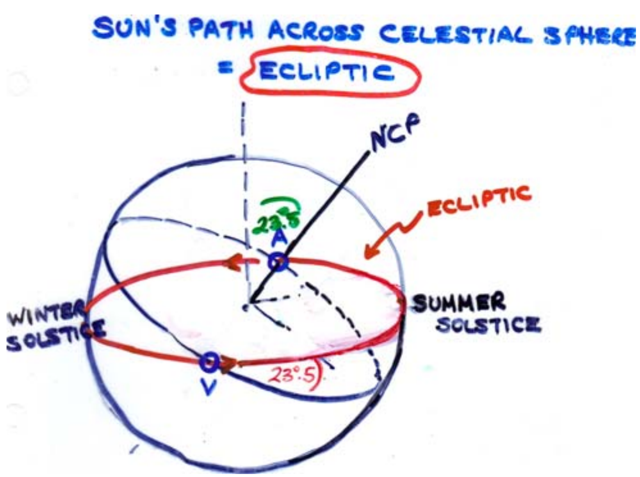
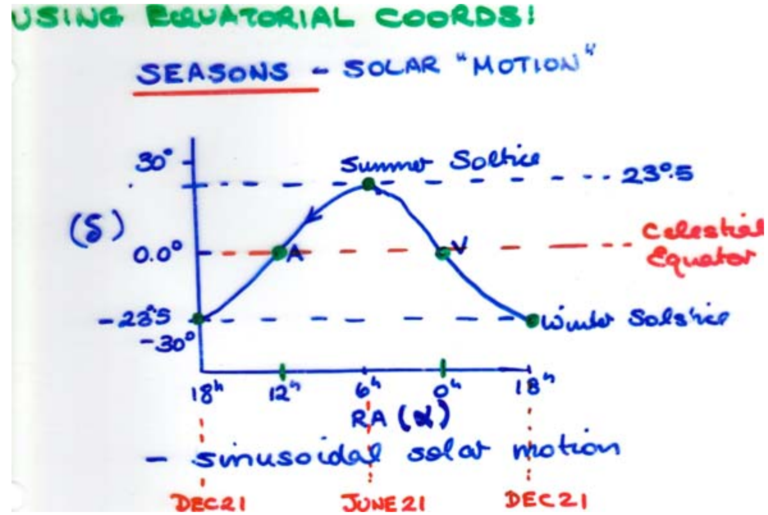
AY 20 Fall 2010

Review - sort of

How do we find objects in the sky consistently? Equatorial coordinate system (Alt/Az system too "local")





RA, α, measured around celestial equator from first point of Aries, ♈ i.e. when Sun on local meridian, α = 00h 00m 00s

Dec, δ, measured from celestial equator towards NCP or SCP

Seasons; due to motion of Sun on ecliptic tilted at 23.5°

Sidereal day: time for individual stars to re-cross local meridian

Solar day: time for Sun to re-cross meridian → stars rise 4^m earlier each day

Local Sidereal Time (LST) = time since ♈, 00h00m00s, last passed local meridian

Stars best observed near *transit i.e.* when crossing local meridian

e.g. Orion @ α~5h, δ~ -5°, best observed at LST 5h = NOW

So we can point. Which instruments' to use?

Radiation at different wavelengths →different information

Wien's law: λT = constant → different λs probe different Ts

Select instrument based on λ, resolution, collecting power

At optical wavelengths, reflectors preferred over refractors

Angular separation on sky related to linear separation in image plane by plate scale $d\theta/dy = 1/f$; longer focal length → increased "resolution"

but prohibitively long telescopes, limited collecting power

Focal ratio $(f/D) \equiv F$ expressed as f/ratio; smaller values best Keck f/1.75

Achievable angular resolution defined in terms of overlap of Airy diffraction patterns of adjacent sources:

$$\theta_{min} = 1.22\, \lambda/D \equiv \text{Rayleigh Criterion}$$

Light-gathering power of telescopes also important
= illumination = J (energy/sec/area of image) $\propto D^2/f^2$

From $\theta_{min} = 1.22\ \lambda/D$ and $J \propto D^2/f^2$:
larger telescopes $\rightarrow$ better resolution, better illumination

Radio telescopes also parabolic reflectors;
$\theta_{min} = 1.22\ \lambda/D$ demands impossibly large diameter dishes
Have to use interferometer arrays of (not necessarily huge) telescopes
Condition for constructive interference of signals from telescope pairs $\rightarrow$ best resolution $\theta_{min} = \lambda/D$

Note: here D is largest separation between telescopes NOT diameter

Typical pattern of astronomy: phenomenological studies, followed by better understanding based on application of fundamental physical principles

- e.g. Newton's Laws + Law of Gravitation [$F=Gm_1m_3/r^2$] can be applied to Kepler's laws (empirical)
  1. orbit of a planet is an ellipse with the Sun at one focus
  2. Equal areas swept ou in equal times
  3. $P^2 = a^3$ (period in years, semi-major axis in AU)
- These become more generalized - apply to binary stars – search for extra-solar planets
  1. Sun is seen to be the effective center of mass
  2. $dA/dt = L/2\mu$ where L = orbital angular momentum, and μ is reduced mass $m_1m_2/m_1 + m_2$
  3. $P^2 = 4\pi^2a^3/G(m_1 + m_2)$

Stellar properties from observables

Direct measurements

- Distances (parallax)
- Luminosities (U,B,V etc)
- Masses (binaries)
- Radii (eclipsing binaries, interferometeric measures)

Rayleigh Criterion
Distance Modulus
Planck Function
Stefan-Boltzmann Law
Kirchkoff's Laws
Maxwell-Boltzmann Distribution
Boltzmann Equation
Saha Equation

Using stellar spectra:

- Spectral type ≡ T_{eff}
- Luminosity classes ≡ gravity, pressure, density
- Radial velocities, z

Position on HR Diagram:

- Stellar radii
- Distances (spectroscopic parallax)
- main-sequence masses (approx)
- Ages of stars (later)

Spectra also provide info on:

- Rotational velocities
- Chemical abundances
- Magnetic fields
- Mass inflow-outflow

Treating stars as black bodies and measuring radiant flux → stellar properties: luminosity, mass, distance, temperature, evolutionary state

Observed brightness $B = L/4\pi d^2$ = radiant flux F

measured in magnitudes – a logarithmic scale, L = luminosity

$m_1 - m_2 = 2.5 \log b_2 / b_1$ where m is apparent magnitude

Defining M, absolute magnitude = magnitude at 10pc

→ $m - M = 5\log d - 5$ and eventually $m - M_V = 5\log d - 5 + A_v$

→ distance measurement if M is known

L, M are intrinsic to star; m, F depend on distance

Distances to nearby stars from trig parallax measures

$d = 1/\pi$ where π is parallax angle in arcseconds

Distance to star with parallax 1″ = 1 parsec = 206265 AU = 3×10^{18} cm

Beyond ~ 1kpc spectroscopic parallax method sometimes used

spectral type of star indicates M_V

At greater distances main sequence fitting methods using clusters,

Even more distant - RR Lyrae variables, Cepheid variables (recall period luminosity relation)

Masses of stars can be determined in binary systems

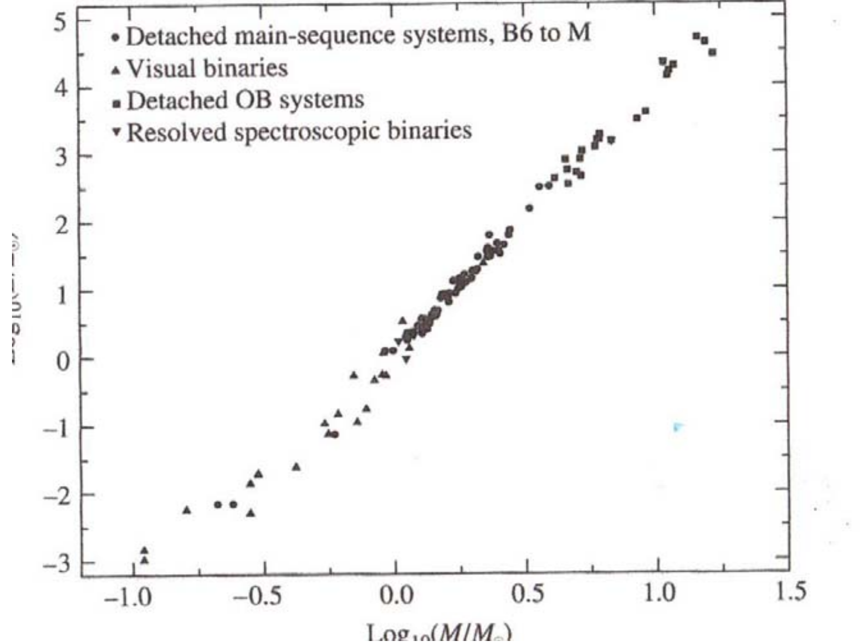
Masses of binary stars define empirical mass-luminosity relation

