Astrophysics - Summary - Introduction

1. $\boxed{\text{Units}}$: - <u>mass</u> : solar mass

- <u>length</u> : AU, pc, kpc, Mpc, Gpc
- <u>time</u> : regular time
- <u>coordinates</u> : Ra. Dec Equatorial system → precession

  l, b Galactic system

- <u>brightness</u>: magnitudes - log scale (absolute, apparent, bolometric)

  $m - M = 5\log_{10}\frac{d}{10}$ → distance measurements

  + colour of objects (B - V)

<u>Sources of astronomical information</u>:

- EM radiation
- neutrinos → Sun + supernovas
- gravitational waves → black hole & neutron star mergers
- cosmic rays → energetic objects

<u>EM radiation</u>:
- various wavelengths
- atmosperic windows (throughput)
- Imaging + Spectroscopy
- Blackbody or syncrotron + spectral lines

<u>Optical</u>: resolution $\Theta = 1.22\frac{\lambda}{D}$

<u>Radio astronomy</u>: single dish vs. interferometry

<u>X-ray astronomy</u>: only from space

<u>Infrared astronomy</u>:

<u>Gamma-ray astronomy</u>: directly only from space

} name a few sources + where are the observatories in general

2.) Radiation transfer - Summary

Describes how radiation interacts with matter
- Macroscopic: using emission and absorption coeficients
- Microscopic: calculating the emission & absorption coeficients

Plancks law - blackbody radiation

Radiation transfer - how does radiation propagate

amount of radiation

$$dE_\nu d\nu = \underbrace{I_\nu}_{} \underbrace{\cos\theta}_{\substack{\text{angle}\\\text{of direction}}} \underbrace{dA}_{\text{area}} \underbrace{dt}_{\text{time}} \underbrace{d\Omega}_{\text{solid angle}} d\nu$$

~~solid~~

Radiation Flux: $F_\nu = \int I_\nu \cos\theta \, d\Omega$ $\quad F = \int F_\nu \, d\nu$

↳ integrate the intensity ↳ integrate over frequency

Energy density: $u_\nu = \int \frac{I_\nu}{c} \, d\Omega$ density of energy in a cylinder filled by radiation

Radiation pressure: pressure associated with radiation

$$P_\nu = \frac{1}{3} u_\nu$$

Radiative transport: how dos radiation propagate trough things
- in empty space: the radiation does not change
- through matter: emission and absorption

emission coef: j_ν } all matter has this
absorption coef α_ν

radiation transfer equation: $\boxed{\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu}$

if the matter only absorbes: $j_\nu = 0$ $\quad \frac{dI_\nu}{ds} = -\alpha_\nu I_\nu$

optical depth: $d\tau_\nu = \alpha_\nu ds \rightarrow \tau_\nu = \int_{s_0}^{s} \alpha_\nu(s')ds'$

$$I_\nu(\tau_\nu) = \underbrace{I_\nu(0)}_{} e^{-\tau_\nu}$$

[illegible] absorption

3) $\tau \gg 1$ optically thick
$\tau \ll 1$ optically thin (can neglect optical depth)

source function: $\boxed{S_\nu = \frac{j_\nu}{\alpha_\nu}}$ describes matter

Kirchofs law: In thermodynamic equilibrium:

$$\underset{\text{emission coef.}}{j_\nu} = \underbrace{\alpha_\nu B_\nu(T)}$$

absorption coef $\times$ blackbody

- Thermodynamic equilibrium → Maxwellian velocity distribution (e.g. stars)

Boltzmann distribution law: $\frac{n_e}{n_0} = \exp\left(-\frac{E}{k_B T}\right)$ → fraction of excited atoms
$k_B T$

Saha equation: fraction of ionised gas

- Local thermodynamical equilibrium
- Radiative transfer trough stellar atmospheres → general considerations
  - plane parallel atmosphere — layers, no variation in ↔ direction
  - LTE
  - radiation field is anisotropic (radial temperature gradient)
  - grey atmosphere model → no dependence on ν (simplification)
  - limb darkening: intensity depends on direction
- Formation of spectral lines (absorption)
  → layers with different α_ν
  → matter actually has α dependent on ν
- Radiative energy transport inside stars:

  opacity(χ): $\alpha_R = \rho \chi$ depends on density and absorption coef.

