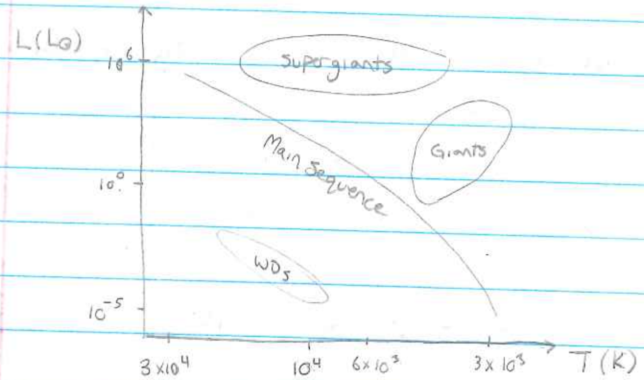
S1

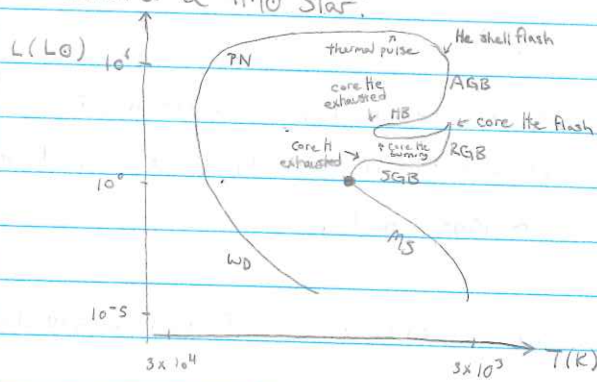
- Draw HR diagram
- Draw 1$M_\odot$ evolution: exhause core H = SGB, RGB, core He burning + exhaustion = HGB, AGB, He shell flash, PN, WD
- Draw 10 $M_\odot$ evolution: exhaust core H, start core He burning = RSG, core C/O burning, SN

- The HR Diagram and Stellar Evolution Tracks



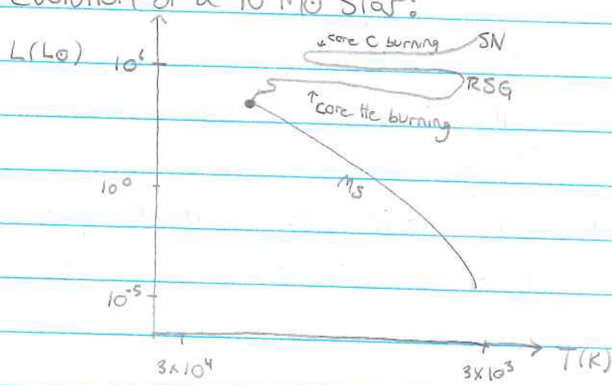
Sp.T.: O B A F G K M (LTY)

- Evolution of a 1$M_\odot$ star:



- MS = main sequence
- SGB = sub giant branch
- RGB = red giant branch
- HB = horizontal branch
- AGB = asymptotic giant branch
- PN = planetary nebula
- WD = white dwarf

- Evolution of a 10 $M_\odot$ star:



- RSG = red super giant
- SN = supernova

S 2

- Draw plot, explain regimes: terrestrial = incompressible = $M^{1/3}$, gas giant = electrorepulsion = M-indep, BD/WD = e^- deg. P = $M^{-1/3}$,
- can derive using HSE and diff pressure EoS
- Upper mass limit due to $M_{chandra}$, when e^- deg P ~~support~~ can't support star, and no other pressure support mechanism in cold objects.

- Radius-Mass Relationship for Cold Objects

- The relevant equations here are Mass conservation, hydrostatic equilibrium, and the various equations of state describing the objects in question:

- $dM = 4\pi r^2 \rho \, dr \rightarrow M = \frac{4}{3}\pi R^3 \rho \rightarrow \rho \sim M/R^3$
- $dP = -\frac{GM}{r^2}\rho \, dr \rightarrow P \sim \frac{M}{R}\rho \rightarrow P \sim M^2/R^4$

- $P \sim \rho^\alpha$ depending on the source of the pressure support.

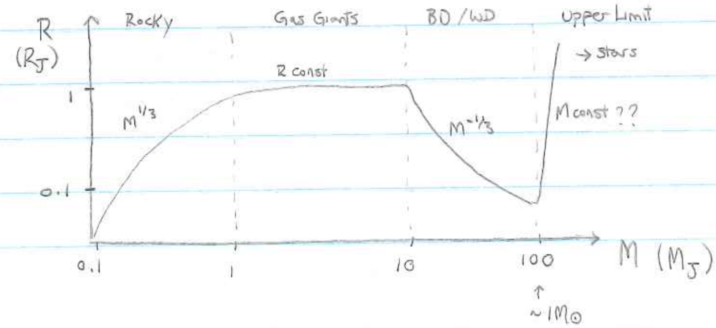
- For rocky objects, they can be treated as incompressible such that ρ is constant with increasing pressure:
  $\rho = \text{constant} \sim M/R^3 \rightarrow \boxed{R \sim M^{1/3}}$

- For gas giants, their pressure support comes mainly from electrostatic repulsion (but they're also partially supported by e^- degeneracy pressure). In this case, $P \sim \rho^2$:
  $P \sim \rho^2 \rightarrow \frac{M^2}{R^4} \sim (M/R^3)^2 \rightarrow \boxed{R \text{ indep. of } M}$

- For BDs and lower mass WDs, the pressure is due to non-relativistic e^- degeneracy, so $P \sim \rho^{5/3}$:
  $P \sim \rho^{5/3} \rightarrow \frac{M^2}{R^4} \sim \left(\frac{M}{R^3}\right)^{5/3} \rightarrow \boxed{R \sim M^{-1/3}}$

- Near the Chandrasekhar Mass, e^-'s become relativistic and $P \sim \rho^{4/3}$:
  $P \sim \rho^{4/3} \rightarrow M^2/R^4 \sim (M/R^3)^{4/3} \rightarrow \boxed{M \text{ indep. of } R}$

- Past the Chandra. limit, e^- degeneracy pressure can't support the star against collapse. This defines the <u>upper mass limit</u> for cold objects, which have no other mechanism for pressure support (like radiation pressure in stars).