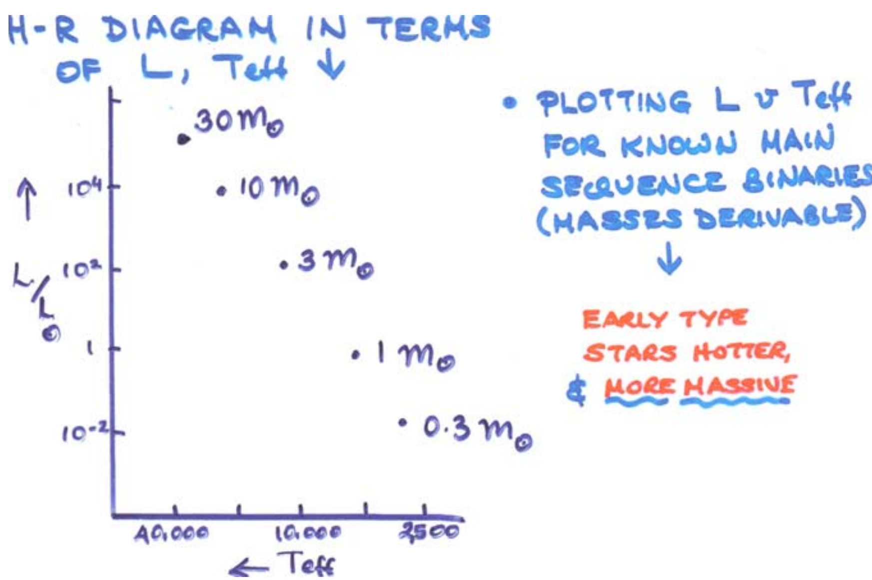
For $M > 3\ M_\odot$, $L \propto M_*^{3}$

For $M < 0.5\ M_\odot$, $L \propto M_*^{2.5}$

VERY approximate

Plotting stars of known mass on H-R diagram (L v. T_{eff}) also instructive





Treating stars as black bodies and measuring radiant flux $\rightarrow$ stellar properties: luminosity, mass, distance, temperature, evolutionary state (continued)

Stellar masses from stars in binary systems

Temperatures: Black body radiation has a characteristic shape:

Stellar temperatures (roughly) from Wien law (empirical)

$\lambda_{max} T = 0.29$ K (λ cm) peak of curve $\rightarrow$ surface temp

Or Stefan-Boltzmann equation $L = A\sigma T^4$ and $F \propto 1/d^2$

lead to $F_{surface} = \sigma T^4_{eff}$ (also empirical)

Nevertheless, explaining in terms of basic physics difficult

Rayleigh-Jeans law: $B_\lambda(T) \approx 2ckT/\lambda^4$ for long λ

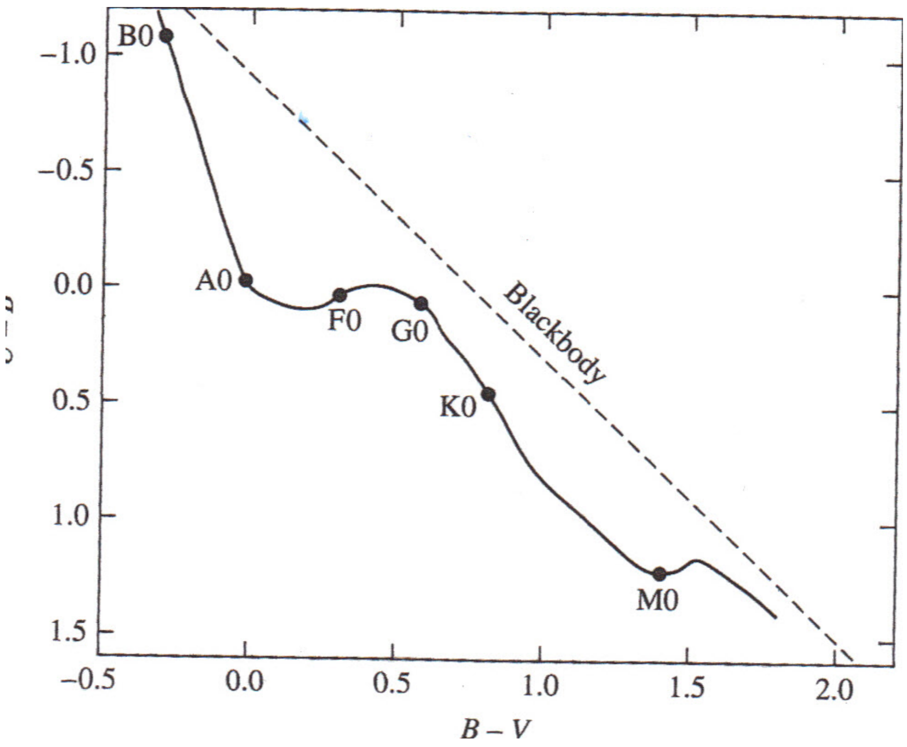
Wien's law: $B_\lambda(T) \approx a\lambda^{-5}e^{-b/\lambda kT}$ for short λ

Planck's interpretation most effective $\rightarrow$ Planck function

$$B_\lambda(T) = 2h\frac{c^2}{\lambda^5}\left(e^{hc/\lambda kT} - 1\right)^{-1}$$

$$B_\nu(T) = 2h\frac{\nu^3}{c^2}\left(e^{h\nu/kT} - 1\right)^{-1}$$

Measuring flux in different bands across Planck function → color-color Diagram and indicates physical properties



Based on color indices B-V etc

$=M_B - M_V = m_B - m_V$

i.e. an intrinsic stellar property

Indicates real stars don't behave like B-Bs

Hottest stars behave most like black bodies

Absorption of radiation displaces stars from B-B line

In any case, not measuring total radiation. To correct introduce bolometric correction

$BC = m_{bol} - V = M_{bol} - M_V$

Usual pattern: Kirkchoff's Laws → empirical definitions
Atomic theory needed to explain spectral lines

Briefly: hot dense gas (or opaque solid) emits continuous spectrum of radiation as described by Planck function

Hot diffuse (low density) gas produces bright emission lines when an electron makes a downward transition from higher to lower orbit. Energy lost = $h\nu$ or hc/λ.

Cool diffuse gas in front of a source of continuous radiation produces dark absorption lines in continuous spectrum when an electron makes an upward transition to higher orbit.

Enables spectral classification of stars – essentially a temperature scale

Balmer lines peak in strength at A0, T_e = 9250K

at lower temperatures harder to excite hydrogen

at higher temperatures ionization is beginning

HeI lines most intense in B2 stars T_e = 22,000K

CII lines most intense in K0 stars T_e = 5250K

Spectra show peak of Planck function moving to shorter λ as T_e increases

Lead to **Hertzsprung Russell diagram**

Needed: a physical basis for spectral classification

For each element:

What determines relative numbers of atoms in each excitation state?

What determines relative numbers of atoms in each ionization state?

