PHYC10008

STUDY NOTES

89 (H1 First Class Honours)

UNIVERSITY OF MELBOURNE (THE)

TABLE OF CONTENTS

NEWTON'S UNIVERSAL LAW OF GRAVITATION

Newton's universal law of gravitation—

- Every mass attracts every other mass
- Attraction is directly proportional to the product of their masses
- Attraction is inversely proportional to the square of the distance between their centres
    - $F_g = G\frac{M_1 M_2}{r^2}$
        - $G = 6.67 \times 10^{-11}\, m^3 kg^{-1} s^{-2}$
- Kepler's laws apply to all orbiting objects (not just planets)
- Ellipses are not the only orbital paths
    - orbits can be bound (ellipses) or unbound (parabola, hyperbola)
        - gravitational force determines shape of these orbits

Centre of mass—

- As momentum is conserved, orbiting objects orbit around their centre of mass
- Heavier objects have the centre of mass closer to them
    - $m_1 r_1 = m_2 r_2$
- Stars observed to be oscillating in regular manner then we know it has planets orbiting it

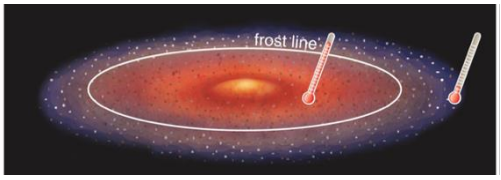
Kepler's third law—

- Newton's laws of gravity & motion showed that the relationship between the orbital period & average orbital distance of a system tells us the total mass of the system
    - e.g. Earth's orbital period (1 yr) & average distance (1 AU) tell us the **Sun's mass**
    - e.g. orbital period & distance of a satellite from Earth tell us **Earth's mass**
    - e.g. orbital period & distance of a moon of Jupiter tell us **Jupiter's mass**
- Newton's laws of gravity & motion showed that the relationship between the orbital period & average orbital distance of a system tells us the total mass of the system

NEWTON'S VERSION OF KEPLER'S LAWS:

- $p^2 = \frac{4\pi^2}{G(M_1+M_2)}a^3$
- $\boldsymbol{M_1 + M_2 = \frac{4\pi^2 a^3}{Gp^2}}$
    - $p \Rightarrow$ orbital period
    - $a \Rightarrow$ average distance (between centres)
- This law allows us to weigh distant objects by observing the period & measuring the separation of the two objects
    - e.g. mass of Sun is much greater than that of Earth ($M_1 + M_2 \approx M_1$)

- INSIDE FROST LINE ⇒ too hot for H-compounds to form ices
- OUTSIDE FROM LINE ⇒ cold enough for ices to form



HOW TERRESTRIAL PLANETS FORMED:

- Small particles of rock & metal were present inside FL
- **Planetesimals** of rock & metal built up as these particles collided
- Gravity eventually assembled these **planetesimals into terrestrial planets**
    - gravity draws planetesimals together to form planets (accretion)
- This explains why planets are evenly spaced
- Planets would keep colliding/accreting & assembling larger masses if they weren't spaced

HOW JOVIAN PLANETS FORMED:

- Ice could also form small particles outside the frost line
- Larger planetesimals & planets were able to form
- Gravity of these larger planets was able to draw in surrounding **H/He gases**
    - i.e. gravity of rock & ice in jovian planets draws (accretes) H & He gases
    - EACH JOVIAN PLANET IS A *MINIATURE SOLAR SYSTEM*
- A combination of photons & solar wind (outflowing matter from the Sun) blew away the leftover gases
    - solar wind turned on & planet formation ceased!