* these axes may not be totally right.

S3

- Kirchhoff's Laws describe production of continuum + lines. Continuum due to hot dense gas, BB.
- emission lines = hot diffuse gas, hot enough to collisionally excite ions, diffuse enough to allow spontaneous emission before collisional deexcitation
- absorption lines = cool diffuse gas in front of hot continuum, excitation by photon from background source

Absorption and Emission Lines

- Kirchhoff's Laws describe the production of spectral lines (and continuum in a star's spectra. A hot dense gas (like the stellar interior) produces a continuum of blackbody radiation described by the Planck function: $B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT}-1}$

- A hot diffuse gas produces emission lines when an e^- makes a downward transition between energy levels, and the difference in energy is radiated away by a single photon. Since excited atoms are required for this, the gas must be sufficiently hot kinetically to collisonally excite atoms, but tenuous enough that collisional de-excitation doesn't occur before spontaneous emission (otherwise the energy is transfered to another electron). Emission lines in the sun likely come from the corona.
  - Emission lines can be produced via either allowed or forbidden transitions. Allowed transitions follow the selection rules for electric dipole moment radiation, while forbidden transitions do not, and are instead due to electric quadrupole or magnetic dipole moment radiation, which occur much less frequently.

- A cool diffuse gas in front of a source of continuous spectrum produces absorption lines. These are produced when an e^- makes an upward transition b/w energy levels due to the absorption of a photon whose energy exactly equals the energy difference b/w the two levels.
  - Absorption lines are produced in the diffuse gas of the stellar atmosphere which sits above the optically thick, dense, gas of the star.

S 4

- opacity describes how photons are removed from a beam by scattering / absorption
- e^- scattering due to oscillation of e^- in γ field, dominates when $n_e \uparrow$ so $T \uparrow$,
- free-free = backwards Bremsstrahlung, Kramer's Law,
  bound-free = photoionization, $h\nu > \chi$
  H^- ion = loosely bound 2nd e^- easy to ionize, important for $\downarrow T$
- Draw opacity v. T plot

Stellar Opacity Sources

- Opacity basically describes how photons are removed from a beam of light via scattering and absorption events. $\underset{\substack{\uparrow \\ \text{absorption coefficient}}}{\alpha_\nu} = n\sigma_\nu = \rho \kappa_\nu \rightarrow \kappa = \frac{n\sigma}{\rho}$ $[cm^2\, g^{-1}]$

i) **Electron / Thomson Scattering**

- An incoming γ causes a free e^- to oscillate in the γ's EM field, reradiating or scattering the γ in a different direction. Its small σ means e^- scattering is most efficient as an opacity source when n_e is high, which requires high T to ionize atoms and free e^-s. Thus e^- scattering dominates the opacity at high T (like the interiors of stars), where bound e^-s can't contribute to the opacity.

$\sigma_T \sim 10^{-25}\ cm^2$, $\sim (e^2/m_e c^2)^2$

ii) **Free-Free Absorption**

- A free e^- in the vicinity of an ion absorbs a γ, causing the e^- speed to increase (the nearby ion is necessary to conserve E and momentum). This mechanism can occur for a continuous range of ν's, contributing to the continuum opacity.

$\sigma_{ff} \sim \sigma_T T^{-7/2} n$ $\leftarrow$ Kramer's Law: $\kappa_{Km} \sim \rho T^{-7/2}$.

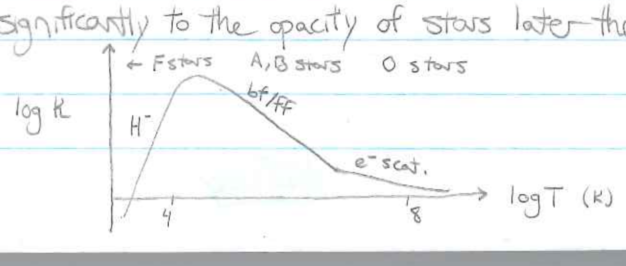
iii) **Bound Free Absorption (Photoionization)**

- Photoionization occurs when an incident γ has $h\nu > \underset{\substack{\uparrow \\ \text{ionization energy}}}{\chi}$, so the atom is ionized. The resulting free e^- can have any energy, so a continuum opacity results.

$\sigma_{bf} \sim \frac{1}{n^5} \frac{1}{\nu^3}$

iv) **H^- Ion Photoionization**

- A second e^- can be loosely bound to an H-atom when the nucleus partially shields it from the repulsion of the other e^-. The 2nd e^- has low binding E (0.75 eV), so even low E γs can liberate it. This photoionization of H^- ions contributes significantly to the opacity of stars later than F0.



S5

- pulsations due to radial oscillations as star expands / contracts, meaning star dims / brightens
- ε mechanism = compression of core $\rightarrow \uparrow T, \rho \rightarrow \uparrow \varepsilon \rightarrow$ expansion. standing wave w/ node at center means oscillations in core can't drive pulsation.
- κ mechanism = compression of layer $\rightarrow$ opaque $\rightarrow$ interior heats $\rightarrow$ expansion $\rightarrow$ transparent - heat escapes. occurs in partial ionization zones of stars.
- Types = Cepheids, RR Lyrae

Stellar Pulsation

- A pulsating star dims and brightens as its surface expands and contracts, varying regularly in luminosity with some characteristic period. This stellar pulsation is a transient phenomenon; as stars evolve they pass through the instability strip on the HR diagram, and their pulsation ceases once they leave (mostly true...).

