holes. – Event horizons & Accretion disks; Inside a black hole ; Calculating the dimensions of black holes from the Schwarzschild radius $R_{sch} = \frac{2GM}{C^2}$; Super-massive black holes – several billion $M_{\odot}$; Black hole – neutron star binaries; Fate of black holes.

ASSESSMENT

Unsupervised Written (Project) – Estimating Dark Matter in a Spiral Galaxy;
CLEA computer simulation and Exercise Questions “The Hubble Law – Redshift/Distance Relation”
CLEA computer simulation and Exercise Questions “The Large Scale Structure of the Universe”

UNIT 16 – GALAXIES (ADDITIONAL UNIT)

14 hours (4 weeks)

UNIT CONTENT

Hubble classification of Galaxies; Spiral galaxies; correlation between tightness of spiral arm to the nuclear bulge; Sa, Sb & Sc subclasses; The winding dilemma; Flocculent spiral galaxies; Grand design galaxies; Spiral density waves; Barred galaxies; Elliptical galaxies & subtypes; Irregular galaxies; Hubble tuning fork diagram; Clusters & Super-clusters; Globular & irregular clusters; Voids; Galactic merging & cannibalism; Galactic halos & dark matter; Red shift of galaxies; Hubble flow (expansion of universe); Hubble Law $v = H_0 \times d$; Different techniques in measuring cosmological distances; Gravitational lensing; Structure of the Milky Way Galaxy; Using Cepheid's to find the Galactic centre; Using 21 cm radio radiation (photon emission from hydrogen) to map our Galaxy; Dimensions of our Galaxy; Visible verses dark matter; The Galactic nucleus; Synchrotron radiation; Orbits of halo & disk stars – presence of dark matter; Rotation of our Galaxy; Quasars (quasi-stellar objects); Large red shits of quasars; Spectrum of quasars; Quasars as the most distant objects in the Universe; Active Galaxies; Radio galaxies; Peculiar galaxies; Seyfert galaxies; BL Lacertae objects; Blazars; Double radio sources; Head-tail sources; Galaxy & quasar luminosity table; Super-massive black holes as *central engines* that drive active galaxies; Gravity as a focus for light.

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