



Stars: Observations



Distances

Direct distance measurements: parallax measurement:

⇒ Measure stellar position several times over year with respect to background stars.

Parallax angle (small angle approximation):

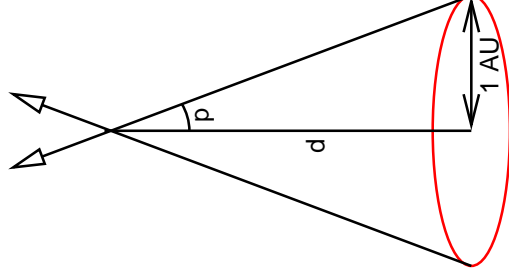
$$p = \frac{1 \text{ AU}}{d}$$

(p is measured in *radians*)

Typical values for p are arcseconds

⇒ define distance unit "Parsec" ("parallax second") such that $d = 1 \text{ pc}$ for $p = 1''$:

The parsec is the distance at which 1 AU subtends an angle of $1''$.



Some people use π instead of p for the parallax...

Observational Properties: Distances



What are stars?

Most important building blocks of the universe: stars

Proper definition:

Stars are gas balls consisting mainly of hydrogen and helium, which produce energy by fusion.

We will now look at observable properties of stars:

1. Distance
2. Brightness and luminosity
3. Spectrum and Temperature

... and later deduce from these data how they live.



Distances

How far is one parsec?

From $p = 1 \text{ AU}/d$ follows with $p = 1''$:

$$d = 1 \text{ pc} = \frac{1 \text{ AU}}{1''} = \frac{1 \text{ AU}}{\pi / (180 \cdot 3600)} = 206264 \text{ AU} = 3.086 \times 10^{16} \text{ m} \sim 3.26 \text{ ly}$$

Note: If parallax p is known and given in arcseconds, then distance can be immediately calculated:

$$\frac{d}{1 \text{ pc}} = \frac{1}{p/1''} \text{ or (sloppy notation) } d = \frac{1}{p}$$

Distances

Best parallax measurements to date: ESA's Hipparcos satellite (with participation from Heidelberg and Tübingen).

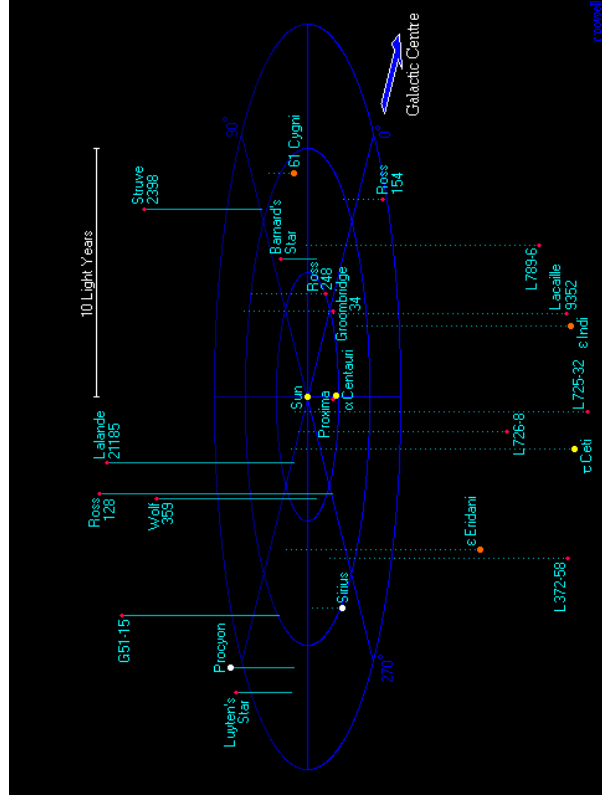
- systematic error of position: ~ 0.1 mas
- effective distance limit: 1 kpc
- standard error of proper motion: ~ 1 mas/yr
- broad band photometry
- narrow band: B - V, V - J (see later what this means)
- magnitude limit: 12 mag
- complete to 7.3-9.0 mag (see later)

Results available at <http://astro.estec.esa.nl/Hipparcos/>:

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

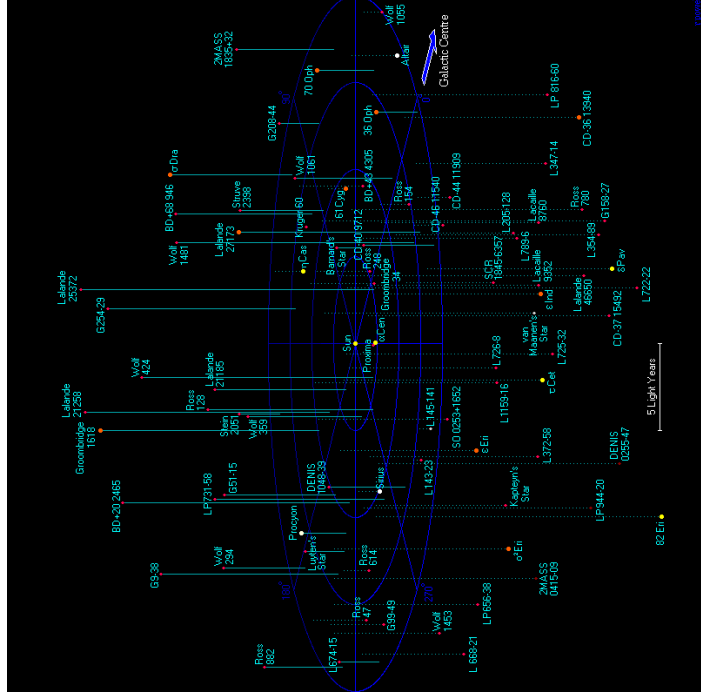
Tycho catalogue: 10^6 stars with 20-30 mas precision, two-band photometry

Observational Properties: Distances



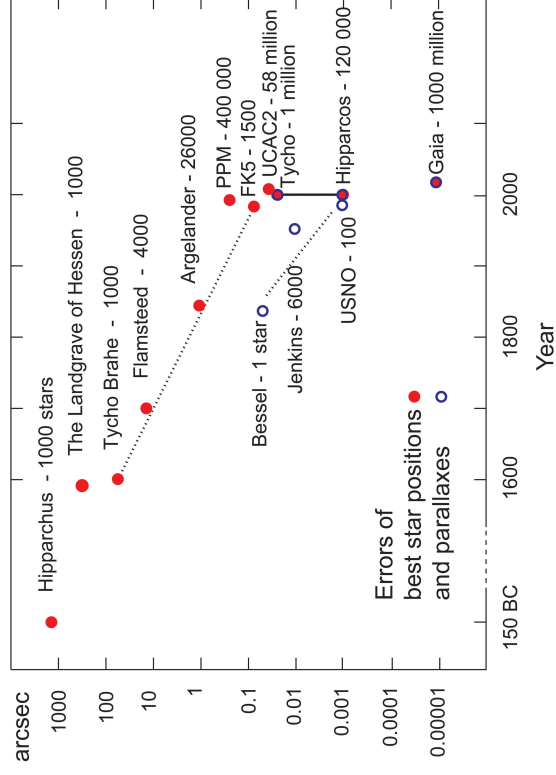
<http://www.anzwers.org/free/universe/12lyls.html>

(12 ly = 3.7 pc)



Known stars within 20 ly =
 6. 1 pc: 83 star systems
 with 109 stars and
 3 brown dwarfs
Note: We are probably
 missing many faint stars
 already in this small
 volume!

<http://www.anzwers.org/>

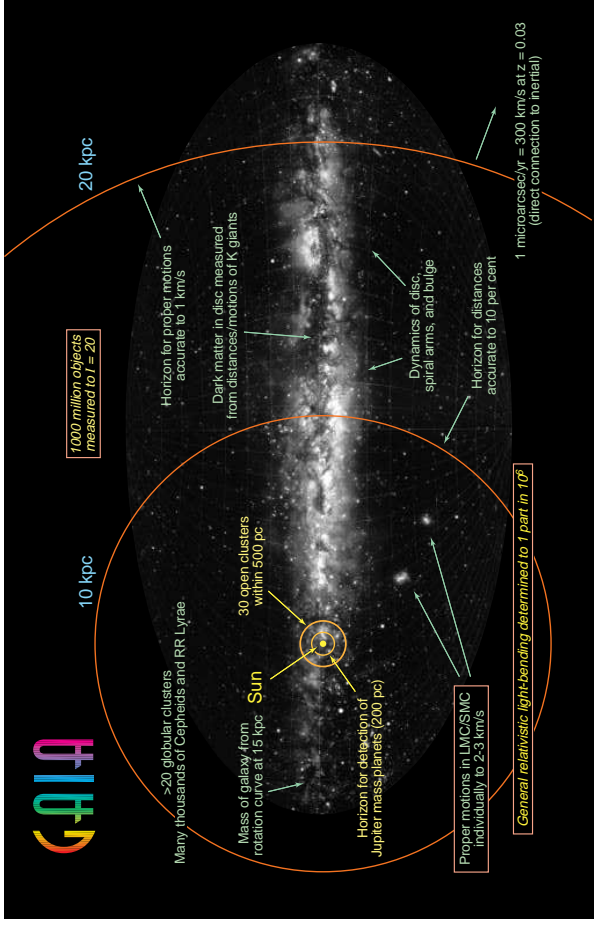


ESA/E. Høg

Today: positional accuracy $\sim 0.01''$ from ground, and better than $1 \text{ mas } (10^{-3}'')$ from space

\implies can measure parallax out to $\sim 1 \text{ kpc}$

further out: "secondary distance estimators" \implies see later/lectures



Luminosity

Definition: Luminosity of a star:

The total energy emitted by a star per second is called its luminosity.