- For simplicity we'll just discuss radial oscillations, which are the result of sound waves resonating in the stars interior, with many modes of oscillation. The pulsation can be driven by a few mechanisms:

Nuclear ε Mechanism

- When the center of a star is compressed (perhaps due to changes in core burning??), its T and ρ rise, increasing the rate of thermonuclear fusion and driving expansion, which decreases fusion and the process repeats. However, there is necessarily a node for the standing wave at the star's center, which means the pulsation amplitude here is small. This suggests that core-driven oscillation is not enough to drive stellar pulsation.

κ Mechanism

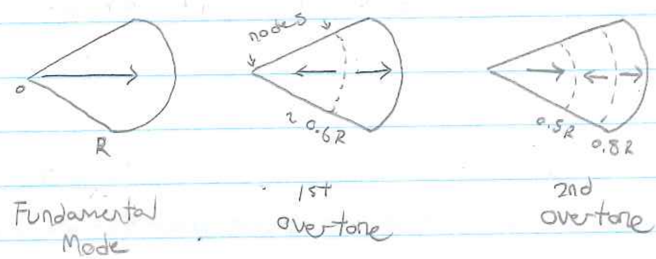
- Compression causes a star layer to become opaque, heating up the interior and driving expansion until the layer becomes transparent and heat can escape, allowing the cycle to begin again.
- This mechanism can operate in the partial ionization zones of stars. Here, part of the work done on the gas during compression goes into ionizing more of the gas, rather than just increasing T. With a smaller rise in T, the increase in density due to the compression dominates the opacity change ($\kappa \sim \rho T^{-7/2}$). The opacity thus increases and the κ mechanism operates in these zones.
- Essentially, the layer absorbs heat during compression (via ionization) and releases heat during expansion (via recombination), resulting in pulsations in the stellar luminosity.

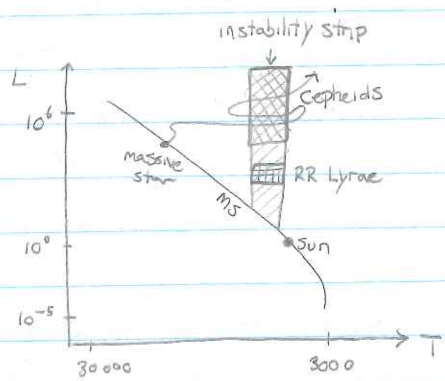
continued $\longrightarrow$

• We can use asteroseismology to study such pulsation modes (radial, p-modes, g-modes) of stars and learn about their internal structure, chemical composition, rotation, and magnetic field.

• Some examples of classes of pulsating stars are:

Type	Period	Population	Radial Mode
Cepheids	1 - 50 d	I	Fundamental
RR Lyrae	1.5 - 24 hr	II	Fundamental & 1st Overtone





S6

- Stars: 2
  - Grav contraction = grav PE → thermal on t_{KH}
  - Fusion = release binding E via photons that are scattered + absorbed
- Planets: 5
  - Incident radiation = heat from star depends on albedo + atm composition
  - Accretion = impacts impart KE into thermal
  - Differentiation = sinking converts grav PE to thermal via friction
  - Radioactive Decay = binding E released imparted to surroundings by collision
  - Tidal Heating = eccentric orbit leads to tidal force, orbital E into friction

- Thermal Energy Sources for Stars and Planets

- Stars:

- Gravitational Contraction

— In the early stages of star formation, gravitational potential energy is converted to thermal energy as the star contracts and heats up on a Kelvin-Helmholtz Timescale. From the virial theorem, $E = \frac{1}{2}U \sim \frac{1}{2}\frac{GM}{r^2}$.

- Nuclear Fusion

— Light elements are converted to heavier ones via the PP Chain or CNO cycle in the star's core. The difference in binding energies is released via photons, which can dissipate their energy via scattering and absorption events within the stellar interior, supplying the star with thermal energy. $E = \varepsilon mc^2$

- Planets:

- Incident Radiation

— Radiation from the planet's host star can heat the planet, either via absorption or the greenhouse effect. This depends on the planet's albedo and atmospheric composition.

- Accretion/Impacts

— During the early stages of planet formation, the accretion of planetesimals colliding with the planet will convert the former's KE to thermal energy.

- Differentiation

— During the early stages of planet formation, dense material will sink inward and v.v., meaning mass moves inward overall. The grav. PE of the material will be converted to thermal energy via frictional heating b/w the material.

- Radioactive Decay

- Planets can contain radioactive isotopes like Ur, K, in their interiors. When these isotopes decay, the resulting nuclei fly apart and collide with surrounding material, thereby converting the mass energy of the radioactive nuclei to thermal E.

- Tidal Heating
- If a planet is in a close-in elliptical orbit, the tidal force exerted on it by its host star will generate internal friction as the planet is deformed throughout its orbit. This friction therby converts the planets orbital/gravitational energy to thermal energy within the planet. Eventually the orbit will decay to circular as the orbital energy is dissipated by this tidal heating. $E \sim R^5 e^2$

S7

- Most photons come from radioactive decay of Fe-like nuclei.
- Type II: Fe production ends fusion, get photodisintegration of Fe which removes E and causes collapse until n^0 deg. P kicks in, causes shock wave that blows off outer layers. 10^{53} erg but only 10^{49} erg in γs
- Type Ia: $M > M_{chand}$, and T increases until C/O burning sets off runaway fusion, exploding star. so e^- deg P fails,
  - 10^{51} erg and 1.5×10^{49} erg in γs b/c more radioactive nuclei like ^{56}Ni

Supernova Energy/Light Production

Core Collapse/Type II SNe

- Once Fe is produced in the core, further fusion ceases b/c it becomes endothermic. The high T of the core ($\sim 10^9$ K) means high E γs are able to photo-disintegrate the Fe, eventually returning it to a bunch of p^+ and e^-. This is highly endothermic and removes E from the core.
- The loss of energy results in contraction past the point where e^-s can provide support via degeneracy pressure. At this point it becomes energetically favorable to combine e^- and p^+ to create n^0 (and ν), and the collapsing core bounces back due to neutron degeneracy pressure support. Neutrinos stream out.
- This creates a shock wave that propagates through the outer layers. As the material is expelled outward the optical depth decreases until the material is optically thin, and photons can escape the exploding star.
- Type II SNe produce $\sim 10^{53}$ erg of energy, most of which is in the form of ν's, 1% of which is KE of the expanding material, and 0.01% is photons.
  $\therefore$ 10^{49} erg of light.