  Kramers's law $\chi \propto \frac{\rho}{T^{3.5}}$ depends on temperature → higher T lower χ

However: opacity drops at low temperatures!

(4) Thompson scattering : radiation scattering on free electrons
elastic scattering - wavelength does not change

→ additional opacity due to thompson scattering

Spectral lines : Equivalent width : the integral of the fractional dip in intensity for an absorption line

$$W_\lambda = \int \frac{I_c - I_\nu}{I_c} \, d\lambda$$

I_c - continuum intensity
I_ν = absorption line

photon diffusion inside the Sun → it takes a very long time for photons to get out from the core $\sim 10^4$ years

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Stellar Physics

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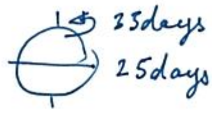
Solar phenomena :

rotation : differential rotation → from oscillations
→ movement of sunspots



magnetic field: sunspots : colder spots associated with magnetic fields

solar cycle : 11 years of variation for number of sunspot
+ polarity change ⇒ 22 years cycle

solar flares + CME's → space weather, Aurorae

Exo planets : 5 methods for detection:
- radial velocity
- transit
- direct imaging
- gravitational micro lensing
- astrometry

End state of stars:

- White dwarf
- neutron star
- BH

} discussed

White dwarfs : Fermi gas (not Maxwellian ~~Boltzmann~~ velocity) → degeneracy pressure
↳ degenerate e^- gas

For the pressure we have two cases
→ relativistic case $P = K_2 \rho^{4/3}$
→ non relativistic case $P = K_1 \rho^{5/3}$

5.) degenerate matter → stellar structure symplifies: only need to solve ~~two~~ 3 of the stellar structure equations ~~→~~ the first 2 combine

⇒ $R \propto M^{-1/3}$ → increasing mass → smaller star

depending on the ~~size~~ mass of the star we can use ~~seat~~ non-rel for low mass and relativistic pressure for higher masses

↳ mass limit for white dwarf : Chandrasekhar mass limit

→ mass of a star in the size of a planet (10^4 km)

<u>Neutron star</u> : degenerate neutron gas → "neutron drip" neutrons drip out of atoms at very high pressures, $e^- + p^+ \to n + \nu$

→ degenerate pressure

→ also have ~~a~~ mass limit

→ mass of a star in a size of a city (10 km)

→ rotating neutron star : pulsar

→ binary pulsar → grav waves

→ milisecond pulsars → binary system

↳ X-ray binaries

|The Milky Way|

"Astro summary:

Stellar models - observed properties of stars, models vs. observations
Stellar evolution

Stellar models:
What is a star: self-graviteting bodys of dynamical equilibrium
internal pressure $\leftrightarrow$ gravity
hydrostatic equilibrium
- loose energy by radiation $\rightarrow$ need energy production : nuclear energy, gravitational energy
- temperature structure $\rightarrow$ infulences energy transport: radiation, conducti...

Basic equations of stellar structure:

(1) mass conservation $\frac{dM_r}{dr} = 4\pi r^2 \rho$

(2) hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$

$\hookrightarrow$ assuming perfect gas: $\rightarrow$ calculte P and T

Virial theorem: thermal energy $\leftrightarrow$ balances gravity

$$2E_T + E_G = 0$$

(3.) ~~Energy transport~~ - Energy conservation

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

(4.) Energy transport

$$\frac{dT}{dr} = -\frac{3}{4a_B c}\frac{\chi\rho}{T^3}\frac{L_r}{4\pi r^2}$$ radiative E transport

$$\frac{dT}{dr} = \left(1-\frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr}$$ convective E transport

γ - adiabatic pressure

$\hookrightarrow$ Schwarzschild criteria stability condition

$$\left|\frac{dT}{dr}\right| < \left(1-\frac{1}{\gamma}\right)\frac{T}{P}\left|\frac{dP}{dr}\right|$$

if the temperature gradient is steeper than this than the atmosphere is unstable
$\rightarrow$ ~~and~~ convection

2) → composition of the star is important $P, \chi, \varepsilon\ (\rho, T, X_i)$
→ adding boundary conditions for the inside and outside of the star
→ solving the equations to get a model

Voigth - Russel theorem of unique solutions → not true, possible degeneracy

⇒ models - simplifications ⇒ relations between different quantities

$P \propto \frac{M^2}{R^2}$ $P \propto \frac{M}{R^3} T$ ⇒ $\boxed{T \propto \frac{M}{R}}$ $\boxed{L \propto M^3}$

mass - luminosity relation → more massive stars → more luminous

$\boxed{M \propto T^2}$ $\boxed{L \propto T_{eff}^6}$ T_{eff} - surface temp.

