Contents

Part I

Class Notes

Chapter 1

Astro210

1.1 Early Astronomy

Greek

- Aristotle
  - earth is spherical
  - partial lunar eclipses
  - some stars visible from southern locations but not northern and vice versa
  - had ideas regarding perfect geo influenced by Pythagoras and Plato
- Aristarchus (310-230 BC):
  - unpreceded heliocentric framework
  - trig distances earth-moon-sun system
  - angular diameters $\theta_{sun} \approx \theta_{moon} \therefore \frac{A}{C} = \frac{D_{moon}}{D_{moon}}$
  - diameters from lunar eclipses $D_{moon} < D_{earth}$
- Eratoshs (176-195 BC):
  - Determined radius of spherical earth R_E
  - Sun at zenith at noon on summer solstice at Aswan
  - But further north in Alexandria, Egypt, the sun is south of the zenith by angle α
- Hipparchus (190-120 BC):
  - Discover precession of the equinoxes from examination of star catalogs over centuries
  - established the magnitude system
- Copernicus (1473-1543):
  - heliocentric
  - earth rotates
  - still assumed uniform circular celestial motion
  - inferior planets: orbit smaller than earths
  - superior planets: orbits larger than earths

1.1.1 Emergence of modern Astro

Inferior planets

- B/C = sin θ_E
- B=C Sin θ_E
- C is AU
- Early astronomers didnt know C, so they could only infer rations of B/C. Ie. Orbital radii measured in AU

Superior Planets

- Measure time between opposition and eastern quadrature
- want angle θ between opp and east quad
- $\theta = (\omega_E - \omega_p)$ and $C/B = cos\theta$
- measure τ and synodic period, calculate sidereal period and ω_p; know ω_E and infer C/B

Galilean Revolution

- Galileo Galilei (1564 -1642)
-
  - improved and used a basic refracting telescoping
- def publication of early results 1610 *"starry messenger"*
-
  - Moon is cratered; not a perfect Sphere
  - milkyway is made out of stars
  - Jupiter has moons (or as he thought, stars)
  - measured phases of Venus

Phases of Venus

- direct confrontation with Ptolemaic geocentric models
- in Ptolemaic models you only see crescent phases

Tycho Brahe (1546-1601)

- Denmark, later Prague
- Given island by king Fredrick (and staff)
- made a accurate and vast database of celestial motion
- had a lead nose?
- Threw giant ragers
- supernova named after him

Johannes Kepler (1571–1630, Prague)

- 'Inherited' (maybe stole) Brahe's data
- also has a SN
- Kepler fit a new empirical model of heliocentric orbits, abandoning perfect circles
    - "*It was as if I awoke from sleep and saw a new light*" (Kepler, New astronomy)

Kepler's Laws

First law

- The planets travel on elliptical orbits with the sun at one focus
- Semimajor axis, half the major axis
- eccentricity: how elliptical (stretched) an orbit is - distance between foci divided by major axis.

second law

- A line drawn from the sun to a planet sweeps out equal areas in equal time intervals'
- perihelion: orbital point closet to the sun
- aphelion: furthest orbital point from the sun

third law

Def: *The square of the sidereal orbital periods of the planets are prop to the cubes of the Semimajor axis of their orbits*

$$p^2 = Ka^3$$

P = planets sidereal period
a= length of semimajor axis
K = constant

Consequences of heliocentric model

- retrograde motion of outer planets
- positions of outer and inner planets wrt sun
- annual parallax
- aberration of starlight
- Coriolis effect

Parallax

- annual parallax: change in the apparent position when seen from two diff locations due to earth revolving around the sun. First measured by Bessel in 1838

Aberration of starlight

- deflection of apparent stellar positions in the direction of the observers motion
- analog: running throw rain and getting wet in the front and not in the back

- detected (Picard, 1680); explained (Bradley, 1729)
- telescope is moving along orbital vector around the sun; translation along orbit cannot exceed transit time of light through telescope

Coriolis effect: evidence of earth rotation

- Coriolis acceleration is perp to the direction of motion
- $$a_{\vec{cor}} = s\vec{v} \times \vec{\omega}$$
- can be deduced from a pendulum
- and in hurricanes!

1.2 Orbital Mechanics I

1.2.1 Newtonian mechanics

Parametric vectors
Displacement $\vec{r}(t) = x(t)\hat{i}y(t)\hat{j} + z(t)\hat{k}$
distance: $r(t) = |\vec{r}(t)| = \sqrt{\vec{r} \cdot \vec{r}}$

1.2.2 Newtons laws

First law

- Isaac newton(1642-1727)
- an objects' velocity remains constant unless a net outside force acts upon it
- $\vec{v}(t) = \vec{v_0} = const$

second law

- $\vec{F} = m\vec{a}(t)$
- $\vec{F} = \frac{d\vec{p}(t)}{dt}$
- $d\vec{v}/dt = \vec{f}/m$
- force changes velocity
- used a lot in computational math

third law

- forces come in pairs, equal in magnitude, and opposite in direction

Newtonian gravity

- a force, grav, exsits between any two objects having mass m and M, prop to the product of their masses mM and inversely proportinal tothe square of the separtation distance r of their centers
- for coordinates centered on M:
- $\vec{F} = -G\frac{Mm}{|\vec{r}|^2}\hat{r}$

1.2.3 Displacement vector and polar coordinates

- cartesian coordinates are often written a (x,y,z) in a coordinate system centered on mass M
- Axis orientations are chosen so that the planet orbits in the x-y plane
- Displacement $\vec{r}(t) = x(t)\hat{i} + y(t)\hat{j}$

velocity vector and polar coordinates

- unit vectors in polar coordinates vary with $\theta(t)$
- $$\frac{d\hat{r}(t)}{dt} = \frac{d\hat{r}(t)}{d\theta}\frac{d\theta(t)}{dt} = \frac{d\theta(t)}{dt}\hat{\theta}(t)$$
- .
- .
- .
- $$\vec{v}(t) = v_r\hat{r} + v_t\hat{\theta}$$
- two velocity components in polar coords

1.2.4 Kepler laws: angular momentum

- .

1.2.5 keplers 2nd law = consv, angular momentum

- $$d\vec{L}/dt = 0$$
- $$\vec{L} = \vec{R} \times \vec{p} = \vec{r} \times m\vec{v} = const$$
- $$\rightrightarrows |\vec{v}| = L = mrv_1$$

1.2.6 Keplers Laws

Keplers First Law

- $\frac{d\vec{v}}{dt} = -\frac{GM}{r_2}\hat{r}$
- $$\frac{L}{GMm}\frac{d\vec{v}}{dt} = \frac{d\hat{\theta}}{dt}$$
- $$\frac{L}{GMm}\vec{v} = \hat{\theta} + e\hat{j}$$

- take dot product of both sides with unit vector $\hat{\theta}, using$
- $\hat{j} \cdot \hat{\theta} = \cos\theta$
-
$$\vec{v} \cdot \hat{\theta} = v_t = \frac{L}{mr}$$

1.2.7 Kepler III

- we know that $\frac{dA}{dt} = \frac{l}{2m} = const$
- area of a ellipse $a = \pi ab$ of orb period p.
-
$$\therefore \frac{A}{P} = \frac{\pi ab}{P} = \frac{L}{2m}$$
- eclipse geo : $b^2 = a^2(1 - e^2)$
- also, $\frac{L^2}{m^2} GMa(1 - e^2)$
-
$$P^2 = \frac{4\pi^2}{GM} a^3$$

1.3 Orbital energetics

- total energy e is conserved
  - sum of K and U
  -
  $$E = K + U$$
  -
  $$= \frac{1}{2}mv^2 - \frac{GMm}{r}$$
- total E is conserved
-
$$E = (\frac{GMm}{L})^2 \frac{m}{2}(e^2 - 1)$$
- Hyperbolic orbit: $e > 1, E > 0, K > |U|$
  - open orbit, unbound;, single perihelion passage at $\theta = 0$
- Parabolic orbit: $e = 1, E = 0, K = |U|$
  - marginally unbound; velocity approach zero at infinite time
- elliptical orbit: $e < 1, E < 0, K = |U|$
- objects originating outside our solar system are easily identified by their total energy
  - measure total energy (how far away it is, how fast is it moving)

1.3.1 Checking energy in circular orbits

- governing equation for circular orbits in scalar from
- $$f = ma$$
- $$\frac{GM}{r^2} = \frac{v^2}{r} = \omega^2 r$$
- $$v = \sqrt{\frac{GM}{r}}$$