Type Ia SNe

- Mass from a companion spills over its Roche lobe and accretes onto the WD. Because the WD is supported by e^- degeneracy pressure, the increase in M (and resulting increase in T) means the radius actually contracts (see S2), and as the mass continues to grow the WD approaches the Chandrasekhar mass limit ($\sim 1.4\ M_\odot$). Nearly simultaneously, the core T ignites C-burning and e^- degeneracy pressure becomes unable to support the star as $M > 1.4\ M_\odot$. The sudden C ignition sets off a runaway nuclear explosion, destroying the star.
- Type Ia SNe produce $\sim 1.5 \times 10^{51}$ erg of energy, and 1% is photons.
  $\therefore$ 1.5×10^{49} erg of light.

☆ • Type Ia are brighter b/c they produce more radioactive elements (^{56}Ni) which will decay and emit light. They produce more b/c they're more dense than Type II, plus they're just entirely different processes that cause the explosion.

S8

- large T gradient required so $\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad}$, $\frac{dT}{dr} \sim \frac{\kappa l}{T^3 m}$
- In $\downarrow m$: $\uparrow \kappa$ in outer layers + $\downarrow T$ means convection
- In $\uparrow m$: CNO cycle's ε much more T-dep, so stronger T gradient in core means convection

- Convection in Low and High Mass Stars

- A large T gradient is required for convection. Essentially, the actual T gradient must be super adiabatic such that:

$$\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad}$$

- this means an adiabatically expanding bubble in P equilibrium w/ its surroundings will always be hotter (and ∴ less dense) than its surroundings, allowing it to rise and carry its heat upward. The temperature gradient is roughly:

$$\boxed{\frac{dT}{dr} \sim \frac{\kappa l}{T^3 m}}$$, where κ = opacity, l = luminosity, T = temperature, m = mass

- In low mass stars, the opacity in the cold outer layers drives convection in the envelope, while the PP chain has a low enough T dependence (T^4) that there isn't as steep of a T gradient in the core, and the requirement for convection is not met.
- In high mass stars, the temperature is much higher in the outer layers, so radiation dominates in the envelope. In the core, the luminosity per unit mass is much higher due to the CNO cycle (probably but IDK), so convection dominates within the core.

S9

- L_{Edd} describes point at which F_{rad} exceeds F_{grav}, and outer layers can be ejected
- $F_{rad} = P_{rad}\,\kappa m = \frac{L}{4\pi r^2 c}\kappa m$
- Important b/c affects stability of massive stars, AGB stars can exceed L_{Edd} and have strong winds, which is important for understanding evolution and remnant.

Eddington Luminosity Limit

- The Eddington L describes the L at which the radiation force exceeds the grav. force, at which point the outer layers of a star can be ejected.

$$F_{rad} = F_g$$

$$P_{rad} \cdot \underbrace{\kappa m}_{\text{units of } cm^2} = \frac{GMm}{r^2}$$

$$\frac{L}{4\pi \cancel{r^2} c} \kappa \cancel{m} = \frac{GM\cancel{m}}{\cancel{r^2}}$$

$$\boxed{L_{Edd} = \frac{4\pi c GM}{\kappa}}$$

- This limit is important because it affects the stability of massive stars. For instance, AGB stars can exceed L_{Edd}, resulting in strong stellar winds that cause a lot of mass loss. This is important for understanding the evolution of the star and the resulting remnant. Some stars can have a mass loss rate up to $\sim 10^{-4}\,M_\odot/yr$.
- In high mass stars, the opacity is generally dominated by e^- scattering, so $\kappa \sim \sigma_T/m_p$.

S10

- Get T_c by assuming HSE and ideal gas: 1.2×10^7 K
- Get actual T_c by measuring neutrino energy from sun. Compare avg E of ν_e from ^7Be e^- capture, see broadening due to KE of Be and e^-'s, compare to lab E, get T profile of Sun → T_c.

- Central Temperature of the Sun

We can determine what T_c should be by considering that the Sun is in HSE, and can be roughly assumed to be described by the ideal gas law:

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho \rightarrow P = \frac{GM}{R}\rho$$

$$P = \frac{k_B}{\mu m_H}\rho T$$

$$\therefore T = \frac{P \mu m_H}{k_B \rho} = \frac{GM\rho}{R} \cdot \frac{\mu m_H}{k_B \rho} = \frac{GM \mu m_H}{k_B R}$$

- assuming $\mu = 0.5$ (which is for H, but really should be 1 b/c the core of the Sun is mostly He), we get:

$$\boxed{T_c = 1.2 \times 10^7 \text{ K}}$$

- One way to actually determine the central T of the sun is by measuring the difference in average energy b/w the neutrino line produced by ^7Be e^- capture in the Sun (PP chain) and the line produced in the lab. The high T of the sun broadens this line due to the KE of the Be ions and e^-'s. Comparing this E difference then informs us about the T profile of the Sun, and we find $\boxed{T_c = 1.5 \times 10^7 \text{ K}}$.