⇓

L vs. T_{eff} ⇒ Herzsprung Russel diagrams

$\tau \propto \frac{M}{L}$ → $\boxed{\tau \propto M^{-2}}$ liftem of a star is related to the mass inversely

Surface temperature → spectral lines → composition → spectral classes (O, B, A, F, G, K, M)
→ colour → blackbody

↓
O, B - young massive
G - Sun

Spectra → doppler shift → moton of the star (binary, planet, etc.)
→ Zeeman effect → magnetic field (e.g. sunpots)

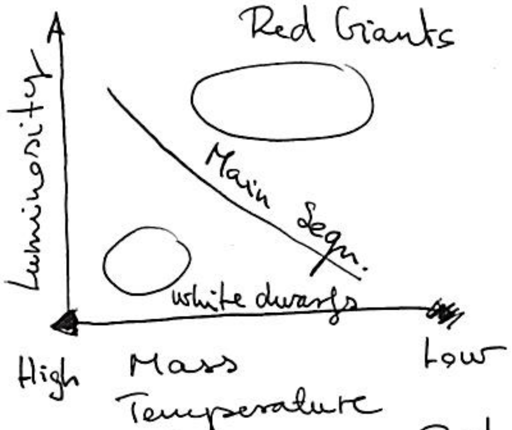
Luminosity - needs distance measurment:
- parallax
- globular clusters
- variable stars

distance → absolute magnitude, abs. bolometric magnitude, luminosity

Stellar mass - binary systems (dynamic measurment)
- eclipsing binarie
- spectroscopic binaries

- Mass - Luminosity relation

⇒ H-R diagram



spectral type:

O, B, A, F, G, K, M

⇒ mass limit of stars: $0.1 - 100 M_\odot$

Lower limit: no fusion : brown dwarf

upper limit: Eddington luminosity limit

(based on radiation pressure

Star clusters – globular clusters : old, gravitationally bound

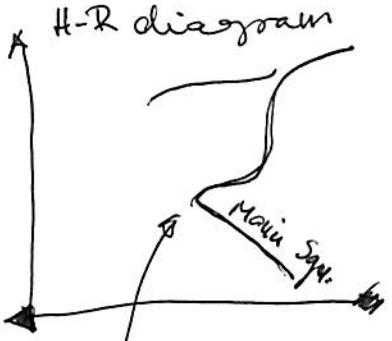
– open clusters : young, less bound

↓

born together

↓

same distance → distance measurement with the H-R diagram



→ match the main sequence to nearby stars → absolute magnitude → distance

tourn off point - related to age of cluster

Stellar nucleosynthesis :

mass-binding energy relation $E_B = \left[Z m_p + (A-Z) m_n - m_{nuc}\right] c^2$

tightest bound nucleus: Fe → lighter elements fusion } energy release

→ heavier elements fission

Stars: nuclear fusion - quantum mechanics tunneling

reaction rate - related to the cross-section $r = n_1 n_2 \langle \sigma v \rangle$

reaction rate → energy release ΔE, $\rho \varepsilon = r \Delta E = n_1 n_2 \langle \sigma v \rangle \Delta E$