1.3.2 Negative total energy orbits

- bound orbits have E ¡ 0
- must add energy to break "unbind" the orbits

1.3.3 Parabolic orbits: escape speeds

- Escape speed is the speed that will bring your total pot energy to 0
- velocity becomes zero at infinite distance
- $$\frac{1}{2}mv^2 = \frac{GMm}{r}$$
- $$v_{esc} = \sqrt{\frac{2GM}{r}}$$

1.3.4 Hohmann transfer orbit

- Elliptical transfer orbit from earth to superior planet
    - earths orbit becomes the transfer orbits perihelion passage
    - inserted into superior planet orbit at aphelion. This constrains launch windows
    - theoretically requires only two burns: at launch and aphelion insertion point
- semimajor axis os transfer orbit
- $$a_{to} = \frac{a + a_{sup}}{2}; Earth$$

1.4 Earth-Moon Systen

1.4.1 Motion of the moon

- 27.3 sidereal orbit
- 29.5 synodic orbit
- rises in east and sets in west diurnally, but moves eastwards by about 12 deg per day rel to stars
- rises hour later per night

1.4.2 Precession

- earth is an oblate spheroid with equatorial bulge of .3% cause by separation
- sun, moon, and planets exert a torque τ on earth
- $$\vec{\tau} = \vec{r} \times \vec{F}$$
- results in precession of spin axis of earth around ecliptic pole
- NCP moves. Polaris will not always be at NCP
- moves through stars with $P \approx 28500yr$
- opening angle
- $$47°(= 2 \times 23.5°)$$

1.4.3 Tidal Forces

- Moon exerts diff tidal forces on matter on earth
- esp noticeable on earths ocean surface as tides
- when sun and moon align (sun-earth-moon at $0° and 180°$) high-amp tides result, called spring tides
- when sun and moon are at 90° they sum destructively, producing neap tides

Diff gravitational tidal forces

- arise from the r^{-2} dependence of grav force
- Taylor expansion about center of earth r_0
- $$\delta F = \frac{2GM_{moon}m}{r^3}(r - r_0)$$
- Sun exerts about half as strong as moon tidal forces

Rotation of tides

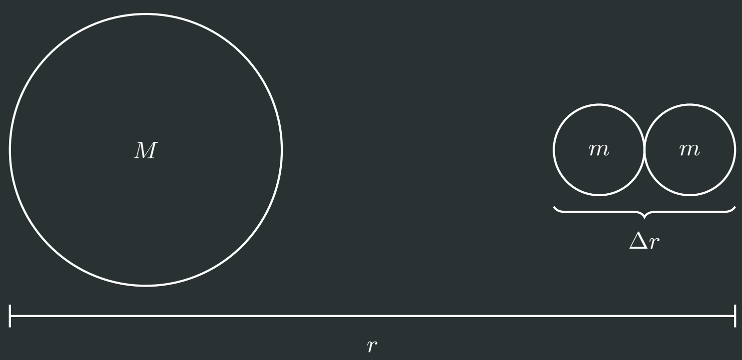
- tidal bulges produced on earths by the moon rotate at the same angular rate as the moons orbit around earth
- but the earth is rotating faster at once per sidereal day by 4 minutes. Drags the tides forward from where they would otherwise be by about 10° by friction
    - therefore high tides occur shortly after upper transit of moon
    - the misalignment drives angular momentum transfer between earth and Moon
        - moon pulls strongly on nearer tidal bulge than farther tidal bulge
        - net torque to slow earth rotation
        - but conversely the tidal bugle pulls more strongly on the moon, pulling it forward, increasing its angular momentum

1.4.4 Earth Shape

- moon stretches earth in a prolate deformation
- spin of the earth causes an oblate deformation
- oblate is much greater the prolate def

1.4.5 Roche Limit

- object get too close, forces on one side much greater then other, rip object apart
- approx a planet as two spheres 2m
- $$\Delta F = \frac{dF}{dr}\Delta r = \frac{2GMm}{r^3}\Delta r$$
- Is there a force holding 2m together? yes, self grav
- $$F = -\frac{Gmm}{(\Delta r)^2}$$



1.4.6 Hill radius

- Tidal forces of sun on earth-moon systems means that there is a maximum orbital distance for the moon, if it is to remain bound to the earth

1.4.7 Plane of lunar orbit

- Inclined by 5.1°
- the moon is near the cele equator so the moon is above the horizon about 50% of the time for most observers on earth
- moves north and south in the sky in addition to its motion around the earth. greatest dec is $23.5 + 5.1 = 28.6$ and min is $-23.5 - 5.1 = -28.6$
- causes eclipses to be retrograde

1.4.8 Tidal forces: earth vs moon

- earth exerts greater tidal forces on moon than the moon does on the earth.
- $$\Delta g_{moon \to earth} = \frac{\Delta F}{m} \propto \frac{M_{Moon} R_{Earth}}{r^3}$$
- $$\Delta g_{earth \to moon} = \propto \frac{M_{Earth} R_{Moon}}{r^3}$$
- $$\frac{\Delta g_{moon \to earth}}{\Delta g_{earth \to moon}} \frac{M_{moon} R_{earth}}{M_{earth} r_{moon}} \approx \frac{1}{20}$$

1.4.9 lunar librations

- E-w and n-s nodding motions of the moon seen from earth, caused by parallax
- tidal locking is not perfect, so the libration happens in longitude
- because the rotation axis is inclined there is libration in lat

1.5 Waves

1.5.1 Spectra (How do we know what the universe if made out of?)

Multi-messenger astronomy

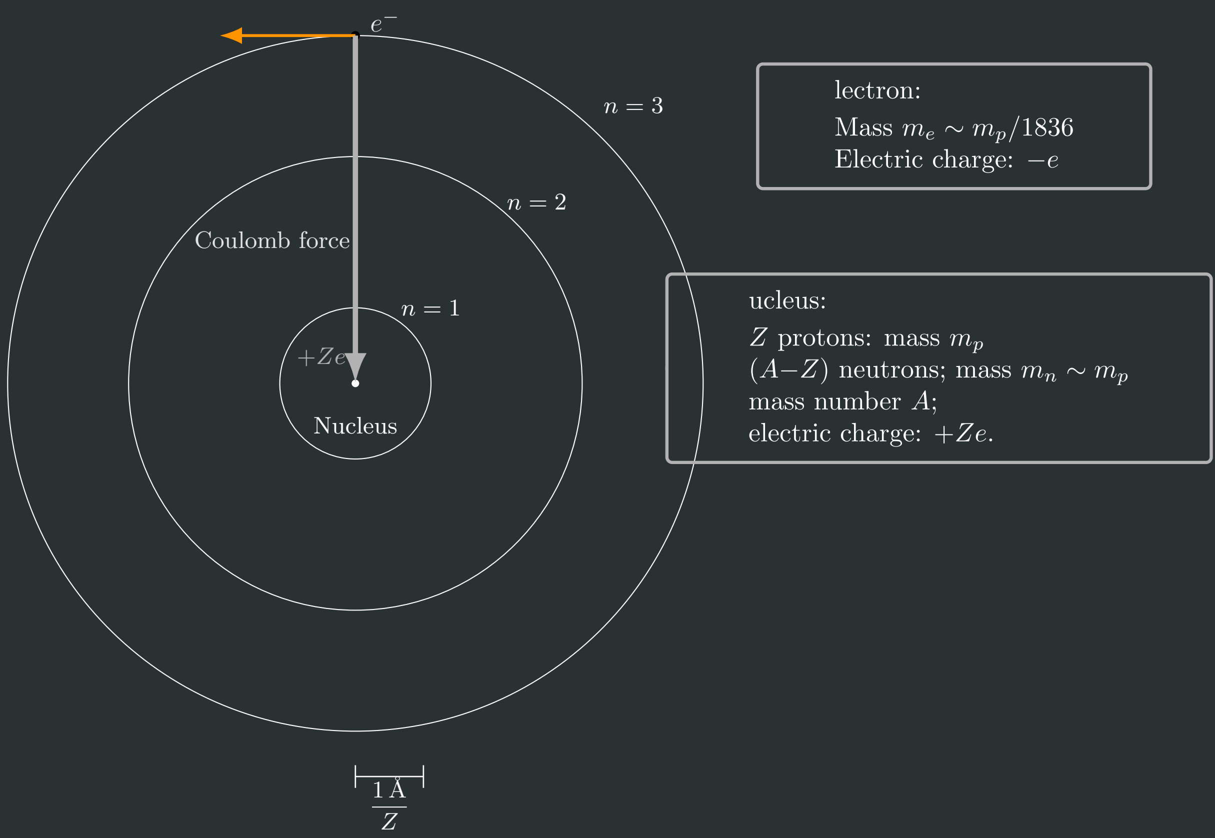
- Electromagnetic radiation
- cosmic rays
- meteorites
- neutrinos
- gravitational waves