Maxwell-Boltzmann Distribution Function: $n_v dv = n\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{\frac{-mv^2}{2kT}} 4\pi v^2 dv$

Boltzmann equation: $N_b/N_a = g_b e^{-E_b/kT}/g_a e^{-E_a/kT} = g_b/g_a e^{-(E_b-E_a)/kT}$

Saha Equation: $$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_i/kT}$$

Finally $N_2/N_{total} = N_2 \times (N_1 + N_2)^{-1} \times N_I/N_{total}$ (can assume NI = N1 + N2)

$= N_2/N_1(1 + N_2/N_1)^{-1} \times (1 + N_{II}/N_I)^{-1}$

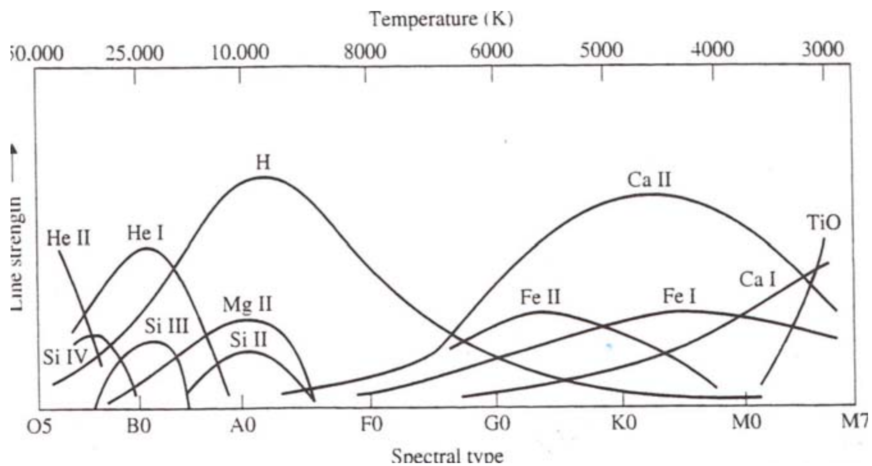
- Most stars have similar relative abundances of elements as Sun
- Dominated by H, He, and then “metals”
- Spectral line intensities strongly dependent on T

TABLE 9.2 The Most Abundant Elements in the Solar Photosphere. The relative abundance of an element is given by $\log_{10}(N_{el}/N_H) + 12$. (Data from Grevesse and Sauval, *Space Science Reviews, 85*, 161, 1998.)

Element	Atomic Number	Log Relative Abundance
Hydrogen	1	12.00
Helium	2	10.93 ± 0.004
Oxygen	8	8.83 ± 0.06
Carbon	6	8.52 ± 0.06
Neon	10	8.08 ± 0.06
Nitrogen	7	7.92 ± 0.06
Magnesium	12	7.58 ± 0.05
Silicon	14	7.55 ± 0.05
Iron	26	7.50 ± 0.05
Sulfur	16	7.33 ± 0.11
Aluminum	13	6.47 ± 0.07
Argon	18	6.40 ± 0.06
Calcium	20	6.36 ± 0.02
Sodium	11	6.33 ± 0.03
Nickel	28	6.25 ± 0.04

LATER: fractions by weight — H: X = 0.70; He: Y = 0.28; Metals: Z = 0.02

[32] Details of the construction of a model star will be deferred to Chapter 10.



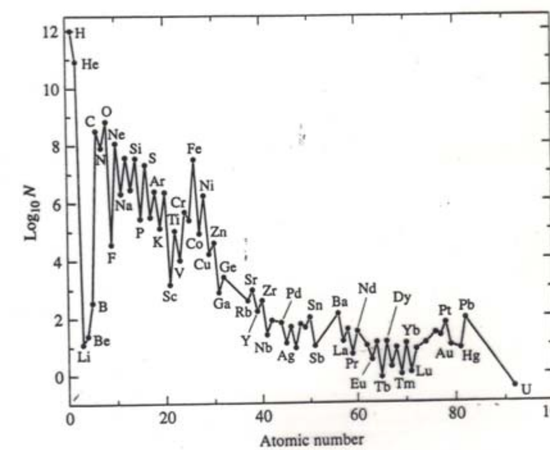


FIGURE 15.16 The relative abundances of elements in the Sun's photosphere. All abundances are normalized relative to 10^{12} hydrogen atoms. (Data from Grevesse and Sauval, *Space Sci. Rev.*, 85, 161, 1998.)

Stellar Properties from the Hertzsprung-Russell diagram

$L_* = 4\pi R_*^2 F = 4\pi R_*^2 \sigma T_e^4$

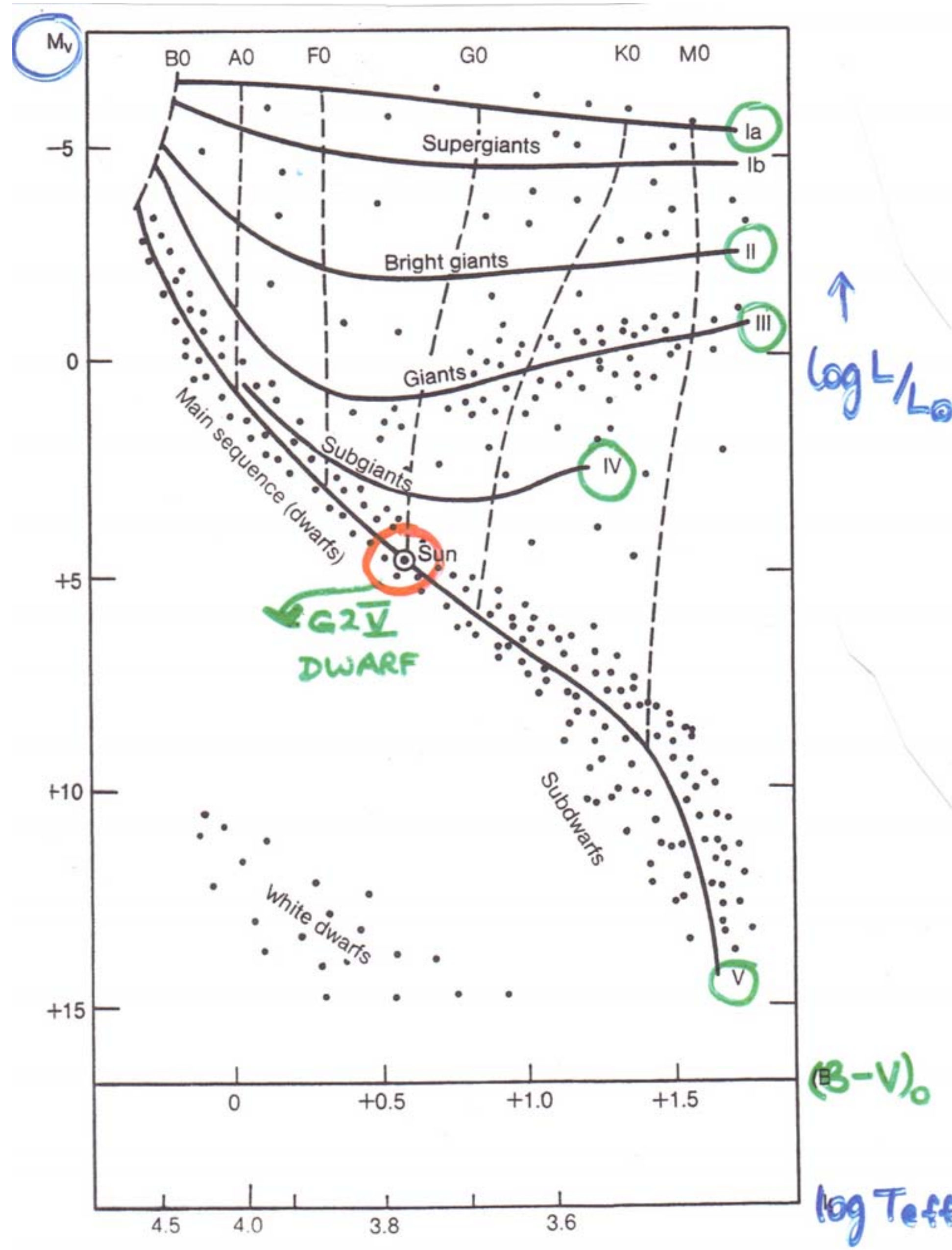
→ absolute magnitude of stars of same spectral type varies with R_*