Solar rotation:

- In nebular theory ⇒ **young Sun rotated much faster than now**
- Friction between solar magnetic field & solar wind probably slowed the rotation over time
    - magnetic field of the Sun traps charged particles

Composition of SS—

- H/He gas ⇒ 98%
    - do not condense in nebula
- H-compounds (e.g. water, methane, ammonia) ⇒ 1.4%
- Rock (various minerals) ⇒ 0.4%
- Metal (e.g. iron, nickel, aluminium) ⇒ 0.2%

What asteroids & comets are—

- They are leftover junk from the formation of planetary accretion process
    - **rocky asteroids inside FL & icy comets outside FL**
    - **they are not spherical in shape** (not heavy enough for gravity to affect its shape)
        - white comet tail is made of particles (dust + ice) & blue tail is made of ions
            - tail of charged particles are swept to one side by solar wind
- **Heavy bombardment** = leftover planetesimals bombarded other objects in late stages of SS formation (i.e. cratering)

TERRESTRIAL PLANETS I

The interior of terrestrial planets—

- Mercury ⇒ heavily cratered, has long steep cliffs
- Venus ⇒ cloud-penetrating radar revealed a twin-peaked volcano
- Earth ⇒ portion of surface appears as
- Moon ⇒ heavily cratered in most places
- Mars ⇒ features that look like dry riverbeds, impact craters

DENSITY:

- $Density = \frac{mass}{volume} = \frac{M}{\frac{4}{3}\pi r^3}$
- Usually measured in g/cm^3
- Earth has average density of 5.5 g/cm^3 ⇒ must have a metallic core (& lots of rock)
    - since density of rock & iron are 2.7–3.7 & 7.8 g/cm^3 resp.

Earth's interior—

- Core ⇒ highest density part (= nickel + iron)
- Mantle ⇒ moderate density (= silicon + oxygen etc.)
- Crust ⇒ lowest density (= granite + basalt etc.)

TERRESTRIAL PLANET INTERIORS:

- Possible to use knowledge of Earth's interior infer about the interiors of other planets may be like

Differentiation:

- **Gravity pulls high-density material to the centre** ⇒ low-density material rises to surface
    - material ends up separated by density!

Lithosphere:

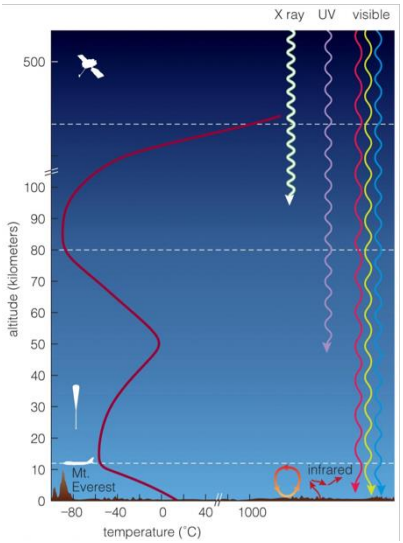
- A planet's outer layer of cool, rigid rock which ***floats*** on warmer/softer rock lying beneath

SEISMIC WAVES TRAVEL THROUGH THE EARTH:

- P-waves **push** matter back & forth
- S-waves **shake** matter side to side
- **Velocity of seismic waves as a function of depth**
- P-waves go through Earth's core BUT S-waves do not
    - = Earth's core must have a liquid **OUTER** layer
- Accretion & differentiation when planets were young (loss of potential energy) made the **core of the Earth HOT**
    - **radioactivity (fission) inside the core contributes to high temperatures**
- Convection, conduction & radiation heat losses made the **interior of the Earth COOL**
    - convection = transports heat as hot material rises & cool material falls

TERRESTRIAL PLANETS III

Atmospheric properties vary with altitude—



- Heating caused by light of different energies from the Sun
- Heating from below by Earth's surface
    - denser atmosphere near surface

LIGHT'S EFFECT ON ATMOSPHERE:

- Ionisation ⇒ removal of an electron (UV/X-ray)
- Dissociation ⇒ destruction of a molecule (UV/X-ray)
- Scattering ⇒ change in photon's direction (optical)
    - shorter wavelengths scatter more
- Absorption ⇒ photon's energy is absorbed (IR)

SKY IS BLUE:

- Atmosphere scatters blue light from Sun = makes it appear to come from diff. directions
- Sunsets are red because red light scatters less
- Magnetic field of Earth's atmosphere protects us from charged particles streaming from Sun (solar wind)
- Charged particles from solar wind energise the upper atmosphere near magnetic poles (= aurora)