$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

S11

- Derive M-R relation by assuming HSE, ideal gas, assume T = const
- T = const by considering ε, L, P_{rad} → T doesn't strongly depend on M
- $P = M^2/R^4 = M^2/M^4 = M^{-2}$ → ↓M stars = ↑P_c

Central Pressure and M-R Relation of Stars

- Let's start by deriving the M-R relation, which will then inform us about P_c. To do this, we assume the star is in HSE and that the ideal gas law is a decent approximation for the interior of the star.

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho \rightarrow P \sim \frac{M}{R}\rho \sim \frac{M}{R}\cdot\frac{M}{R^3} \sim \frac{M^2}{R^4}$$

$$P \sim \rho T \rightarrow \frac{M^2}{R^4} \sim \frac{M}{R^3}T \rightarrow M \sim RT$$

- to proceed, we'd like to assume T = const. Justifying this takes some work. We basically want to show that T has very little dependence on M, which we can do by considering the energy generation per unit mass, ε. In the PP chain, $\varepsilon \sim T^4$, and in the CNO cycle, $\varepsilon \sim T^{20}$. We also have that $L \sim M\varepsilon$, and by relating L to P_{rad}, we can relate L to T:

$$\frac{dP_{rad}}{dr} = \frac{\kappa\rho}{c}\frac{L}{4\pi r^2}, \quad P_{rad} = \frac{a}{3}T^4$$

$$\therefore \frac{d}{dr}T^4 \sim \frac{\rho L}{r^2} \rightarrow T^4 \sim \frac{\rho L}{R} \sim \frac{ML}{R^4}$$

↳ if $T \sim M/R$, then $\left(\frac{M}{R}\right)^4 \sim \frac{ML}{R^4} \rightarrow L \sim M^3$

↳ $L \sim M\varepsilon \sim M^3 \rightarrow \varepsilon \sim M^2$

PP: $\varepsilon \sim T^4 \sim M^2 \rightarrow T \sim M^{1/2}$

CNO: $\varepsilon \sim T^{20} \sim M^2 \rightarrow T \sim M^{1/10}$

$\therefore$ T weakly depends on M, so its roughly constant for all stars

$\therefore T \sim \text{const} \sim M/R \rightarrow \boxed{M \sim R}$

- relating this back to P_c:

$P_c \sim M^2/R^4 \sim M^2/M^4$

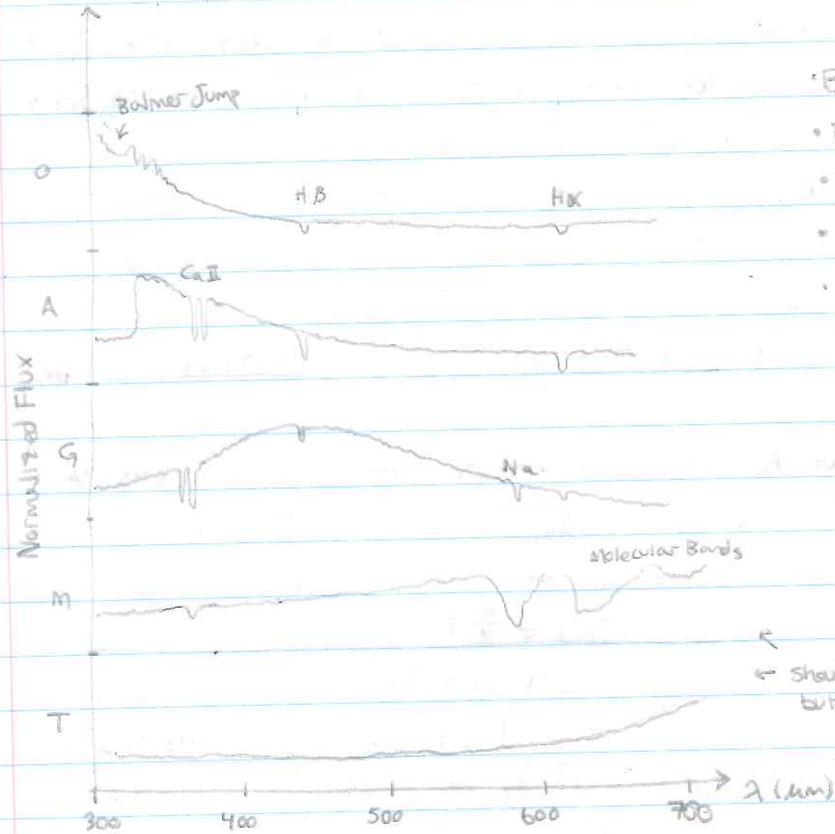
$\therefore \boxed{P_c \sim M^{-2}}$

- Thus low mass stars will have higher central pressure.

S12

- Draw SEDs, show BB peaks and spectral lines
- Describe color, peak T

SEDs of MS Stars



- Balmer Jump = 365 nm
- Balmer α = 656 nm
- Balmer β = 486 nm
- Ca II = 395(ish) nm
- Na = 589 nm

← should probably draw an IR SED but IDGAF.

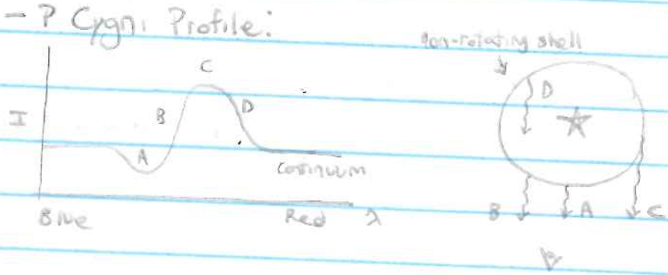
- <u>O star</u> – 3×10^4 K, 100 nm
  - hottest, blue/white, few lines, strong He II absorption lines, He I gets stronger as SpT decreases
- <u>A star</u> – 10^4 K, 300 nm
  - white, Balmer absorption lines strong, Ca II lines become stronger
- <u>G star</u> – 6000 K, 500 nm
  - yellow, stronger Ca II lines, Fe I / other neutral metal lines become strong
- <u>M star</u> – 3000 K, 1000 nm / 1 μm
  - cool red, molecular absorption bands (TiO, VO) dominate, neutral metal lines still strong.
- <u>'T star'</u> – 2000 K, 1500 nm / 1.5 μm
  - coolest, IR, strong CH_4 bands, weak CO bands