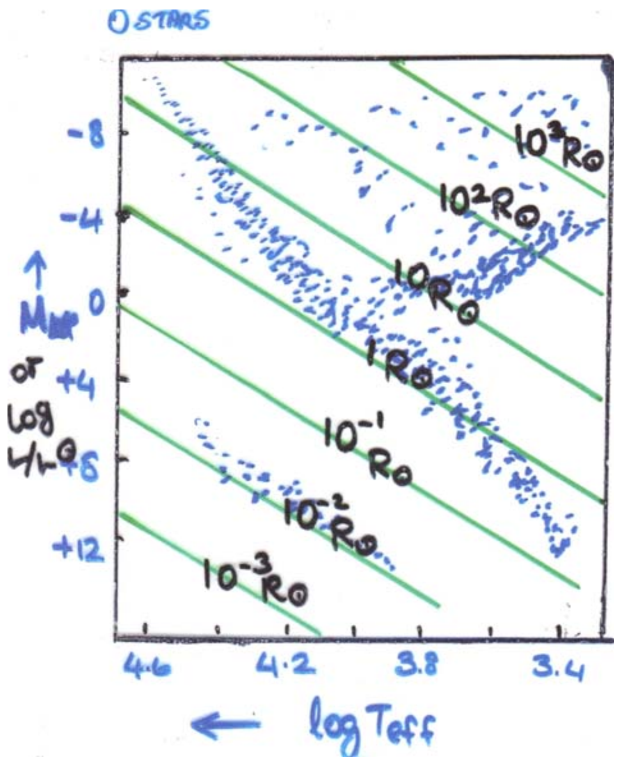
$$R_* = \frac{1}{T_{eff}^2}\sqrt{\frac{L}{4\pi\sigma}}$$

for fixed R_*, $\log L_* \propto \log T_{eff}$

→ lines of constant R_* in H-R diagram

Express R_*, T_*, L_*, in terms of $R_\odot$, $T_\odot$, $L_\odot$,





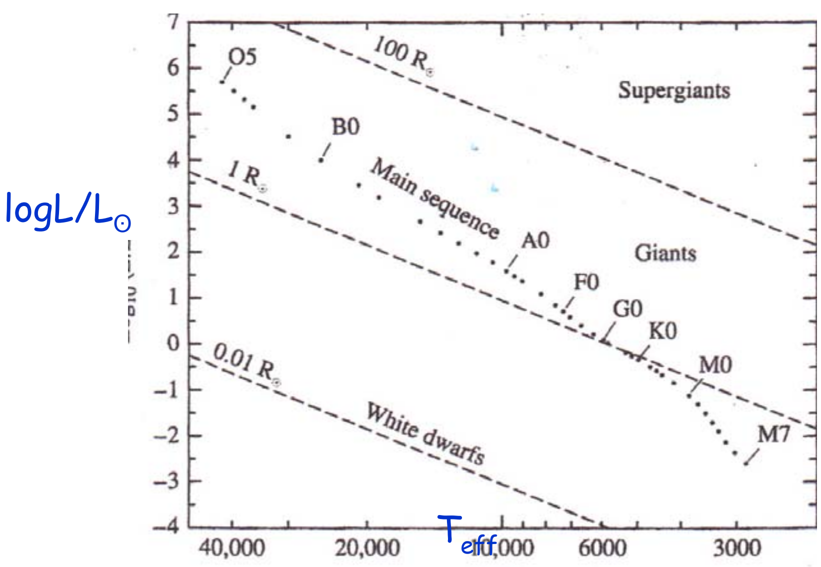
- spectral type + luminosity class (class indicates line width) → M_v distance from m-M =5logd -5

- stellar density, $\rho_* = \dfrac{M_*}{\frac{4}{3}\pi R_*^3}$

varies with position in H-R diagram

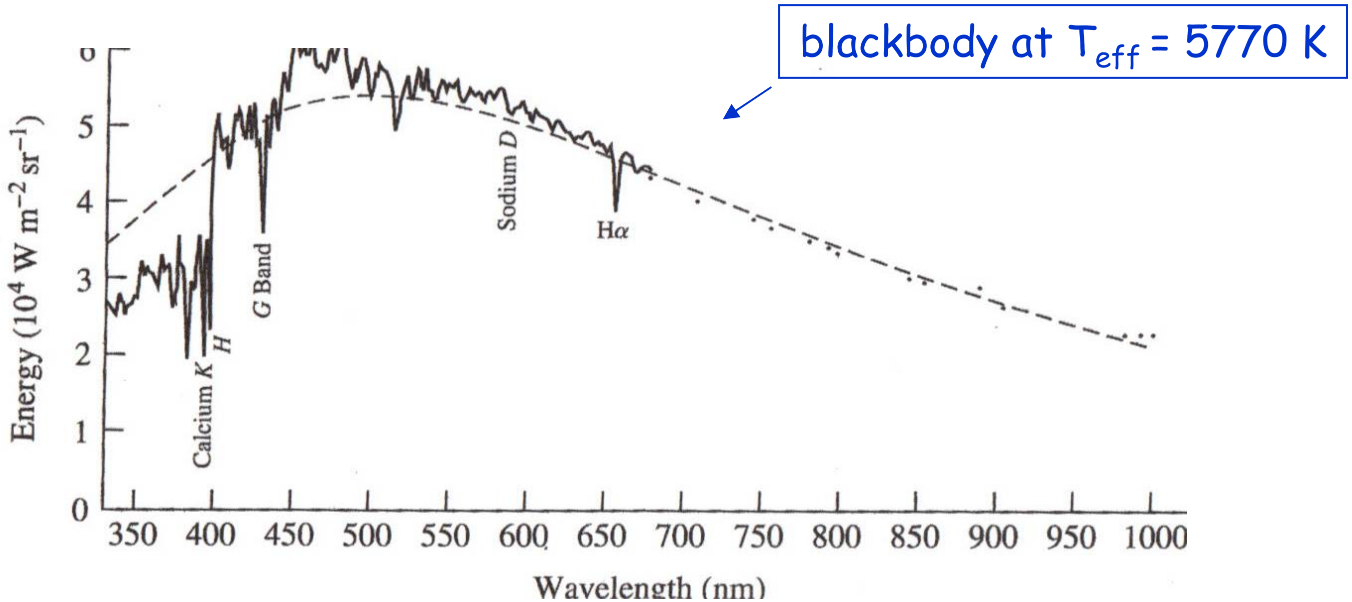
radii from L + T_{eff} , hence density if masses known (e.g from binaries)

<u>white dwarfs</u>	<u>supergiants</u>
R ~ 0.001 $R_\odot$	R ~ few x 10^3 $R_\odot$
ρ ~ 10^9 kg/m^3	ρ ~ 10^{-4} kg/m^3



Eventually saw that position of star on main-sequence depends on its mass

Stars are not blackbodies



Sun is clearly not a blackbody

Spectral lines impact continuous spectrum of emission

Line blanketing by dense pattern of metal absorption lines

(emission lines in UV or X-ray bands possible)

Absorption effects ≡ "opacity" effects

Larger implication: T_{eff} from $F_{surface} = \sigma T^4_{eff}$ is not *true photospheric* temperature

To compensate (and understand transfer of radiation) introduce concept of Local Thermodynamic Equilibrium

Define a "local box'" over which temperature remains "constant"
i.e. distance over which T changes >> mean free path of ptcles/photons

$\rightarrow$ T_{ex} (Boltzmann), T_i (Saha), T_{kin} (Max-Boltz), T_{color} (Planck fu^n) equal and thermodynamic equilibrium applies within "box"

(note: T_{eff} applies to specific levels in star)

To determine how radiation traverses star assume LTE and define absorption as any process that removes photons from beam

Decrease in intensity of beam = $dI_\lambda = -\kappa_\lambda I_\lambda \rho ds$, ($\kappa_\lambda$ is absorption coefft = opacity

$$I_\lambda = I_{\lambda,0}\, e^{-\kappa_\lambda \rho ds}$$

$\therefore$ For pure absorption, intensity falls off exponentially i.e. by factor e^{-1} at characteristic distance $\ell = 1/\kappa_\lambda\rho$

define optical depth $d\tau_\lambda = -\kappa_\lambda \rho ds$ (s measured in direction of photon's motion i.e. at stellar surface $\tau_\lambda = 0$)

Hence τ_λ and I in terms of τ_λ

, $dI_\lambda = -\kappa_\lambda I_\lambda \rho ds \rightarrow I_\lambda = I_{\lambda,0} e^{-\int \kappa \rho ds}$

pure absorption: I falls off by e^{-1} at characteristic distance $\ell = 1/\kappa_\lambda \rho$

scattering: ℓ = photon mean free path = $1/n\sigma_\lambda = 1/\kappa_\lambda \rho$