1.5.2 Atoms and spectra

Hydrogen gas exhibits emission lines at discrete visible wavelengths, fit by empirical relation by Balmer in 1885

$$\frac{1}{\lambda} = R(1/4 - 1/n^2)$$
$$n = integer > 2$$

1.5.3 Bohrs model



Because orbital angular momentum is quantized, so is r_n and $E_n \to$ discrete orbtial levels

1.5.4 Atomic transition processes

- Transitions to free unbounded states behave similarly, however, they have diff names
- ionization and recombination
- photoionization (electron is knocked free). photon knocks electron free
- collisional ionization (electron becomes free). any other particle knocks electron free
- a positively charged ion may combine with a free leectron, and atom emits radiation (photons) as the electrons drop to lower levels. called **recombination**

1.5.5 Kirchoff's Laws

- blackbody
- emission lines
- absorption lines

1.5.6 Tempature affects internal states of atoms and molecules

- temp of gas dermines the kinetic energies of the colliding particles
- and the incoming photons
- we observe outgoing photons

1.5.7 Temperature vs velocity

- Thermal motions: emitted or absorbed photos inherent their energy from the doppler velocites of the thermal motions of particles/atoms
- equilibrium distribution of particles speeds in an ideal gas is given by the Maxwell-Boltzmann distribution

1.5.8 mean free path and opt depth

- mean free path x_m. Distance which intensity decrease by a factor of 1/e
- optical depth $\tau = x/x_m$. Thickness of slab in units of mean free path x_m
- column density, $N(x)$: total number of absorbing particle sin a column with cross-section area 1 m^2 and length x

1.6 Telescopes

1.6.1 photoeletric effect

- Photoemission emisison of a electron from a material in response to a incident photon
  - photoemissive material (underlying material)
  - work function (min energy requried to produce light)
  - photoeletric effect (photoemission from atoms in certain materials)
  - photoelectron (release electron)
- particle energy of EM radiation

1.6.2 Sun

Chromosphere

- Very sparse layer of gas above the photosphere
- very hot gas, emission spectra by Kirchhoff laws
- easily seen during total eclipse or with an Hα filter

Corona

- Low density out layer of suns atmosphere. Most easily visible during total eclipse
- T = 2×10^6
- Emission lines from highly ionized atoms
- x-ray emission from thermal Bremsstrahlung (not black body)
- Optical continuum is originally from photosphere
- scattered by free electrons in coronal plasma
- coronal streamers show how plasma follows magnetic field lines

Solar Wind

- Bunch of protons and other various particles ejected from the sun
- Speed of protons in the corona
-
$$V_{rms} = \frac{3kT}{m_p}^{1/2} \approx 160km/s$$
- Escape speed as function of distance
-
$$\frac{GM_{\odot}}{r}^{1/2} \approx 620km/s$$
- Sun produces a solar wind with $v = 400km/s$, density$p$ $10^{-21}kgm^{-3}$ earth
-
$$\Delta M = (4\pi r^2 \Delta r)\rho$$
- therefore mass flux through shell
-
$$\frac{dM}{dt} = 4\pi r^2 \frac{dr}{dt}\rho$$
-
$$\dot{M} = 4\pi r^2 v\rho$$
-
$$\dot{M} \sim 10^8 kgs^{-1}; t_m \sim 10^{14}$$
- Maybe try this myself with various sizes of stars?? Seems easy to verify large stars ejecting large amounts of wind

Magnetic Fields

- Lorentz force $\vec{F} = q\vec{v} \times \vec{B}$
- Charged particles follow curved helical paths
- Magnetic field energy
-
$$P_B = \varepsilon_B = \frac{B^2}{2\mu_0}$$

Sunspots

- Cooler than surroundings because the magnetic field is enhanced in the spot
- Pressure due to a magnetic field
-
$$P_B = 4 \times 10^5 Nm^{-2}(\frac{B}{1T})^2$$
- pressure due to ideal gas
-
$$P_{gas} = nkT$$

Pressure balance in sunspots

- gas and magnetic pressure inside sunspot must equal surrounding gas pressure
-
$$\frac{\rho k T_s}{m_p} + \frac{B^2}{2\mu_0} = \frac{\rho k T_P}{m_p}$$
- $B \approx .1T$

Sunspot Cycle

- Star near 30° N/S, migrate towards solar equator
- more numerous every 11 years

1.10 The planets

1.10.1 Mecury

- always 30° from the sun
- strong tidal forces, permanent prolate tidal bulge
- sidereal rotation $P_{rot} = 58.65d$
- $P_{orb} = 87.97$
- Orbit is tidally locked at perihelion

1.10.2 Venus

- Retrograde Motion
- atmosphere
  - Clouds are sulfuric acid
  - $\sim$ 96.5 co2% and $\sim$ 3.5% N2
  - Very strong greenhouses
- Earths liquid water ocean dissolves co2
- runaway greenhouse

1.10.3 Earth

- Temperature and pressure on earth allow significant qualities of gas, liquid, and solid water. Not true for Venus or Mars

1.10.4 Mars

- $\alpha = 1.52$AU
- $P_{sidereal} = 1.88$
- $24h40m$
- Atmosphere
  - Pressure $\sim$ .006atm (earth)
  - 95% CO_2
  - UV photodissociastes H_2O, the oxygen oxidizes iron in soil
- Seasons caused by obliquity
- polar caps of CO_2 form and melt in winter and summer

1.10.5 Jupiter and Saturn

- they are in hydrostatic equilibrium
- $\frac{dP}{dr} = -\frac{GM_r\phi}{r^2}$
- M_r is the mass within radius r assuming constant density ϕ
- $\int_{P_c}^{0} dP = \frac{4\pi}{3}\phi^2 G \int_0^R$
- solving shows that there must be very high pressures in centers of Jovian planets
- Metallic hydrogen is a conductor
- convection + rotation in a conducting fluid produce magnetic dynamos and magnetic fields

energy deficit for jupiter

- Jupiter's luminosity is twice its rate of solar irradiation from the sun
- Consider gravitational potential energy of a shell of thickness
- extra energy comes from the radius shrinking

1.10.6 Fast rotation

- Polar diamter of jupiter is 6.5 shorter thne equatorial bulge
- saturn is 10% shorter than equatorial diam

1.10.7 rings

- all Jovian planets have rings; Saturn are the most prominent
- tidally disrupted satellite inside Roche limit
- internal structures caused by orbital resonances

1.12 Solar system in perspective

1.12.1 Solar system config

- Planetary orbits are coplanar
- suns equator close to orbit Plane
- nearly circular orbits
- planets all orbit in same direction
- most planets rotate in the same direction as their orbital motion

1.12.2 Porotstellar Neb

- Cloud of gas compressing and spinning

1.12.3 Compartive planetology

- Massive colder planets retain atmospheres
- planet masses and compositions were driven by the temperature gradient in the protoplanetary disk and its relation to the condensation Temperature profile

1.12.4 Origin of the solar system

- Giant jovian satellites are a mini version of the whole solar system
- rings are temporary and provide evidence for a dynamic, evolving planetary system
  - all Jovan planets have rings
  - produced by bodies that failed to form or were disrupted due to tidal forces
  - triton is scheduled to explode

1.12.5 Dynamic solar system

- our moon, large satellite of a small planet
- triton captured by Neptune
- retrograde rotation of Venus
- large impact craters

1.12.6 Detecting exoplanets

Transit

- can theoretically resolve some based on angular resolution, but very hard to separate from the star itself
- $L_{jup} = (\frac{L_\odot}{r\pi a^2}(\pi R_{jup}^2 A))$
- if you look at infrared radiation it is "easier" to resolve to planet

Indirect

- Wobble due to the planet pulling on the star
- They orbit their COM

Doppler effect

- Measure redshift and blue shift on the star

1.12.7 Unknown orbital inclination angle

- We do not know the inclination of the plane of the system relative to our line of sight
- Doppler can only measure velocities projected onto the line of sight
- if $i = 90°$, the plane is viewed edge on, and we measure true veloicty. Otherwise, we measure a smaller velocity, giving a lower limit of planet masses.