S13

· T Tauris are surrounded by expanding dust cloud / disk
· Spectral features like Balmer / Ca II emission lines, Li absorption lines, P cygni profiles
· Can learn about age (Li abs), disk size (IR slope), accretion (inverted ")

· Spectral Features of T-Tauri and Pre-MS Stars

· T-Tauri stars are transitioning from protostars shrouded in dust to MS stars. They live on the Hyashi track, have accretion disks or expanding shells of material, and can have outflows like jets.
· Their spectra are the combination of the optical spectrum of the star (now visible b/c most of the surrounding dust cloud is gone), and the IR spectrum of the disk (plus dust re-radiating in IR). Their spectra typically show strong H (Balmer), Ca II, and Fe I emission lines, as well as Li absorption lines.
· Many emission lines show P Cygni profiles indicative of an expanding shell of material around the star. This indicates that the environment around T Tauris is pretty unstable
– P Cygni Profile:



· A – absorption, due to comparatively cool diffuse shell in front of hot star, is blueshifted b/c its approaching.
B/D – emission from hot diffuse shell either approaching / receeding is blue/red shifted
C – emission w/ no bkg source and no λ shift, b/c moving ⊥.

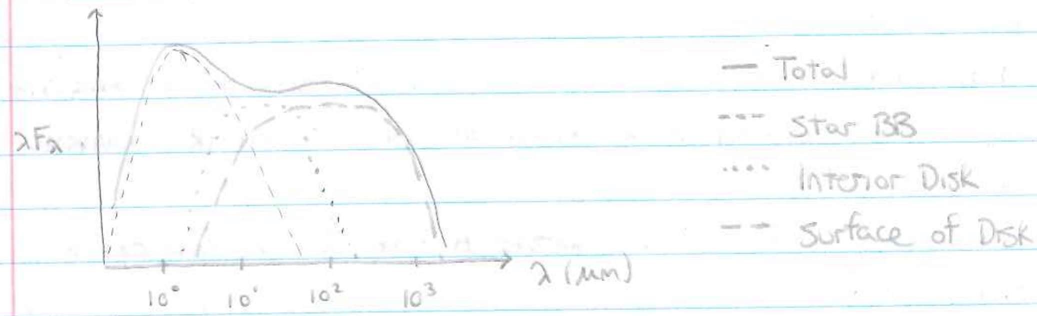
· What we can learn from such features:
– Age: The amount of Li absorption is an indicator of age, as Li is consumed by the PP chain in MS stars.
– Disk Size & Evolutionary Stage: We can infer how much material is in the circumstellar disk / surrounding envelope by looking at the Mid-IR slope of the spectrum.
– Accretion: Any UV excess or inverted P Cygni profiles of emission lines can inform us about any ongoing accretion
– Jets: Balmer lines may be blue shifted by a jet.

S14

- T Tauri SED is combination of star, interior disk, and disk surface
- Hole = less material at ↓R, less radiation from inner disk, surface mostly unaffected, same w/ interior → slight decrease
- ↑Size Grains = fewer grains, lower κ, less flux absorbed, T_{disk}↓, overall decrease in disk SED.

- SED of a T Tauri Star

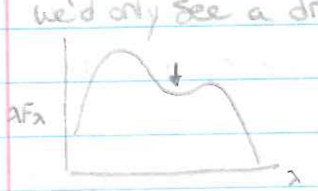
- Since a T-Tauri star has a substantial circumstellar disk around it, its SED will be a superposition of the stellar BB and the disk BB. The disk of a T Tauri is usually flared, which we assume b/c its the best way to explain the amount of radiation we see from the disk. 



- Note that we assume we're viewing the disk face on. If we saw it edge on, the disk would shroud the star and we'd see little contribution to the SED from the star.

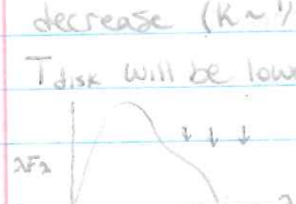
i) Hole in Inner Disk

- With less material at small R, we would see less radiation from the inner disk. However, the outer layers of the disk would remain largely unaffected, as would the interior of the disk (which doesn't directly receive flux from the star, but is instead in radiative equilibrium). Thus we'd only see a drop in flux from the inner disk.



ii) Larger Dust Grains

- If dust grains combine and grow in size, the # of small grains is reduced, the opacity of the disk will decrease ($\kappa \sim 1/s$). Thus less of the stellar flux will be absorbed, so T_{disk} will be lower, meaning its IR emission overall will decrease.



S15

- Jupiter = contraction, differentiation in atm
- Earth = cooling molten interior from early heat sources, reradiated sunlight
- Io = reradiated sunlight, tidal heating

- IR Luminosity of Jupiter, Earth, and Io

- See S6 for details, but the main heat sources for planets in general can be:
① gravitational contraction ③ differentiation ⑤ Tidal heating
② accretion/impacts ④ radioactive decay ⑥ Stellar radiation

- Jupiter
- Jupiter emits ~2.5 times more radiation than it absorbs from the Sun (I assume over all λ so maybe not explicitly in IR luminosity). We don't have a great grasp on gas giant interiors yet, but it's been suggested that Jupiter may still be contracting. A rate of 0.5 mm/century could explain the discrepancy b/w emitted and absorbed radiation. Alternatively (or in addition), differentiation of He and H in Jupiter's atm (ie separation and settling) could also explain the heat source w/ only a small fraction of Jupiter's total He content.