, $d\tau_\lambda = -\kappa_\lambda \rho ds;\ \therefore I_\lambda = I_{\lambda,0} e^{-\tau\lambda}$

s in direction of photon motion –outward; τ_λ inward from surface

Since $\tau_\lambda = \kappa_\lambda \rho \int ds = \int ds/\ell$, optical depth = number of mean free paths from original position to surface

optically thick if $\tau_\lambda >> 1$ optically thin if $\tau_\lambda << 1$

Sour

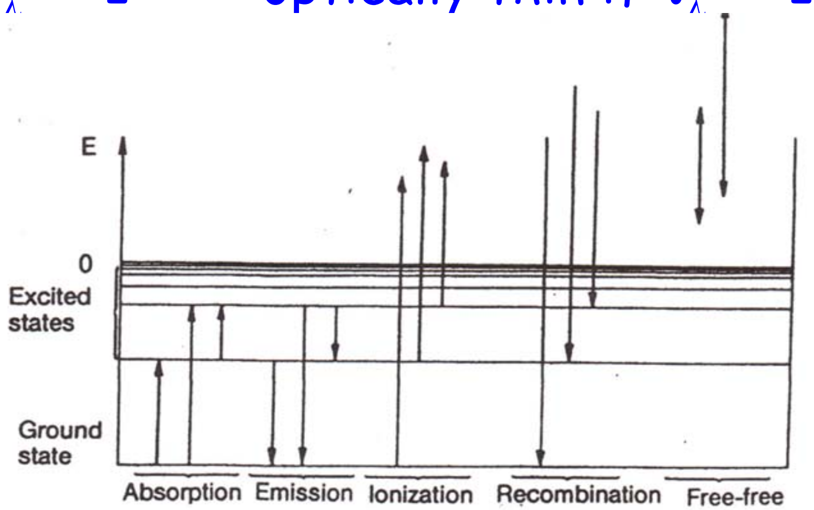


Fig. 5.2. Different kinds of transitions between energy levels. Absorption and emission occur between two bound states, whereas ionization and recombination occur between a bound and a free state. Interaction of an atom with an free electron can result in a free-free transition

Sources of Opacity: slowly varying affects continuum; rapid variations → dark spectral lines

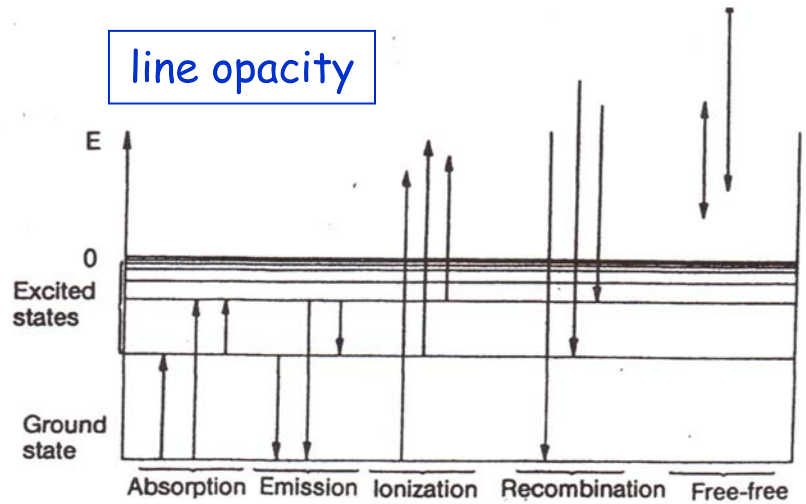
1. bound-bound transitions: photons "lost" to beam at discrete λs
2. free-free transitions: absorption & bremsstrahlung – no preferred λ
3. bound-free transitions: photoionization* – any photon w. $\lambda < hc/\chi$
4. electron scattering:

* photoionization of H^- ions important continuum opacity source in stars cooler than F0

B and A stars: continuum opacity from photoioniz. of H atoms or free-free absorption

O stars: electron scattering and photoionization of He

Fig. 5.2. Different kinds of transitions between energy levels. Absorption and emission occur between two bound states, whereas ionization and recombination occur between a bound and a free state. Interaction of an atom with an free electron can result in a free-free transition



continuum opacity

5.2

the H atom)

Real Radiative Transfer (not just removing photons from beam)

- For stars, T and P_{rad} decrease outwards; $P_{rad} = 4\sigma T^4/3c$
  $\rightarrow$ net flow of photons outwards
- introduce emission coefficient j_λ, analogous to κ_λ
  $dI_\lambda = -\kappa_\lambda \rho I_\lambda ds + j_\lambda \rho ds$ and $j_\lambda / \kappa_\lambda = S_\lambda$, source function
  $1/\kappa_\lambda \rho \times dI_\lambda/ds = I_\lambda - S_\lambda$ transfer equation*
  in LTE, for optically thick gas, $S_\lambda = B_\lambda$
- a plane parallel, *gray*, atmosphere $\rightarrow$ $\cos\theta \, dI_\lambda/d\tau_{\lambda,v} = I - S$
  $\tau_{\lambda,v}$ is vertical optical depth, *independent* of direction of "ray"
- expressing in terms of P_{rad}, F_{rad}:
  $dP_{rad}/d\tau_v = F_{rad}/c$ or $dP_{rad}/dr = -\kappa\rho F_{rad}/c$; (Rosseland mean κ)

integrating $dP_{rad}/d\tau_v$, with $P_{rad} = 4\pi/3c\langle I\rangle$ and Eddington apprx

$T^4 = \frac{3}{4} T^4_{eff}(\tau_v + 2/3)$, $T = T_{eff}$ at $\tau_v = 2/3$

$\therefore$ photosphere at $\tau_v = 2/3$ (width ~ 1% R_*)

Note: for Sun, T_{eff} = 5777K. At $\tau_v = 0$, T =4852K,

Equations of Stellar Structure

Describe how star "works" assuming equilibrium

Validity can be tested:

- observable properties should match those computed from models based on structure equations

The equations govern:

- the variation in pressure with radius in the stellar interior
  (equation of hydrostatic equilibrium)
- the distribution of mass
  (equation of continuity - or mass conservation)
- the production of energy
  (energy conservation equation)
- the transport of energy
  (variation of temperature as a function of radius; depends on way energy is transported – by radiation, convection, or conduction)

Important questions

- What is mean molecular weight, μ? (1)
- What determines ε = total energy released /gm/sec? (2)
  - nuclear burning (fusion) can sustain observed luminosity of Sun for > 10^{10} years
  - Temperature required for fusion ~ 10^7 K (if quantum tunneling allowed) ≈ central temp of Sun
  - and $\varepsilon = \varepsilon_{nuclear} + \varepsilon_{gravity}$
- How is energy transported and how does that affect temperature structure? (3)

Mean molecular weight of gas $\mu = \langle m \rangle / m_H$ (1)

$$\frac{1}{\mu_n} = \sum_j \frac{X_j}{A_j}$$ for completely neutral gas

$$\frac{1}{\mu_i} = \sum_j \frac{(1+z_j)X_j}{A_j}$$ for completely ionized gas

Where X_j = mass fraction for atoms of type j; $A_j = m_j/m_H$

Usual usage: X = total mass of H/total mass of gas

Y = total mass of He/total mass of gas

Z = total mass of metals/total mass of gas

Typically abundances are solar: X= 0.70 Y = 0.28. Z= 0.02

$$1/\mu_n = X + \tfrac{1}{4}Y + \langle 1/A \rangle_n Z$$

$1/\mu_i = 2X + \tfrac{3}{4}Y + \langle (1+z)/A \rangle_i Z$ (zj =# free electrons releasedby atom j)

$$1/\mu_i = 2X + \tfrac{3}{4}Y + \tfrac{1}{2}Z$$

Transport of Energy (3)

a) Conduction, b) Radiative Energy Transport, c) Convection

Conduction not very effective in most stars

Radiative Transport – energy from nuclear processes (2)

– net flow of photons to surface impacted by opacity

Convection – hot buoyant mass elements move outwards, cooler fall inwards

Distinguish between b) and c) thru condition for convection

$$|dT/dr|_{act} > |dT/dr|_{ad}$$

actual temperature gradient *superadiabatic* for constant μ

Express also as: $d \ln P / d \ln T < \gamma/(\gamma-1) = 2.5$ for monatomic gas

For $d \ln P/d \ln T < 2.5$, convective transport

For $d \ln P/d \ln T > 2.5$ radiative transport

Energy Sources (2)

Nuclear reactions produce sufficient energy to sustain luminosity over stellar lifetimes. Dominant processes depend on stellar temperatures, masses, evolutionary state (composition)