1.12.8 Radial Velocity method

- we need the complete more accurate version of Kepler III
- $$p^2 = \frac{4\pi^2(a_A + a_B)^3}{G(M_A + M_B)}$$
- can find p by looking at when the velocity pattern repeats
- we want a_b and M_B. get a_B from
- $$a_b^3 \approx \frac{GM_AP^2}{4\pi^2}$$
  $$M_A \gg M_B$$

-
$$\frac{a_A}{a_B} = \frac{M_B}{M_A}$$

-
$$M_B = (\frac{4\pi^2 M_A^2}{GP^2} a_A^3)^{1/3}$$

1.12.9 Transit method

- Detected by planet passing in front of the star, causing a dip in the brightness
- find mind transit flux reduction
- find planet velocity (same method at radial vel)
- time before t_1 and t_2 yields planet radius or measuring the fraction of the starlight blocked (if r_s is known)

Chance of detection

- Range of inclinations for which transit is observed
-
$$\cos i \leq \frac{R_A + R_B}{a}$$

1.12.10 Surprising exoplanet discoveries

- **Hot Jupiter's** - exoplanets with Jupiter like masses which are very close to their host stars
- very eccentric and/or inclined planet orbits
- current perspective biased by observational methods

1.14 Stellar Atmospheres

1.23 Galaxies and Super clusters

Stellar streams

- Galaxies (r $\sim$ 10 kpc)
- Groups (r $\sim$ 1Mpc)
- Supercluster (r $\sim$ 100Mpc)

Coma Cluster

- rich cluster dominated by elliptical Galaxies

Cluster ISM

- Bright x-ray emitting gas

- low density, but very large quality
- Total mass of ISM is around double that of the galaxies
- Motion through the ISM causes ram pressure stripping

1.23.1 Dark matter in galaxy clusters

- Use viral theorem...
-
$$M \approx 7.5 \frac{\sigma^2 r_h}{G}$$
- Where σ is a velocity distribution, and r_h is radius of the cluster
- If we look at the mass to light radio of the Coma Cluster, which is 250 (in solar units), we find a very different distribution as compared to our sun (= 1), and the Milky Way (~ 10)

1.23.2 Large Scale Structure

- Cosmic web structure
- Sloan great wall
- Few galaxies measured far away, simply because they're hard to measure

1.23.3 Galaxy collisions

- Can estimate velocity is cluster from velocity dispersion (σ) of galaxy motions
-
$$v \sim \sqrt{3}\sigma$$
- Can then compute collision rates
- In rich clusters about a 50% chance

Rates of collisions

Consider a galaxy of radii R moving at velocity in, in an elapsed time t it will collide with any other galaxy within a cylindrical volume $V(t)$ of radius R^2 and length vt

$$V(t)(4\pi^2)(vt)$$

If galaxy density is n then the total collisions is $N_\star$ and the average time to collision is $t_\star$

$$N_\star = nV(t) = v(4\pi R^2)(vt)$$

$$N_\star = 1 \rightarrow t_\star = \frac{1}{nv(4\pi R)}$$

Galaxies collide, but stars to not

If you repeat the previous equation but for stars, you find a 1 in 10^8 chance of stellar collision, in the age of the entire universe

Physics of collisions

- Raise tidal bulges and resulting tidal tails
- They are inelastic, the kinetic energy is converted into funny motions of the stars themselves

1.24 Cosmology

1.24.1 CMB

- $ct \rightrightarrows$ theoretical size of the universe
- Does not account for expansion of the uni while the light is travelling
- Surface of last scattering, point where the universe becomes opaque, also the CMB

olbers paradox

- We do not see a galaxy everywhere we look
- this is because the universe is finite, not infinitly large

Equivalence principle

Gravitational Mass

$$F_{grav} = \frac{-GM_g m_g}{r^2} \tag{1.1}$$

Interial mass

$$a = \frac{F}{m_i} \tag{1.2}$$

Equivalence Principle

$$m_g = m_i \tag{1.3}$$

Einstein v Newton

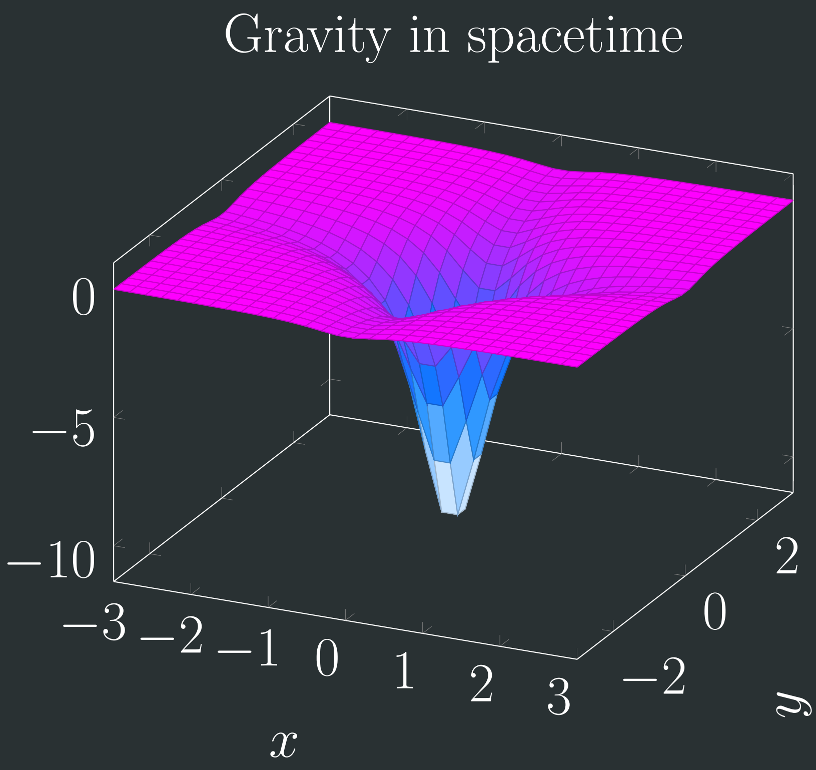
- In a small volume of space the downward pull of gravity cannot be distinguished from an upward acceleration of the observer

1.24.2 General relativity

- Space and time bind together to form curved spacetime
- 'free-fall' is motion in a straight line in 4d spacetime (this is grav acceleration)
- Matter (Mass-energy) tells spacetime how to curve
- Curved spacetime tells matter how to move

Predictions of GR

- Gravtional field sdeflect light (grav lensing)
- more accurate orbit for Mercury
- grav fields slow clocks
- moving objects will produce gravitational waves



1.24.3 Surface of spacetime

- How do we know the curvature and angles?
- If we draw a triangle what do the angles add up to?

Curvature and Angles of a triangle in 4d space

$$\alpha + \beta + \gamma = \pi + \frac{\kappa A}{r_{c,0}^2} \tag{1.4}$$

Where $\alpha + \beta + \gamma$ are angles of an equilateral triangle.
Flat is $\kappa = 0$, spherical is $\kappa = 1$, Hyperbolic is $\kappa = -1$

Newtonian Friedmann Equation

$$\frac{\dot{a}}{a}^2 = \frac{8\pi G}{3}\rho(t + 2\frac{k}{r^2}\frac{1}{a^2(t)}) \tag{1.5}$$

Newtonian version of Friedman equation

Relativistic Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} - \frac{\kappa c^2}{r_{c,0}^2}\frac{1}{a^2(t)} + \frac{\alpha}{3} \tag{1.6}$$

where κ is curvature parameter

Currently, $\dot{a} > 0$, thus the universe is expanding

Measuring curvature

- Look at angular diam vs distance
- We look at something which we know the size of, a 'standard ruler'
- if flat... $\Rightarrow \alpha = \frac{D}{d}$
- Can't use galaxies, non standardized size
- Use sound saves before recombination
    - Use sound waves! $t < 380000yr$
    - Sound waves in early fluid like plasma in universe
    - wave equation for sound waves relates wavelength to the properties of the gas
- Apply the sound wave logic to the CMB

- the reason that the CMB is not homogeneous is because of the sound waves traveling through the plasma in early universe
- If universe was curved, the light traveling from the CMB would take a different path, resulting in a different angular resolution

Predicting angular scale distribution in CMB from sound waves

- large fluctuations are caused by patches of varying temperature
- small fluctuations are from
- Look at how CMB is 'distorted' from the sound waves
- Then infer wavelength of soundwaves
- Then apply previous logic for measuring angular res and comparing it to known wavelength