- Earth
- Early on, Earth experienced (and in some cases continues to experience) nearly all of the heat sources listed. This heating produced a molten core whose heat can now be transported outward via convection in molten regions and conduction in solid regions. This heat can then be radiated to space from Earth's surface. However, the heat expelled from the cooling interior is not the main source of IR luminosity. Most of the heat lost is re-radiated solar flux. The Earth's albedo is ~0.3, so 30% of light is reflected, but 70% is absorbed and can be re-emitted as IR light.

Io
- Io's heat comes from ~~the~~ reradiated sun light as well as tidal heating by Jupiter. Io is in a resonance w/ other Galilean moons, which sustains its eccentric orbit and thus its internal heat source from tidal stresses. This keeps Io volcanically active and contributes to the IR heat it loses to space.

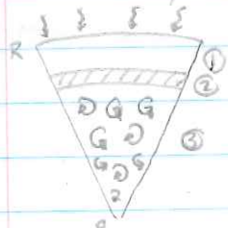
S16

- Transiting HJs have radii too large to be explained by typical atm models that consider stellar irradiation. Something else at play.
- Atm circularization = day-night T contrasts drive winds, push KE downward, dissipates in deep layers, heats planet
- Tidal effects = eccentric orbit → tidal dissipation, slows contraction, but many HJs have circular orbits

- Radius Inflation of Hot Jupiters

- See Seager (2010), p. 408.
- A significant fraction (~0.4) of transiting planets have radii larger than what can be explained by typical atm models. Typical models take into account planet mass, stellar properties and orbital distance to describe the <u>thermal irradiation effects</u> from the host star, but this irradiation is insufficient to describe the observed radius inflation. Some other mechanism must be involved, and it must be common to many HJs.

- Many potential solutions to this problem have been proposed, but there's been no consensus yet. Before describing them, let's review the process of radius inflation by stellar irradiation alone:



PIZZA

① <u>Outer layer</u> of the HJ atm where stellar flux is absorbed
② <u>Isothermal layer</u> produced when the outer layer is irradiated and heated
③ <u>Convective zone</u>, which moves inward due to the presence of the isothermal layers, thus making heat transfer from the interior more difficult. Gravitational contraction ∴ slows down, and a larger radius results (but not large enough to explain observed HJ radii).

- this thermal irradiation would explain a radius inflation of ~10-20% for a Jupiter-mass planet around ~0.2-0.5 AU from a Sun-like star. I assume that means observed inflation is > 20% for such planets.

i) • <u>Atmospheric Circulation</u>
- The idea here is that stellar irradiation produces strong day-night T contrasts, which drive winds in the atm. This results in a 'downward KE flux' which dissipates in the deep layers of the HJ.
- Confirming this scenario will require more advanced atm circulation models to explain the process by which heat from the star is converted to mechanical energy (winds).

continued →

- Tidal Effects
  - If the HJ has an eccentric orbit (or nonsynchronous rotation, but meh), internal tidal dissipation produces an energy source which can slow down contraction and even re-inflate the planet after a contraction phase.
  - However, tidal dissipation will circularize the orbit on a timescale of $\sim 10^{8-9}$ yr; shorter than the age of many exoplanet systems. Thus the eccentricity must be maintained, perhaps by an unseen companion. Unfortunately this mechanism can't explain all inflated radii. The measured eccentricities of some HJs (based on secondary eclipse timing) suggest many HJs have circular orbits and thus no tidal heating to explain their inflated radii.

- Other possible solutions include enhanced atmospheric opacities and double diffusive convection.

S17

- Define HZ, explain $T_{surf}^4 \propto L/d^2$
- Atm effects = thicker atm, greenhouse gas, winds, clouds
- M dwarfs = close in HZ, long lived, prone to flares, tidal locking

Planetary Atmospheres and Habitability

- The presence of an atm strongly affects the habitability of terrestrial planets. Habitability is (partly) dependent on the Habitable Zone, which is the range in orbital distance at which liquid H_2O could exist and be sustained on a planet for a significant length of time (ie long enough for life to develop).
- At least some atm will be necessary to prevent H_2O from just evaporating off the surface, but the composition and atmospheric pressure will have further effect on both the HZ and surface T.
- the surface T can be determined (w/out any atm considerations) via:

$P_{in} = P_{out}$ * P ≡ power

$(1-a)\frac{L}{4\pi d^2}\pi r^2 = 4\pi r^2 \varepsilon \sigma T^4$ * a = albedo

$\therefore T_{surf} = \left[(1-a)\frac{L}{16\pi\varepsilon\sigma d^2}\right]^{1/4}$

- Thicker atms (↑Pressure) will provide insulation, pushing the HZ outward. The insulating power will offset the decrease in radiant energy received at farther orbital distances.
- Greenhouse gases (H_2O, CH_4, CO_2) reduce the amount of heat able to escape the planet by IR radiation. This causes Tsurf to increase.
- Winds in the atm can also help to circulate heat from the day to night side, regulating Tsurf.
- Clouds in the atm can be highly reflective, increasing the albedo of the planet and thus reducing Tsurf. However, this effect is offset by the other effects in the atmosphere - consider Venus as an example.

- M-dwarfs are cool (3000 K ish), so their HZ's are very close in (~0.1-0.5 AU). They also have very long MS lifetimes (100s of Gyr), so any potentially habitable planets would have a long time for life to develop and evolve.
- However, M-dwarfs are prone to stellar activity (flares) due to their fully convective interiors, which isn't ideal for life sustainment... A planet would need a strong magnetic field to prevent atmosphere stripping and keep the planet habitable.

continued →

• Since the HZs of M dwarfs are so close in, planets here might be tidally locked. This could result in a strong T contrast b/w the day and night sides, and may also weaken or eliminate a planet's magnetic field.