Weather & climate—

- Weather ⇒ daily variations in wind, clouds, temp. & pressure
    - LOCAL & hard to predict
- Climate ⇒ long-term average of weather (i.e. stability)
    - depends on global conditions & more predictable
- The hot/cold of the equator & poles plus Earth's rotation produce **circulation cells**
    - rotations cause **smaller** circulation patterns

Factors that affect the atmosphere—

SOLAR BRIGHTENING:

- Sun very gradually grows brighter with time
    - increases amount of sunlight warming the planets (billions of years timescale)

CHANGES IN AXIS TILT:

- Larger tilt creates more extreme seasons & while smaller tilt keeps polar regions colder
- Small gravitational tugs from other bodies in SS causes Earth's axis tilt to vary between 22˚ & 25˚
    - **axis tilt is usually 23.5˚**

CHANGES IN REFLECTIVITY:

- HIGHER reflectivity tends to cool a planet & LOWER reflectivity leads to warming

SPECIAL & GENERAL RELATIVITY

Special relativity—

REFERENCE FRAME TRANSFORMATIONS:

- Special relativity is consistent (no paradoxes) if length & masses also change
    - time (t) dilation is given by $\boldsymbol{t' = \frac{t}{\gamma} = t\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$
    - length (l) contraction is given by $\boldsymbol{l' = \frac{l}{\gamma} = l\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$
    - mass (m) increase is given by $\boldsymbol{m' = m\gamma = \frac{m}{\sqrt{1-\left(\frac{v^2}{c^2}\right)}}}$

LENGTH CONTRACTION:

- Length contracts if measured from observer moving with respect to object
    - effect becomes significant ONLY close to $\boldsymbol{v = c}$

Consistency & interstellar travel—

- On Earth we see time dilation & astronauts will see time contraction

INTERSTELLAR TRAVEL AT NEAR SPEED OF LIGHT:

- ALL is consistent & near-c travel is theoretically a good opportunity to reach other exo-planets
- To maintain consistency with universal speed of light ⇒ c is the maximum speed attainable
- Velocities DO NOT simply add in special relativity
    - & ONLY massless particles travel at c

MOVING MASS INCREASE:

- v CANNOT grow significantly ⇒ momentum gained has to **change mass**
    - $p = mv$
    - $\Delta p = Ft$

Deriving the most famous equation—

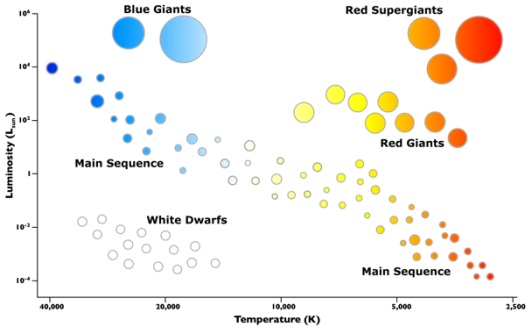
- Imagine a spaceship travelling at the speed of light (therefore $L = ct$)
- Since $p = mv$ & $\Delta p = Ft$ then $\boldsymbol{\Delta mc = Ft}$
    - $\boldsymbol{\Delta E = FL = Fct}$
    - $\boldsymbol{Ft = \frac{\Delta E}{c}}$
    - $\boldsymbol{\frac{\Delta E}{c} = \Delta mc}$ then $\boldsymbol{E = \Delta mc^2 = mc^2}$

MASS-ENERGY EQUIVALENCY:

- Energy & mass are equivalent & can be transformed into each other
- HUGE amount of energy can be extracted from mass

SURVEYING THE UNIVERSE

Hertzsprung-Russell Diagram (HR diagram)—



- Very useful plot for showing how stars relate to each other
- Relates star luminosity to surface temperature

LUMINOSITY:

- Apparent magnitude ⇒ how bright a star is as viewed from the Earth
    - could be either **HIGH luminosity star far away** or **LOW luminosity star closer by**
- Absolute magnitude ⇒ how bright a star is as viewed from a set distance (e.g. 10 pc)