Equations of stellar structure

- equation of hydrostatic equilibrium $$\frac{dP}{dr} = -\frac{GM_r \rho}{r^2}$$
- mass conservation equation $$\frac{dM_r}{dr} = 4\pi r^2 \rho$$
- energy conservation equation $$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$
- radiation transport $$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L_r}{4\pi r^2}$$
- adiabatic convection $$\frac{dT}{dr} = -\left(1 - \frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM_r}{r^2}$$

$$P = P_{gas} + P_{radiation} = \frac{\rho k T}{\mu m_H} + \tfrac{1}{3} a T^4$$

- For modelling, have to supplement structure equations with constitutive relations – expressions for ρ, κ, Є, in terms of properties of local material P, T, composition
- Also have to impose boundary conditions
- As $r \rightarrow R_*$ (surface). $T \rightarrow 0$, $\rho \rightarrow 0$, $P \rightarrow 0$
- As $r \rightarrow 0$ (center) , $M_r \rightarrow 0$. $L_r \rightarrow 0$
- All parameters are inter-related: P, <κ>, ϵ_{pp} (ϵ_{CNO} etc) depend on local composition, ρ, T
- Vogt Russell "theorem" – once mass and composition structure defined, the radius-luminosity combination is defined, and also subsequent evolution.
- Effectively, evolution determined by composition changes due to nuclear burning
- Implications; Hydrogen burning stars lie on main sequence – a mass sequence; Eddington Limit constrains mass? Sun, Standard Model, provid great tests for theory

Effects of the Interstellar Medium

Distance modulus changes $m - M = 5\log d\,(pc) - 5 + A_\lambda$ (mag)

change of magnitude ≈ optical depth in line of sight: $A_\lambda \approx \tau_\lambda$

$A_\lambda \approx \tau_\lambda = \sigma_\lambda N_d$, where N_d = column density of dust particles

Extinction ∝ number of grains in line of sight if σ_λ constant

Mie scattering: when particle size ~ wavelength of radiation, $\sigma_\lambda \propto 1/\lambda$

optical radiation is reddened since blue light scattered preferentially

reddening distorts T_e, distance modulus, color-color diagram etc

Correct using color excess: $E_{B-V} = (B-V)_{measured} - (B-V)_0$

Empirically, $E_{B-V} = 3A_v$

Also gas in ISM: mostly HI, HII, or H_2 (70% H, 28% He, 2% metals)

gas, dust well-mixed: $n_{dust} \sim 10^{-13}/cm^3$, $\langle n_{gas} \rangle \sim 1/cm^3$

mass ~ 100 X dust mass

dust opacity/unit mass >> gas opacity/unit mass

Five phases of interstellar gas

	T(K)	n (cm^{-3})
Very cool molecular clouds (mostly H_2)	20	> 10^3
Cool clouds (mostly HI)	100	20
Warm neutral gas envelopes of cool clouds	6000	0.5-0.3
Hot ionized gas (HII regions)	8000	>0.5
Very hot diffuse ionized "coronal" gas ionized, heated by supernovae explosions	10^6	10^{-3}

Manifestations of Star Formation in ISM

HII Regions: simplistically: boundary from balancing ionization and recombination in gas around massive young star → Stromgren sphere

Central stars, $T \sim 3 \times 10^4$; Wien→ $\lambda_{peak} < 912$Å, very blue

HII region; $n = 3 \rightarrow 2$ transition dominates =Hα (6565 Å)

∴emission from HII regions is red

Ionization /recombination balance: $N_* / \frac{4}{3}\pi r^3 = \alpha n_e^2$

$R_S = (3N_*/4\pi\alpha)^{1/3} \times n_e^{-2/3}$

Collapsing Cores → new young stars: Virial Theorem $2K + U = 0$

Jeans mass

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

Jeans length

$$R_J = \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)^{1/2}$$

Various timescales for stellar evolution

Free fall time = t_{ff} = $[3\pi/32 \times 1G\rho_0]^{\frac{1}{2}}$

core in approximate hydrostatic equilibrium

Kelvin-Helmholtz t_{KH} = thermal energy only/Luminosity

= $3/10\ GM_*^2/R_*L_*$

$t_{nuclear}$ = time to radiate all energy from fusion

=M*C2/L*

Nuclear reactions change μ

Stellar evolution $t_{ff} \rightarrow t_{KH} \rightarrow t_{nuclear}$

Hydorostatic core Hayashi H-burning…

track to

main-seq

- Evolution & Nuclear burning a function of mass etc.

3 populations of stars in our Galaxy

Initially Pop I and Pop II only;
kinematically different

- Pop I star velocities relative to Sun much lower than Pop II velocities
- Pop I stars mainly in disk of galaxy; Pop II well away from plane

Later, metallicity differences noted:

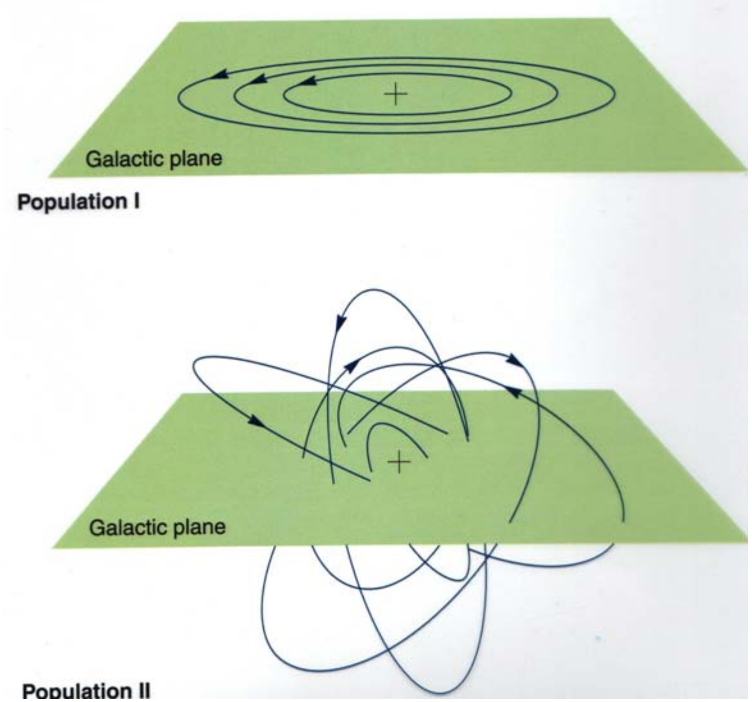
- Pop I metal rich, Z up to 0.03 ; Pop II metal poor, Z > 0

Theorists postulate Pop III:

- PopIII: first stars after Big Bang; no metals Z=0

Open clusters	Globular clusters
loosely bound	gravitationally bound
$T_{evap} \sim 10^8$ yrs	$T_{evap} \sim 10^{11}$ yrs
younger	typically old
metal rich	metal poor
Pop I	Pop II
(galactic clusters)	