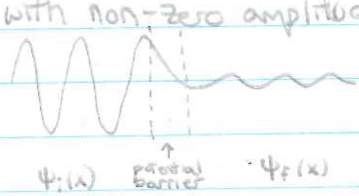
Hilroy

S18

- Fusion due to release of binding E, p^+'s overcome Coulomb barrier by tunneling
- PP chain = series of Rxs w/ H/He to get ^4_2He, T^4, 10^7 K
- CNO cycle = C acts as catalyst for series of p^+ capture & β decay that eject ^4_2He, T^{20}, 10^8K

- Nuclear Fusion Processes

- Nuclear fusion is the process by which smaller nuclei combine to form larger nuclei. This requires a very high $T/P/\rho$ to activate and maintain, because the nuclei must first overcome the Coulomb barrier (electrostatic repulsion) to get close enough for the strong nuclear force to take over and fuse the particles.
  - Quantum tunneling allows this Coulomb barrier to be penetrated. Basically the wavefunction of a free particle must be continuous at the barrier and will show an exponential decay inside the barrier. Since it's continuous there will be a finite probability that the particle/wavefunction tunnels all the way through with non-zero amplitude.



- For elements lighter than Fe, energy is released by the fusion process, where $E = \Delta mc^2$. This mass difference b/w the reactants and product is due to difference in the strong nuclear force binding energy b/w the two.

- PP Chain
  - net reaction: $4\,^1_1H \rightarrow\, ^4_2He + 2e^+ + 2\nu_e + 2\gamma$
  - of course it's very unlikely that 4 H-atoms will come together simultaneously, so the PP chain is a series of smaller reactions involving ^1_1H, ^2_1H, ^3_2He that build up to ^4_2He.
  - The energy generated per unit mass is $\varepsilon_{pp} \sim T^4$, and $T_{ignite} \sim 10^7$ K. This process dominates in low mass stars that can't reach the $T_{central}$ needed for CNO.

- CNO Cycle
  - net reaction is basically the same, but this uses C as a catalyst for various p^+ capture and β-decay reactions until a ^4_2He atom is ejected.
  - $\varepsilon_{CNO} \sim T^{20}$ and $T_{ignite} \sim 10^8$ K, so if a star is centrally hot enough the CNO cycle will quickly dominate the energy production. Stars $> 1.3\,M_\odot$ do this.

S19

- lack of evidence for aliens and ↑ prob estimates of their existence
- given ↑ galaxies, stars, planets, frequency of life, should see them
- lack of evidence = SETI, prob. estimates = exoplanet pop'n studies
- possible solns = life is rare, too far apart, destroyed

- Fermi's Paradox

- Fermi's paradox is the apparent contradiction b/w the lack of evidence of ET civilizations and the high probability estimates of their existence. It goes:
  - Our universe contains ~ 10^{11} galaxies, each of which likely contains about the same number of stars as the MW: 10^{11} stars. Many of these stars will be older than our sun, and some fraction will host habitable planets. Assuming that life develops at a reasonable frequency, there is a high likelihood that not only does other life exist, but that it could be older and more advanced than us, and thus capable of making contact or at least being detectable by us. Yet we see no signs of life beyond Earth. Where is everyone?
  - The Drake eqn attempts to systematically estimate the probability of the existence of ET life. However, many of its factors remain entirely unmeasurable and so guesses must be made. Estimates ∴ range wildly from <1 to 10^9 civilizations in the MW alone.

- The lack of empirical evidence for ET life is being addressed by SETI, either by direct (radio communication) or indirect (biosignatures, Dyson spheres/swarms, etc) evidence searches. Nothing yet.
- Studies of the exoplanet population can help constrain the fraction of habitable planets around stars, but this is still a work in progress too.

- Possible explanations for the paradox include:
  - complex multicellular life develops more rarely than we think
  - civilizations are just too far apart (in time and/or space) to communicate
  - intelligent life destroys itself (or natural events do) before becoming capable of space travel/communication
  - ET life doesn't want to be detected/interact/explore the galaxy
  - Many more...

- ns can form heavier unstable isotopes (no Coulomb barrier) which can β-decay to ↑ Z elements
- s-process = n-capture slower than β decay, interiors of stars, C-/O-burning
- r-process = " faster " ", NS mergers
- Look at abundance of Metals in ~~very~~ old Pop II stars

S20

R- and S-Process Mechanisms

- As nuclei with more and more p^+ form, it becomes increasingly difficult for other charged particles (p^+, α particles) to overcome the Coulomb barrier and fuse into heavier elements (ie past Fe). However, neutrons don't face this issue and can form heavier isotopes, which may be stable or unstable against β-decay ($n^\circ \Rightarrow p^+$). If they're unstable, they can β-decay to higher $\underset{\uparrow \, p^+ \#}{Z}$ elements.

S-Process

- Here, the rate of n°-capture is slower than the rate of β-decay. This occurs in the normal phases of stellar evolution, and the n°'s are supplied by reactions in the C- and O-burning stages. The n° density is low though, so n°-capture takes years and the build up of s-process material is slow. S-process nucleosynthesis typically produces stable elements with $A > 60$.

R-Process

- Here the rate of n°-capture is much more rapid than the rate of β-decay. This occurs in Type II SNe and Kilonovae (mergers b/w 2 NSs or NS + BH), and the n°s are supplied by the plethora found in NSs. The n° density is $\sim 10^{22}$ cm^{-3}, so the n°-capture takes seconds and n°-rich, unstable isotopes can be quickly created. As the n° density decreases, β decay becomes possible and many high Z elements are produced w/ $A > 130$, many more of which are unstable compared to s-process nucleosynthesis.

- The abundance of heavy elements in very old metal-poor stars indicates that the r-process was in operation early in the universe's history, before the s-process significantly contributed to nucleosynthesis. This fits with our understanding of each process; the s-process takes a long time to build up element abundance since C-/O-burning stages are short and n° density is low, so little s-process material existed in the early universe. The r-process has far more n° to use thanks to NSs, so the abundance patterns we observe make sense.