1.24.4 Density of the universe

- $$\Omega_m = \frac{M/V}{\rho_c}$$
- Matter ...
- $$\Omega_m \sim .3$$
- Radiation ...
- $$\Omega_{rad} \sim .00007$$
- Something else ...
- $$\Omega_{rest} \sim .7$$
- Because the universe is flat we know that
- $$\Omega_m + \Omega_{rad} + \Omega_{res} \sim 1$$

Energy density components

- Looking for a solution for $a(t)$
- Wavelength of a photon scales with the size of the universe
- Lambda cosmological constant
- $$\Omega_\Lambda \sim .7$$
- Non-Relativistic particles:

-
$$\Omega_{m,0} \sim .3$$

-
$$\Omega_{(bary,0)} \sim .04$$

- Relativistic particles

-
$$\Omega_{r,0} = \Omega_{cmb,0} + \Omega_{v,0} \sim 8.4 \times 10^{-5}$$

Behavior of nonrelatvistic partciles

$$n(t) \propto V^{-1}(t) \propto a^{-3}(t) \tag{1.7}$$

If matter is conserved

Cosmological redshift

Redshift Z

$$Z = \frac{\lambda_0 - \lambda_e}{\lambda_e} \tag{1.8}$$

If we use 1.8 combined with expansion of the universe ...

$$1 + Z = \frac{1}{a(t)}$$

Universe at different stages

- Solve 1.6 for different Ωs
- We find that all are decelerating, except for Ω_Λ (Dark Energy)

Friedmann Consensus Model

$$\dot{a} = H_0 \left[\frac{\Omega_{r,0}}{a^2} + \frac{\Omega_{m,0}}{a} + \Omega_{\lambda,0} a^2 \right]^{1/2} \tag{1.9}$$

unitless acceleration of the universe

Standard candles for expanding universe

Flux

$$L = \frac{L}{4\pi r^2} \tag{1.10}$$

Photon Energy

$$\epsilon = \frac{hc}{\lambda_e}; \quad \epsilon_0 = \frac{hc}{\lambda_0} \tag{1.11}$$

- One can combine 1.8 and 1.11
- We can use type 1a SN as a standard candle
- Plot the redshift and distance, see what expected path it lies on (based on DE DM content)

1.25 Equations

$$F_{grav} = \frac{-GM_g m_g}{r^2} \quad (1.1)\ (\textit{Gravitational Mass})$$

$$a = \frac{F}{m_i} \quad (1.2)\ (\textit{Interial mass})$$

$$m_g = m_i \quad (1.3)\ (\textit{Equivalence Principle})$$

$$\alpha + \beta + \gamma = \pi + \frac{\kappa A}{r_{c,0}^2} \quad (1.4)\ (\textit{Curvature and Angles of a triangle i}$$

$$\frac{\dot{a}}{a}^2 = \frac{8\pi G}{3}\rho(t + 2\frac{k}{r^2}\frac{1}{a^2(t)}) \quad (1.5)\ (\textit{Newtonian Friedmann Equation})$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} - \frac{\kappa c^2}{r_{c,0}^2}\frac{1}{a^2(t)} + \frac{\alpha}{3} \quad (1.6)\ (\textit{Relativistic Friedmann equation})$$

$$n(t) \propto V^{-1}(t) \propto a^{-3}(t) \quad (1.7)\ (\textit{Behavior of nonrelatvistic partciles})$$

$$Z = \frac{\lambda_0 - \lambda_e}{\lambda_e} \quad (1.8)\ (\textit{Redshift } Z)$$

$$\dot{a} = H_0\left[\frac{\Omega_{r,0}}{a^2} + \frac{\Omega_{m,0}}{a} + \Omega_{\lambda,0}a^2\right]^{1/2} \quad (1.9)\ (\textit{Friedmann Consensus Model})$$

$$L = \frac{L}{4\pi r^2} \quad (1.10)\ (\textit{Flux})$$

$$\epsilon = \frac{hc}{\lambda_e}; \quad \epsilon_0 = \frac{hc}{\lambda_0} \quad (1.11)\ (\textit{Photon Energy})$$

Part II

Paper Notes

Chapter 2

Elusive hot stripped helium stars in the Galaxy [1]

2.1 Stripped Helium Star Properties

- nondegenerate He-cores of which retained a $\lesssim 1M_{\odot}$ hydrogen-helium envelope. This chemical abundance is formed by numerous aspects
  - the retreat of an H-burning convective core in MS
  - Mixing!
  - Mass loss during RLOF
  - Stellar wind from a post RLOF remnant
- Masses of $(1-7)M_{\odot}$
- None have been identified
- Most are lower mass ($\gtrsim 2M_{\odot}$)
- Their formation is heavily constrained by runaway RLOF
- Likely progenitors of both hydrogen-poor and hydrogen-rich core-collapse SNe, occurring when their CO core exceeds $\approx 1.4M_{\odot}$
- stars with mass $\lesssim 2M_{\odot}$ with hydrogen-depleted envelopes are sdO/B-type subdwarf and stripped stars with mass $\gtrsim 7M_{\odot}$ are Wolf-Rayet stars. This gap is believed to be filled with HeS stars
-

2.2 Case B RLO

"At solar metallicity $Z = Z_{\odot}$ this results in the formation of a system with a He white dwarf component, if the ZAMS donor mass is $\lesssim 2.5M_{\odot}$ or a hot ($\log(T_{eff} \lesssim 4.4)$) stripped helium star (HeS) component, if the donors ZAMS mass is higher and the mass-loss by its stellar wind does not prevent RLOF"

Chapter 3

An upper limit on the frequency of short-period black hole companions to Sun-like stars [2]

3.1 Abstract

- Seeking to narrow the uncertainty regarding the survival rate in the formation of stellar-mass BHs.
- This uncertainty is most extreme in LMXB systems
- Defines 'close' systems as $P_{orb} \lesssim 3$d
- Searching through for AFGK-type stars in TESS[1]. These are the ***non-accreting*** companion and progenitors of LMXBs
- Detecting the BHs via the deformation of the main star via the light curves
- Found a selection of 457 candidates from a sample of 4.7×10^6
- However, after spectra follow-up on 200 of the sample, *none showed spectra consistent with a BH companion*[2]
- On the basis on non-detection they conclude that fewer than one in 10^5 *sun-type* stars host a *close* BH companion
- This upper limit is in tension with that some models predict ($\sim 10^{4-5}$), but congruent with other models that predict on in 10^{7-8}

[1] I wonder why TESS was picked

[2] Very curious what "spectra consistent with a BH companion" means, especially as these are non accreting. Is this using a radial velocity method?...

3.2 Introduction

- Isolated stars with mass greater than $\gtrsim 15 - 25 M_\odot$ are believed to end their lives as BHs, suggesting that there are $\sim 10^8$ stellar mass BHs in our galaxy. The majority of which are believed to evolve with a stellar companion, half of which will interact with said companion at some point during their lifespan.
- A very small number (7) BH-LS systems have been detected
- Because of the scarcity of these systems, it's useful to try and set an upper limit on their distribution

Part III

General Notes

Chapter 1

Misc

1.1 WD SNe

- This, simply-ish put, is caused by because a WD cannot reach hydrostatic equilibrium. A pressure increase does **not** lead to increase and radius, and thus cooling, instead, it just increases heat, and thus fusion, quickly getting out of hand. Can b trigged if the Chandrasekhar Limit is crossed, as well as if a layer of H/He on top entities, called a edge limit detonation or "sub-Chandrasekhar" explosions.
- In DD systems the WDs must have a small separation, causing GWR to shrink the separation until merger $\rightarrow$ SNe

1.2 Pauli Exclusion Principle

The property of matter that two identical particles with half integer spins (fermions) cannot occupy the same quantum state.

> https://en.wikipedia.org/wiki/Pauli_exclusion_principle
> "In a poly-electron atom it is impossible for any two electrons to have the same two values of all four of their quantum numbers, which are: n, the principal quantum number; ℓ, the azimuthal quantum number; $m\ell$, the magnetic quantum number; and ms, the spin quantum number. For example, if two electrons reside in the same orbital, then their values of n, ℓ, and $m\ell$ are equal. In that case, the two values of ms(spin) pair must be different. Since the only two possible values for the spin projection $ms$are +1/2 and -1/2, it follows that one electron must have ms= +1/2 and one ms= -1/2."