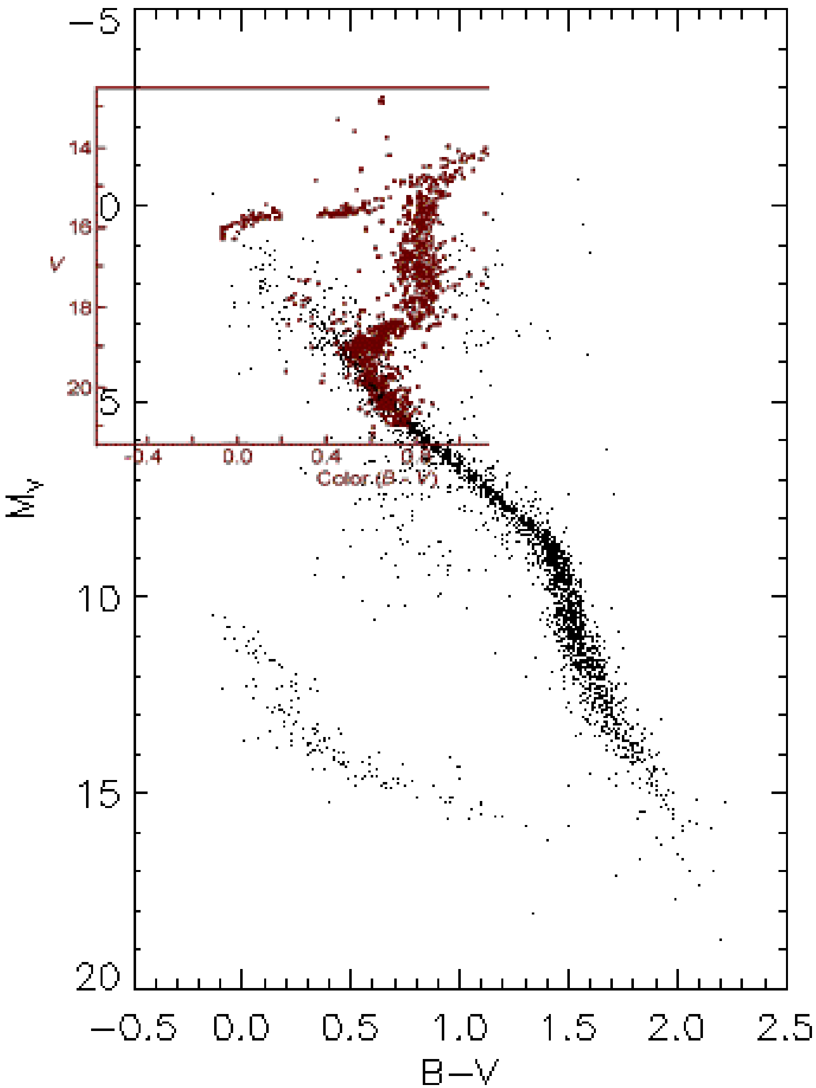
Orbits of disk stars and halo stars

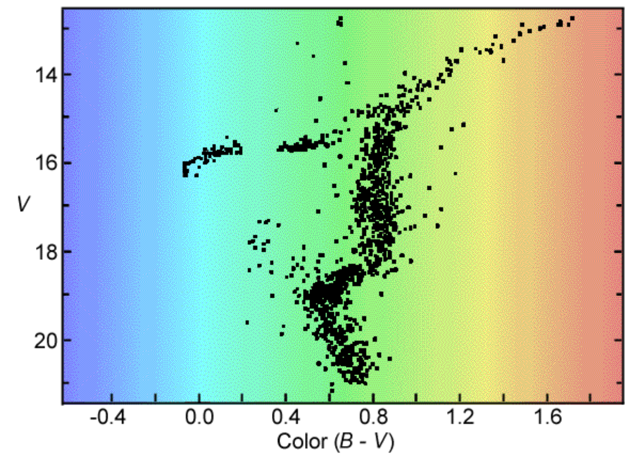


Distance scales from:
main sequence fitting
RR Lyrae variables*
Cepheid variables

*RR Lyrae stars fainter: use for smaller distance scales than Cepheids

M3 in Canes Venatici - ~ 0.5 x 10^6 stars; many variables
(RA 13h 44m Dec 28°11^h)





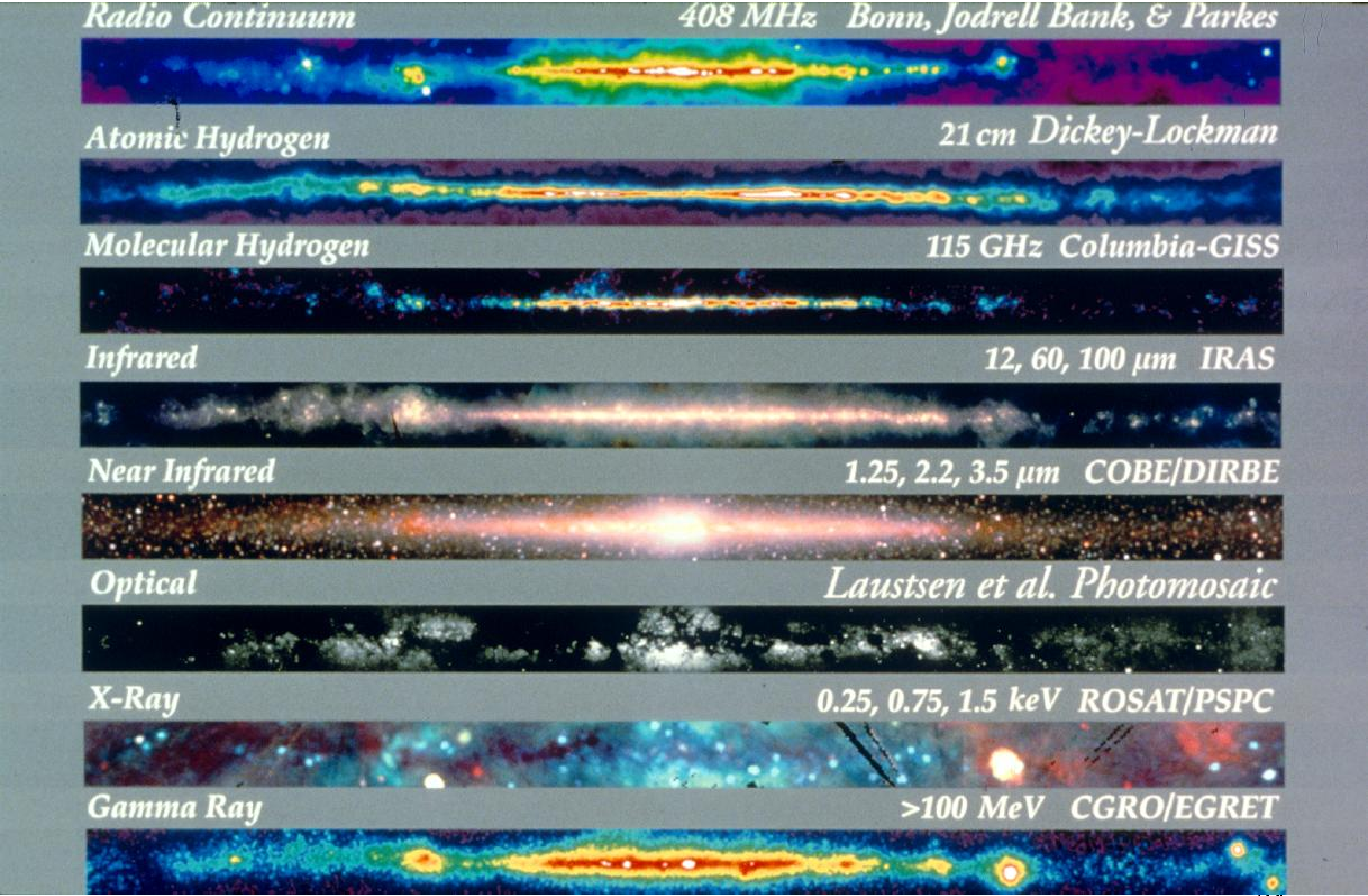
Age = 2.6 x 10^9 yrs (Sandage)

Vertical shift ~ 19 - 3.5 = 15.5 (15.4)

= mv –Mv = 5logd – 5

∴ logd = (15.4 + 5)/5 = 20.4/5 = 4.1

∴ d = 12kpc


Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen
21 cm Dickey-Lockman
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET

The Rotation of the Milky Way

- Flatness of MW suggests rotation about axis perpendicular to plane
- Observations of stars, gas confirm differential rotation
- i.e. Milky Way does not rotate like a rigid body
- angular velocity depends on distance from GC
- Observable effects of galactic rotation derived by Jan Oort
- Sun shares in differential rotation – has to be taken into account

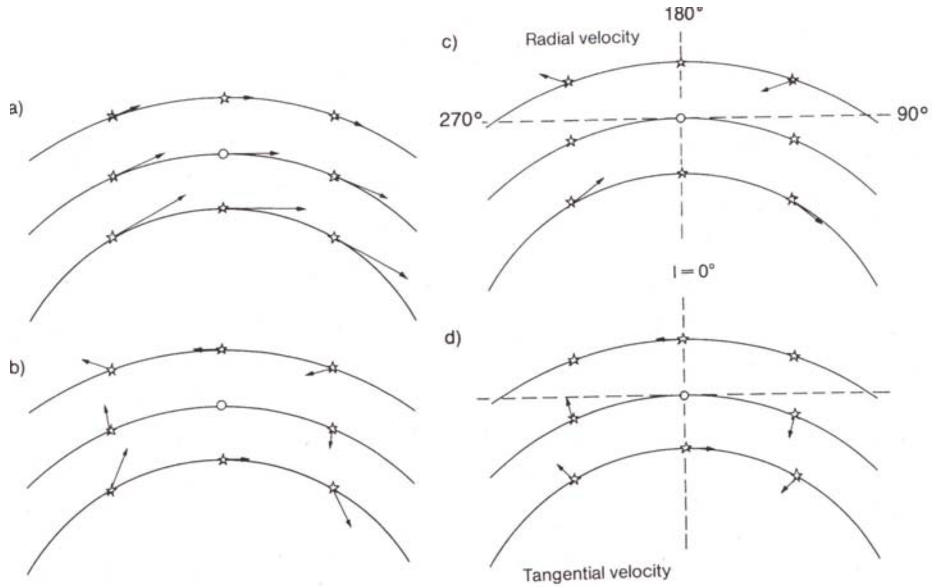


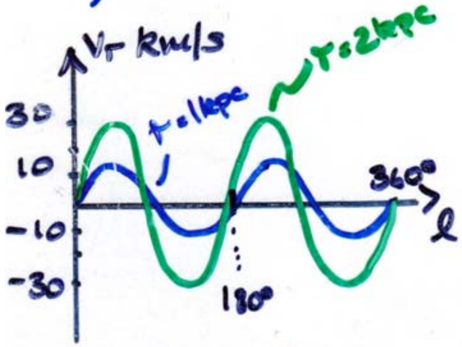
Fig. 18.13a – d. The effect of differential rotation on the radial velocities and proper motions of stars. **(a)** Near the Sun the orbital velocities of stars decrease outwards in the Galaxy. **(b)** The relative velocity with respect to the Sun is obtained by subtracting the solar velocity from the velocity vectors in **(a)**. **(c)** The radial components of the velocities with respect to the Sun. This component vanishes for stars on the same orbit as the Sun. **(d)** The tangential components of the velocities