DETERMINING DISTANCE USING PARALLAX:

- Measure **apparent movement** of stars over a year
    - apparent movement is caused by Earth's actual movement around the Sun
- **Parsec** = new distance unit invented for parallax method of distance measurement
    - it is the distance at which an object would have a parallax of **one arcsecond**
    - $parsec\ (disance) = \frac{1}{parallax\ angle\ (arcsec)}$
        - 1 parsec = 3.26 light years
        - smaller parallax angle ⇒ larger distance

Apparent brightness vs luminosity—

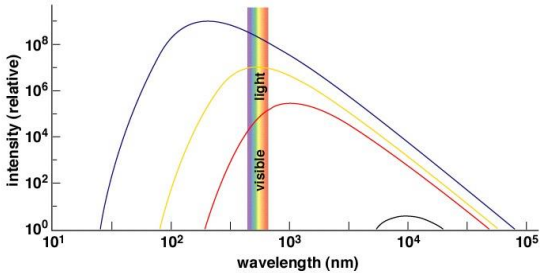
- Apparent brightness ⇒ how bright an object appears to telescopes on Earth
    - depends on **distance** to observer
- Luminosity ⇒ actual power output of the object
    - intrinsic property of the object

Stellar luminosity—

- $Apparent\ Brightness = \frac{Luminosity}{4\pi \times distance^2}$
    - $Luminosity = Apparent\ Brightness \times 4\pi \times distance^2$
- Can infer (absolute) LUMINOSITY ⇒ how much power is emitted

Temperature of stars—

- Peak of thermal spectrum (Wien's Law) tells us that hotter objects are blue
    - **COOLER ⇒ REDDER**
    - **HOTTER ⇒ BLUER**



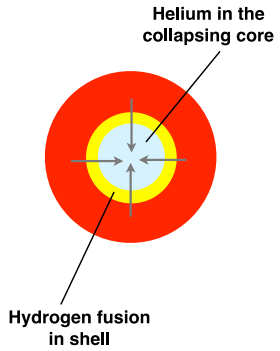
LIVES OF STARS

Rules for stellar evolution—

- There is a struggle b/w **gravity** (wanting to crush it) & **thermal pressure** (wanting to expand it)
    - IN gravitational equilibrium ⇒ balance
    - NOT in gravitational equilibrium ⇒ out of balance

Main sequence (stage 1)—

- 90% of its life is spent on MS ⇒ fuses H into He in the core (T=15 million K for Sun)
    - stellar thermostat keeps luminosity & temp. stable (10 billion years for Sun)
- The core starts to collapse w/o fusion
    - temp. is **NOT HIGH enough** to fuse He (100 million K needed)
    - no more fusion in core (= no heat) lowers thermal pressure
        - i.e. gravity causes **MORE** collapse!
    - core temp. starts to heat up (T~50 million K)
        - i.e. layers above the core must collapse (& heat up) too



- NOW hot enough for Hydrogen fusion in shell around the core
- Hydrogen shell burning is closer to surface of star = RED GIANT!
    - HIGH temp. w/o as much mass above it to keep pressure balanced
    - outer layers of star puff up & cool off (= radiation can leave more easily)
- He in collapsing core (hot), H shell fusing to He & expanding outer layers (w/ H)
    - Sun swells to 100+ times original radius & 1000 times more luminous
    - temps. drop to ~3000 K (= red)

Red giants (stage 2)—

- No more core fusion (thermostat is broken)
- Hydrogen SHELL fuses faster as core collapses ⇒ more energy created
    - MORE pressure & LESS gravity ⇒ star becomes larger/cooler BUT brighter
    - core continues to shrink = becomes denser & hotter

HELIUM FUSION:

- He starts to fuse into C when core contracts enough to heat to 10 million K ⇒ **Helium flash**
- Triple-alpha fusion = THREE He nuclei ⇒ ONE C nucleus (plus energy)
- Core **EXPANDS** w/ new He fusion (He burning) ⇒ H fusion in shell **DECREASES**
- After He flash ⇒ He to C (in core) & H to He (in shell)!