This means that in systems of very dense matter, the system ***cannot reach homogeneity***, and thus will actually have an inherent pressure. This pressure can prevent collapse due to gravity in various high dense objects (compact objects in astronomy).

1.3 Relativistic Beaming

The process of an object becoming brighter when it is moving *towards* the Earth. This is *in conjunction* with Doppler shift. This brightness increase can be attributed to the fact that, for a star moving *towards* the earth, from the perspective of the earth, a ‘clock’ placed near the star would run *faster* than one on earth. If photons are emitted at a set rate on this ‘clock’ it would be faster, when scaling the star ‘clock’ to the earth one, it would be faster, meaning that the interval between received photons would be faster, and thus the object would appear brighter.

1.4 Ellipsoidal Modulation

See https://agn.caltech.edu/~srk/Ay215/Presentations/ellipsoidal_mod.pdf!!!

Part IV

Physics of Binary Star Evolution Notes [3]

Chapter 1

Intro

Importance of binaries

- Plays a key role in the evolution of massive stars
- first presumed to exist because of Algol Type stars. These stars were explained with mass transfer
- Mergers are a key source of strongest GW rad, GrBs, and have r-process elements. (i.e. in Kilonova)
- Likely cause of SNe Ia, Ib, Ic (SN with a lack of hydrogen in their spectra)
- cause of low-intermediate mass stars with odd chemical compositions, ex. barium stars.

Chapter 2

Visual binaries and the universal validity of the laws of physics

2.1 Visual binaries

- Visual binary $\rightarrow$ two in proximity through a telescope
- Physical $\rightarrow$ gravitonalty bound orbits
- Optical $\rightarrow$ happen to be close together in the sky
- Visual binaries have longer orbits
- the proof of physical binaries (and not just coincidence) was proved in 1767 by John Michell
- Shows that Newton's law of gravity applied outside just our solar system

2.2 Astrometric Binaries

Wide binaries

- Binaries where one of the stars is too faint to directly observe
- Can still be detected by the following Proper Motion of the visible component
- Center of mass moves along, star orbits this center, showing a periodic wiggle in its apparent motion (I wonder how this can be muddled with and/or separated from parallax. I'm guessing they are in different planes?? (next graphic helped(it wiggles slightly due to yearly parallax, however, the proper motion is much greater and over a much longer duration, so it sort of just becomes "noise" relative)))

2.3 Spectroscopic Binaries

Spectroscopic Binaries

- A binary which is determined to be a binary due to its spectra

- double-lined binary (SB2) $\rightarrow$ when both sets of spectral lines can be observed redshifting and blueshifting
- single-lined (SB1) $\rightarrow$ when only set of spectral lines can be observed redshifting/blueshifting
- this is due to Doppler shifting when one of the binaries is relativistically coming towards us and the other away
- Doppler shift ($\Delta\lambda$) can be related to the radial velocity (the component of the velocity on our line of sight)
-
$$\frac{\Delta\lambda}{\lambda} = \frac{v_{rad}}{c}$$

2.4 Eclipsing Binaries

Binaries where one star passes in front of the other at some point during its period

- A partial eclipse will happen if
-
$$\sin(\phi) < \sin(\phi_0) = \frac{R_1 + R_2}{a}$$
- where inclination i is defined as the angle between the orbital plane and the plane of the sky $\rightarrow \phi = 90° - i$ and a is the orbital radius
- and a total eclipse will occur if
-
$$\sin(\phi) < \sin(\phi_1) = \frac{R_1 - R_2}{a}$$
- We assume that the angles between line of sight and orbital planes are random, the probability of having an angle between 0 and ϕ_0 is the fraction of the surface area of the half sphere between the pole and the circle at an angle ϕ_0 from the pole, which is equal to $2\pi(1 - \cos(\phi_0))$. While the area of the half sphere is 2π[1]. Thus, the probability of having an eclipse is
-
$$\mathcal{F}_{eclipse} = (1 - \cos\phi_0)$$
- Assuming ϕ_0 small
-
$$\sin\phi \simeq \phi_0 \simeq \frac{(R_1 + R)_2}{a}$$
- due to series expansion[2]
-
$$\cos\phi_0 \simeq 1 - \frac{(R_1 + R_2)^2}{2a^2}$$

[1] Try this myself and verify that this makes sense
[2] for sure do this at some point

- Thus
-
$$\mathcal{F}_{eclipse} = \frac{(R_1 + R_2)^2}{2a^2}$$
- Because $R_1 + R_2 < a$, eclipses are most likely for either dwarf stars with a very close orbital radius, or wide binaries where at least one star is a giant

2.5

- It is possible for a spinning WDs to show variation (but not pulses) in star brightness
- This is because of the magnetic fields on WDs causing bright spots
- Pulsation can be determined by the density

Novae/CVs

- Caused my mass transfer onto a WD
- WD shell goes SN, causing Novae
- Standard candle
- Has a variation called dwarf Novae
- caused by instability in the accretion disk
- much weaker

2.6

- Brightest sources of x-rays were found to be CV accreting systems

2.7

- The first NS star XrB
- Regular periodicity of with increase of x-ray emission
- Caused by the NS being obscured by the larger star

2.8 First BH XrB

- Discovered x-ray source with nearby supergiant
- Falls into two classes
- HMXBs and LMXBs
- determined by the mass of the acceptor with respect to the donor

- x-ray emission called by infilling matter
- $\frac{GMm}{R} = .01mc^2$[3]
- much much much more efficient than any fusion reactor on earth
- values as high as $.42mc^2$
- Common in Globular clusters

2.9 Double NSs & BHs

- Proved by GW detection
- Detections are dominated by DBHs
- DNSs formed through lower mass binaries

2.10 MSPs

- Generally remnants of LMXBs
- Systems with MSPs generally have WD partners
- Mass-transfer through evolution, or through orbital momentum loss through or GWR
- The NS is greatly accelerated through accretion
- Old NSs which evolved through this process are called *Recylced Pulsars*

2.11 Results of evolution in binaries

- SNe caused by the death of stars more massive than $\sim 8M_{\odot}$
- SNe types
    - Type I SNe
    - Type Ib SNe
    - Type Ic SNe
    - Type II SNe
- due to the fact that Type Ib SNe and Type Ic SNe are stripped cores, it is incredibly likely that they result from binary systems
- We may also observe both Type Ib SNe and Type Ic SNe in WR star, however, we have **not** yet
- WD SNe (section 1.1) *require* some sort of mass transfer process
- The companion donor can be either a standard star (SD), or another WD (DD)

[3]Shockingly simple eq

2.12 Weird stars

- Blue stragglers
- Barium

Chapter 3

Orbits and masses of spectroscopic binaries

3.1

This is generally all math that I either know from astro classes, or is so specific id need to revisit it to use anyway

$$\frac{L}{L_\odot} = \frac{M}{M_\odot}^{3.5}, M > 1.3M_\odot$$

3.2 Very massive stars

- Most massive has $L \sim 10^{L}_{\odot}$
- Because of the high ($\sim 50000k$) temps, they have strong stellar wind, and thus very similar spectra to WR star, which they are distinguished from by the presence of hydrogen
- Denoted as WNh

3.3 Stuff that screws up rad vel curves

- Rad Vel curve must be off due to a difference in eccentricity values derived from the rad curve and the light curve
- Rotation effect
  - when the stars are eclipsing the rotational Doppler shift can be added (if the half spinning away from us is obscured) or subtracted to the shift, leading to different rad velocity measurements. This is called the Rossiter-McLaughlin effect. [1]

[1] This is actually a super neat and intuitive process which i feel like the book just sorta skips and doesnt explain, maybe wanna write out/make some graphics bout this sometime

- presence of gas streams
    - wow they could have said literally anything about what a gas stream is in this case
    - im guessing it means some sort of flow of mass coming off of the binaries, maybe in accretion, maybe in jets???
- reflection effect
- heating effect
    - Both the reflection and heating effect are caused by that the stars will cast light on each other, both heating and causing reflection
- deformation effect
    - the above effects cause the curve to be shifted from the c.m., leading to wonky radial vel curves
- this is actually pretty important when it comes to HMXBs and properly measuring NS and BH masses

3.4 Interacting binaries

- $> 70\%$ of massive o-type stars are members of binaries so close that they'll exchange mass or merge before either star explode as a SN

the rest of this section follows the "way too niche of math to write down" thing

Chapter 4

Roche equipotential

I have a ridiculous amount of notes and a whole essay written about this, so notes here will be pretty light