↳ ε - nuclear energy generation function

↳ increases with temperature sharply

(4) → reaction of heavier nuclei needs higher temperature

- nuclear burning
- nuclear fuel

} main sequence burn H → He

proton-proton chain : $^1H + ^1H \rightarrow ^2H + e^+ + \nu$

$^2H + ^1H \rightarrow \underline{^3He} + \gamma$

^3He → pp1, pp2, pp3 chains

pp1 : $^3He + ^3He \rightarrow ^4He + H_1 + H_1$ lowest temp

if ^4He & ^7Be & $T > 10^7 K$: $^3He + ^4He \rightarrow ^7Be + \nu$

pp2 : $^7Be + e^- \rightarrow ^7Li + \nu$

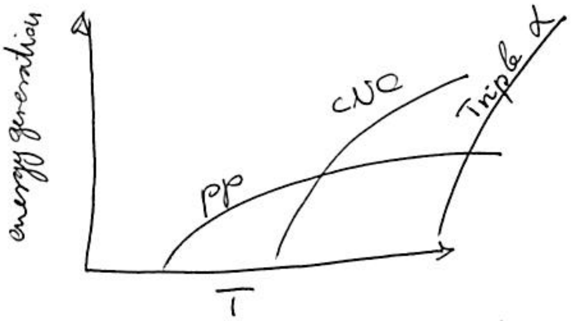
$^7Li + ^1H \rightarrow ^4He + ^4He$

pp3 : $^7Be + ^1H \rightarrow ^8B + \nu$

$B^8 \rightarrow ^8Be + e^+ + \nu$

$^8Be \rightarrow ^4He + ^4He$

if C, N, O present CNO-cycle : higher temperature



low temp : pp
low mass

high temp : CNO → more energy
high mass

triple-α reaction $^4He + ^4He + ^4He \rightarrow ^{12}C + \gamma$

⇒ heavy elements are synthesised in stars

→ after H finished → He can burn in high mass stars

→ up to Si burning into Fe

heavier elements than Fe → in Supernovas

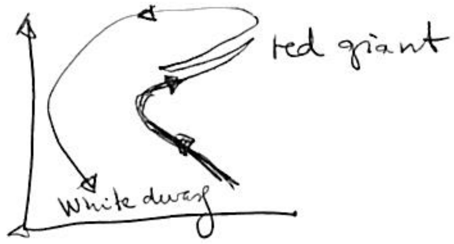
5 → Composition of stars change with time
→ more massive stars hotter → different temp gradient
→ massive stars : convective core
- low mass stars : convective envelop

testing the inside of stars:

stellar oscillations → sound speed inside → pressure and density
- helio seizmology
- astero seizmology
} test models

→ neutrino production in stars (nuclear fusion)
↳ test with observations → neutrino oscillation
^8B neutrinos depend on solar models

Stellar evolution on the H-R diagram



Binary system: equipotential surface → Roche lobe → mass transfer

Mass loss → stellar winds (solar wind)
- thermal driven wind
- radiative driven wind
- centrifugally driven winds

Extreme case: planetary nebula → White dwarf

Supernova explosion → neutron star or black hole
↳ Type I and Type II.
Type Ia supernova → mass transfer onto degenerate star
↳ identical mass → distance measurments

→ heavier elements than iron in supernova explosions (Type II)
↳ neutron capture + radioactive ~~/~~ decay

⑥ Solar properties

→ differencial rotation

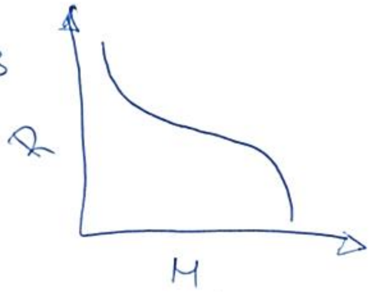
→ magnetic fied - sunspots - magnetogram

→ solar cycle : 22 years → min, max sunspot
+ magnetic field flips polarity

↳ related: solar flares, CMEs ⇒ space weather

Exoplanets: 5 methods to detect:
- astrometry
- transit
- radial velocity
- direct imaging
- gravitational microlensing

End state of stars
→ white dwarf
→ neutron star
} degenerate stars
degenerate matter
→ black hole



WD: degenerate electron gas $R \propto M^{-1/3}$

higher mass → smaller radius

planet sized star

chandrasekhar mass limit

Neutron star: degenerate neutron gas

to high pressure → neutron drip

star of $M_\odot$ → 1km city sized star

→ pulsars
→ rotation → rotation period + mass ⇒ density
→ associated with supernova remnants
→ pulsar glitches
→ mili second pulsars (double system, mass accretion)
↳ X-ray sources