$v_r = A r \sin 2l$ → OBSERVED v_R FOR STARS AT SAME r → DOUBLE SINE CURVE WITH AMPLITUDE A

$v_t = A r \cos 2l + B r$

Hence A if r known

$\mu = A \cos 2l + B$ → OBSERVED μ → CURVE OFFSET → B



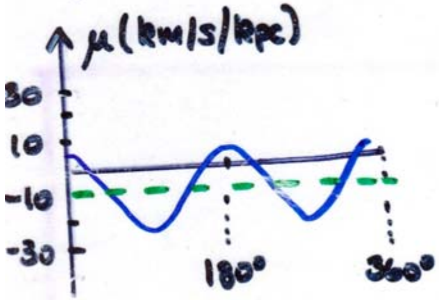
FOR STARS AT SAME DIST r

v_r AS FUNCTION OF l

AMPLITUDE ⇒ A

$= 15 \text{ km s}^{-1} \text{ kpc}^{-1}$

HIPPARCOS → 14.8 ± 0.8



μ INDEPENDENT OF DISTANCE

μ AS FUNCTION OF l

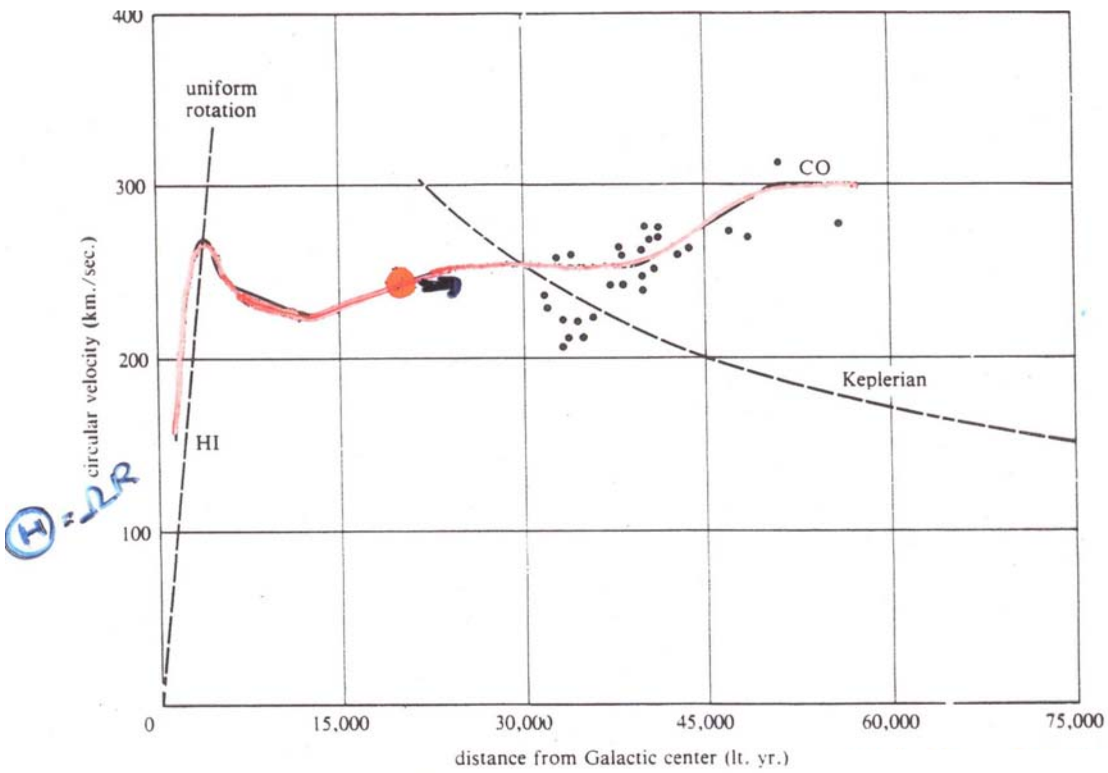
AMPLITUDE ⇒ A

"MEAN" ⇒ B

$= -10 \text{ km s}^{-1} \text{ kpc}^{-1}$

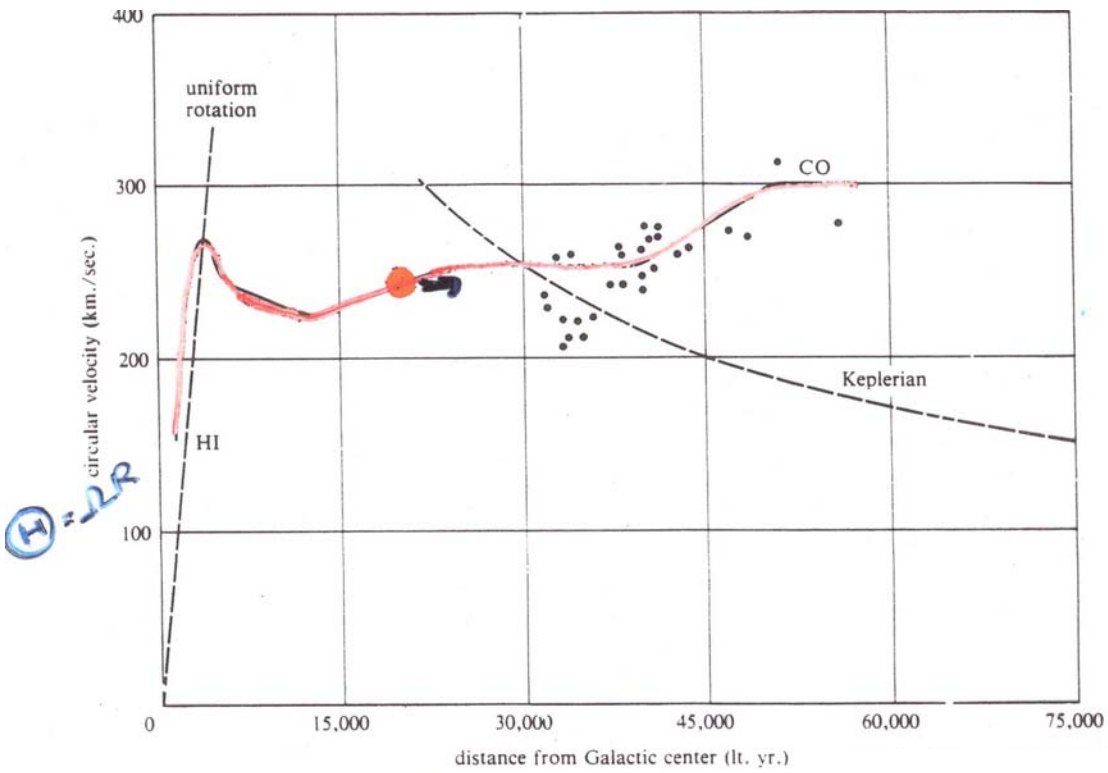
HIPPARCOS → -12.4 ± 0.6

DIFFERENTIAL ROTATION CONFIRMED BY OBSERVATION OF DOUBLE SINE WAVES



CO data here are older
Rotation curve remains approx constant beyond R_0

- Very central part of Galaxy rotates like a rigid body, $\Theta \propto R$
- (Since $\Omega = \Theta/R$ is constant, all stars have same orbital period)
- For centrally concentrated mass, $\Theta \propto R^{-\frac{1}{2}}$ -Keplerian rotation
- No fall-off in Θ observed, suggesting substantial mass beyond R_0
- (note: most luminosity inside R_0)
- Similar rotation curves for other galaxies



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