---

- This is some black magic mathmathmatic reasoning
- Co-rotating binaries with have a tidal bulge that can be 'easily' calculated
- also love the seemingly kinda personal rant about how the RL diagram is actually wrong, then provides a diagram which is way less intuitive

4.1 Mass transfer Galore

- Mass transfer through L_1 does not majority effect angular momentum, however, transfer through L_2 does, causing a shrinkage in separation, and typically mergers
- Different ways of modeling the transfer, depending on how you treat angular momentum with respect to the transfer
- Orbit widens if the donor is less massive then accreter, and shrinks if the donor is more

4.2 Types of RLO

- Conservative Roche lobe overflow
- Mass loss from a circumbinary disk

4.3 General Notes

- Mass transfer onto NS and BH are limited by the Eddington Limit
- However, mass transferred off of the donor is at the rate of the evolution of its envelope. (Thermal Timescale)
- mass transfer off of the donor is much greater (2 to 4 orders of magnitude) then the maximum accretion rate thus, the bulk of the mass will be "blown away"

- if more than half of the total mass of the binary system is lost in a SN, the system will become unbounded
- What on earth is a applegate mechanism
- and what is gravitational quadrupole coupling
- ‘im pretty sure its just when the oblateness of the star various from some convection stuff, which causes the period to variation causing period variations

4.4 Stability Criteria

- Depends on the response of the star losing mass as well as the RL
- more likely to detect it if the mass transfer is stable
- orbit always expands for $q < 1$ and always shrinks when $q = 1.28$
- Depends on whether the donor contracts or swells upon starting to transfer mass
- Donors with radiative envelopes (Case A RLO) or slightly convective envelopes (early Case B RLO) will typically either shrink or stay the same radius
-

4.5 Tidal Evo

- Grav interaction will cause Tidal Bulges to form
- If rotation of the stars is not synced with orbital motion, the movement of the bulges will cause friction, thus dissipating the KE of the star.
- If the orbit is eccentric, the effect is greater in magnitude
- This leads to the orbit becoming perfectly circular
- Happens faster in systems with closer separations
- Tempature can heavily effect orbtial eccentrictiy based on convection rates

4.6 CE

- Trigged by unstable runaway mass transfer
- companion star is engulfed in the envelope of the donor
- the companion moving through this envelope causing friction, thus reducing angular moment, thus shrinking orbit
- In some cases the envelope is ejected, and if it isnt, it leads to merger
- Likely progenitor of some planetary nebulae
- Very hard to predict due to unstable nature
- Onset is caused by runaway RLO, Darwin instability, or the expansion of the accreting star

4.6.1 Stages of CE

- loss of co-rotation
- plunge-in
- Slow spiral-in
- Envelope Ejection

4.6.2 CE ejection

- Whether not the envelope will be ejected is dependent on how good the system is at converting the GPE into KE, this added KE can then eject the envelope
- This can be described as the efficiency α_{CE} of converting orbital energy ΔE_{orb}
- $$E_{bind} = \alpha_{CE} \Delta E_{orb}$$
- Ability to eject a CE depends heavily on the evolutionary status of the donor at the onset of CE
- Separation post CE ejection is about 100-1000x smaller than at Onset
- $$E_{bind} \equiv -\frac{G M_{donor} M_{env}}{\lambda R_{donor}}$$
- λ various heavily on stealer mass and evolutionary status
- For low max systems the envelopes of the donors are typically ejected, as $|E_{bind}|$ is typically quite small
- Many HMXBs with NSs will not survive CE and hence DNS mergers are rare, although these do theoretically form Thorne-Zytkov objects
-

Chapter 5

Evolution of single stars

5.1 Why stars do stuff[1]

- A globe of monatomic gas without energy sources and in HSEq follows
- $$2E_{th} + E_{pot} = 0$$
- E_{th} is given by
- $$E_{th} = \frac{3}{2}Nk\bar{T} = \frac{3}{2}M(\mathcal{R}/\mu)\bar{T}$$
- Where N is the partcile number in the star, k is the boltzman constant, M is the mass of the globe $\mathcal{R} = ak/m_h$, the ideal gas constant, μ is the mean particle mass, in units of m_h of the hydrogen atom
- E_{pot} is given by
- $$E_{pot} = -\alpha GM^2/R$$
- Where R is stellar rad, G is grav const, and α is a constant of proportionality of order unity, which depends on the density distribution of the star.
- From substitution, we find that
- $$\bar{T} = \alpha(\frac{GM}{R})(\frac{\mu}{3\mathcal{R}})$$
- This is import because it shows that internal temp is only depended on the stellar radius, increasing when the star shrinks
- Energy loss is given by

[1] trying to focus on some of the math here, cause while i conceptually understand it, the math is really neat

-
$$E_{tot=E_{th}+E_{pot}} = \frac{1}{2}E_{pot} = -\alpha\frac{GM^2}{2R}$$

- This shows that as E_{tot} decreases the radius of the star must decrease
- However, as shown by $\bar{T}$,as the star contracts the internal temp increases
- This means as the star (or cloud of gas) radius heat away, it actually gets hotter, leading to more radiation, and thus more shrinking
- This applies to the star from the moment it is a gas to the end of its life as BH, NS, WD, etc
- These equations work well for antibiotic index of $\gamma = C_p/C_V = 5/3$, which is great for globes of ionized hydrogen and helium. However, generalized forms can be found with eqs 8.6-8.8
- if $\gamma \leq 4/3$, the star **cannot** reach HSEq, and thus must collapse or explode
- Stars of very high mass have very high luminosites, which mean their interior pressure is dominated by photon gas, which has $\gamma = 4/3$. This sets an upper limit for the mass of a star, also called the Eddington (Luminosity) Limit

5.2 Stellar Timescales

There are three timescales for single star evo that are relevant for binary stellar evo

5.2.1 Dynamical Pulsation timescale

Theorem 5.2.1 – Dynamical-Pulsation-timescale

$$\tau_{dyn} = \frac{R}{c_s} \simeq 50\text{min}\left(\frac{\bar{\rho_\odot}}{\bar{\rho}}\right)^{1/2}$$

Where $\bar{\rho}$ is the mean mass density.

This is the timescale of how long it takes for a start to restore a perturbation of its HSEq. This can be defined as the time it takes for a sound way with velocity c_s to cross the stellar radius

5.2.2 Thermal/Kelvin-Helmholtz timescale

Timescale of how long it takes for the star to react to fusion rate not being equal to the radiative energy loss. This is import with pre-main sequence contraction and after the stars fuel has been used

5.2.3 Nuclear timescale

Time it takes for a star to use all of its available fuel

5.3 High mass evolution$M \geq 12M_\odot$

- Leave behind a collapsing iron core, which creates a NS or BH
-

5.4 Low mass stellar evolution $M \leq 8M_\odot$

- The degenerate mass in the core of the star heavily effects fusion
- For electron degenerate gas, the pressure only depends on the density (and not on the temperature)
- This means that this degenerate gas ignites, it has no way of stabilizing itself, leading to a 'flash', where it all ignites rapidly.
- This will only stop when the temp reaches a point where the ideal gas is able to also do fusion, at which point the star can actually expand and cool
- "In stars with $M < 2.3M_\odot$, the core becomes degenerate during hydrogen shell burning, and when $M_{he} \approx .47M_\odot$, the helium ignites with a flash, the temp rises to $\approx 10^9$K, and the degeneracy is removed"
- This is not violent to actually disrupt the star
- In stars with mass $2.3m_\odot < M \lesssim 8M_\odot$ they instead ignite carbon in a flash. This is strong enough to disrupt the star (albeit rarely)
- However, it is more likely for the star to eject its helium envelope due to helium-shell burning as well as the instability of the RSG stage, leaving behind a CO WD.
- Because of this CO ignition is rare.

5.4.1 Mass limit at $\sim 1.2M_\odot$

- When hydrogen is exhausted in the star, the star contracts. This causes it to drift sharply left on the HR diagram, until the hydrogen-shell begins fusion causing it to have drift slowly upward and to the right on an HR diagram
-

5.4.2 Mass limit at $\sim 1.5M_\odot$

- Masses less than $\sim 1.5M_\odot$ have convective outer envelope and ones higher are radiative.
- This convective envelope creates a magnetic field, this magnetic field can cause magnetic breaking, leading to stars of this mass range having slower spins

5.5 Stars in the range of $8 - 12M_\odot$

- Not very well is known about evolution in this range
- Generally, the carbon in the ore will ignite and leave a degenerate ONeMg core
- This happens after they eject their hydrogen envelope, but in binaries this envelope is lost through mass transfer
- This means that the ONeMg core will grow to the Chandrasekhar Limit, at which point it will then collapse, creating NS and SN explosion
- Might also result in Type I SNe

5.6 Effects of wind mass loss, metallicity, and rotation

- If a star has very fast spin, the helium in the core can get mixed into the whole star, preventing the star from becoming a giant, instead leading it towards becoming a WR star[2]. This can happen with stars with of low of mass as $15M_\odot$, as compared to the typical progenitor mass of $\sim 25M_\odot$
- Non-rotating stars can become much more massive

5.7 Final Evo of stars in the range of $1 - 8M_\odot$

- Unstable pulsing
- Very strong stellar winds
- If they're low enough mass, ($< 8M\odot$), they can become WDs before carbon ignition

5.8 Final Evolution and core collapse of stars more massive than $8M\odot$

5.8.1 Between 8 and $\sim 10 - 12$

- When the core approaches the Chandrasekhar Limit thus begins the onset of core collapse
-

[2]This is cool as shit. Blender star my beloved

Chapter 6

Formation and Evolution of LMXBs

6.1 Rare formation process

- Due to the *lower* mass of the donor star when compared to the accretor, mass transfer in LMXBs can be long stable on large timescales, such as ...
  - nuclear (fuel of the star)
  - orbital shrinking due to loss of angular momentum
- When comapring the theoretical lifespan of them, to the quanity obsreved, we find that they have formation rate of 10^{-7}yr^{-1}
- one out of $\sim 10^5$ finishes in a LMXB system, whereas HMXBS it is *one out of ten*

6.2 Possible formation channels

6.2.1 Common-envelope evolution of a massive binary with a large initial mass ratio

Formulation

Deduced by looking at the Her x-1 system

- far distance (3kpc) from the galactic plane, but a family young star
- must have experienced something to launch hit out of the plane at 120kms^{-1}
- This was from an SN, most likely some sort of Natal Kick
-

6.2.2 Accretion induced collapse (AIC)

6.2.3 Origin from a HMXB with a much lower mass companion (triple star system)

Used Papers

[1] L. Yungelson et al. “Elusive hot stripped helium stars in the Galaxy - I. Evolutionary stellar models in the gap between subdwarfs and Wolf-Rayet stars”. en. In: *Astronomy & Astrophysics* 683 (Mar. 2024). Publisher: EDP Sciences, A37. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/202347806. URL: https://www.aanda.org/articles/aa/abs/2024/03/aa47806-23/aa47806-23.html (visited on 11/18/2025).

[2] Matthew J. Green et al. “An upper limit on the frequency of short-period black hole companions to Sun-like stars”. In: *Astronomy and Astrophysics* 695 (Mar. 2025). ADS Bibcode: 2025A&A...695A.210G, A210. ISSN: 0004-6361. DOI: 10.1051/0004-6361/202453271. URL: https://ui.adsabs.harvard.edu/abs/2025A&A...695A.210G (visited on 02/12/2026).

[3] Thomas M. Tauris and Edward P.J. van den Heuvel. *From Stars to X-ray Binaries and Gravitational Wave Sources*. Princeton: Princeton University Press, 2023. ISBN: 9780691239262. DOI: doi:10.1515/9780691239262. URL: https://doi.org/10.1515/9780691239262.

Glossary

AIC Accretion Induced Collaspe
When a WD reaches the Chandrasekhar Limit in a close binary 4, 56

Algol Type Type of eclipsing binary with properties similar to the Algol system. It appears paradoxical because the more evolved star has a smaller mass, explained by mass transfer. 41

antibiotic index Also called a heart capacity ratio. A very very very simplified and abstract defenition is how much a gas will expand when heated. `https://en.wikipedia.org/wiki/Heat_capacity_ratio` 53

BH-LS Black Hole w/Luminous companion 36

Case A RLO RLO during donor hydrogen core burning (Meaning mainsequence) [1] 50

Case B RLO This is where the donor star is *post* hydrogen core burning. Ex. hydrogen *shell* burning [1]
See 2.2 for more info 50

Chandrasekhar Limit Maxiumum mass of a white dwarf, approx $M \approx 1.4M_{\odot}$
This is support be electron degeneracy pressure 38, 55, 58

Conservative Roche lobe overflow RLO where the total mass and angular momentum remain constant. Is an example of Huangs *slow mode* 49

DD *Double Degenerate*, donor as well as accretor are WDs 38, 45

degenerate Matter which is under the effects of degeneracy from the Pauli Exclusion Principle. This is very commonly seen in neutron stars, as degeneracy pressure is what keeps them from collasping.
34

Eddington (Luminosity) Limit The uper limit of the mass of a star, defined as $3.2 \times 10^4 \left(\frac{M}{M_{\odot}}\right) L_{\odot}$ 53

Eddington Limit $\dot{M}_{Edd} \simeq 1.8 \times 10^{-8} M_{\odot} \mathrm{yr}^{-1}$ For NS
Maxium rate of mass transfer onto a NS or BH 49

edge limit detonation A WD SNe trigged by accreted H/He on the suface which sends a shockwave into the star, trigging runaway fusion. 38

GWR gravitnal wave radiation.
Process of stars losing angular momentum through the radiation of gravitnal waves 38

Kilonova A merger of either a NS+NS (DNS) binary or a NS+BH binary. Results in a bright signal resulting from the rapid decay the the NS material. Results in a peak brightness around 1000x that of a standard nova, hence the name. Likely a standard candle. 41

magnetic breaking the process of a star magnetic field binding with the winds (or gas, etc), causing the stars spin to slow due to consv of ang momentum 54

Mass loss from a circumbinary disk Ejected mass from mass transfer/winds a ring orbiting the system (a circumbinary disk).
Refered to by Huang as an *intermediate mode*. Due to tidal interactions these rings "extract" angular momentum from the system 49

MSP Milisecond Pulsar.
A pulsar with a spin period $\sim$ 30ms 45

Natal Kick A 'kick' imparted on the object born from a SN from the SN itself. This is due to asymetric massloss, causing the star to be 'pushed' in a direction 56

ONeMg Fill this in later hopefully. Pretty sure it just means Oxygen, Neon and Magnesium? 55

Pauli Exclusion Principle See 1.2 58

photon gas A 'gas-like' collection of photons. This means that they have a tempature, pressure, and entropy.
They are most common in black-body equilibrums. https://en.wikipedia.org/wiki/Photon_gas 53

Proper Motion The motion of a star in the sky relative to more distant stars. Allows us understand the velocity of a star relative to the earth 42

Recylced Pulsar A pulsar which obtained its rapid spin through accretion. Has weaker magnetic fields then newly formed NSs 45

RSG Red-supergiant
Supergaint stars with a spectral class of M or K 54

runaway RLOF Unstable RLOF mass transfer which leads to eventual mergers 34

SD *Single Degenerate*, donor is a normal star, accretor is WD 45

Stellar streams Stars follwing a path away from a galaxy 23

Surface of last scattering Point looking deep into the universe where the universe becomes opaque. Also where the CMB is 26

TESS Transiting Expoplanet Survey Satelitte
satelitte dedicated to searching for exoplants via transit method, similar to kepler, albiet in a *much* larger region. 35

Thermal Timescale 49

Type I SNe A SNe **without** hydrogen in its spectra
Generally standard candles. They are thermonuclear explosions of carbon-oxygen WDs. See section(1.1) 45, 55

Type Ib SNe A SNe **without** hydrogen and with helium in its spectra.
Caused by collaspe of the naked helium core star. 45

Type Ic SNe A SNe **without** hydrogen or helium in its spectra.
A star where both the hydrogen and helium envelopes have been fully stripped. 45

Type II SNe A SNe **with** hydrogen in its spectra
generally found in galaxies with high star formation rate. Likely caused by core collaspe 45

WNh Very massive stars with strong stellar winds, leading to spectra very similar to that of WRs, but also with hydrogen emission. These have ejected their outer shells of hydrogen, and show distinct He and/or C emission, buta also is still doing H fusion in the core 47

WR star Wolf-Rayet star.
A helium star of mass They are genally so massive (typically more than $\sim 25M_\odot$) that it sheds its hydrogen layer due to stellar wind. It may also shed its helium layer as well. 45, 47, 55

ZAMS Zero age main sequence This is a star which is has literally just started on the main seqeunce. Hence 'zero-age' 34