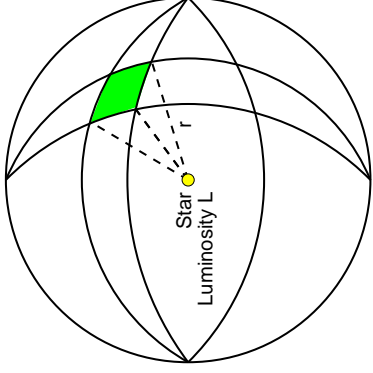
(=luminosity is a power)

In astronomy, luminosities are often measured in units of the solar luminosity,

$L_{\odot} = 3.90 \times 10^{26} \text{ J s}^{-1} = 3.90 \times 10^{26} \text{ W} = 3.9 \times 10^{33} \text{ erg s}^{-1}$



Flux



Assumption: star emits its radiation isotropically.

Flux: energy passing per second through area of 1 m^2 at distance r :

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

(unit: W m^{-2} or $\text{erg cm}^{-2} \text{ s}^{-1}$).

Brightness and Luminosity



Flux

Fluxes from stars (apart from the Sun) are very small.

Example: α Centauri (closest star to the Sun).

- distance: $1.3 \text{ pc} \sim 4 \times 10^{16} \text{ m}$

- luminosity: similar to the Sun ($4 \times 10^{26} \text{ W}$).

Flux arriving on Earth:

$F = \frac{L}{4\pi r^2} = \frac{3.9 \times 10^{26} \text{ W}}{4\pi \cdot 16 \cdot 10^{32} \text{ m}^2} = 2 \times 10^{-8} \text{ W m}^{-2}$

(compare with solar constant, $F = 1380 \text{ W m}^{-2}$)

\implies your eye detects a power of

$P = A_{\text{eye}} F = 5 \times 10^{-12} \text{ W}$

from α Cen (assuming $A_{\text{eye}} \sim 25 \text{ mm}^2$)!

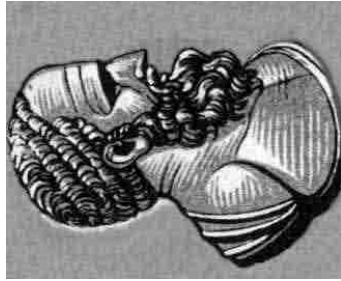
weakest visible stars: $\sim 100\times$ weaker!



Magnitudes

First classification of stars:

- Stars of "magnitude 1": brightest (visible) stars
- Stars of "magnitude 6": faintest (visible) stars
- apparent visual magnitude: m_V = magnitude as observed with the naked eye
- Unit: magnitudo (plural: magnitudines): m
examples: Castor (α Gem): $m_V = 1^m.59$



Hipparchus
(?– ~127 BC)

<http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Hipparchus.html>

Brightness and Luminosity



Magnitudes

Pogson (1865): Eye sensitivity is logarithmic, such that

A brightness difference of 5 magnitudes corresponds to a ratio of 100 in detected flux

So, if magnitudes of two stars are m_1 and m_2 , then

$$\frac{f_1}{f_2} = 100^{(m_2 - m_1)/5}$$

This means:

$$\log_{10}(f_1/f_2) = \frac{m_2 - m_1}{5} \log_{10} 100 = \frac{2}{5}(m_2 - m_1)$$

or

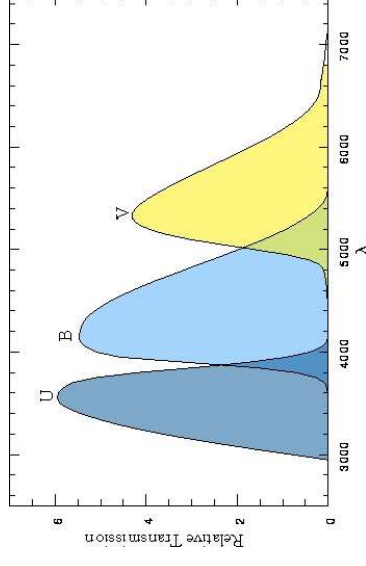
$$m_2 - m_1 = 2.5 \log_{10}(f_1/f_2) = -2.5 \log_{10}(f_2/f_1)$$

Note: Larger Magnitude = FAINTER Stars

Brightness and Luminosity



Magnitudes



photometry: for quantitative measurements with electronic detectors

UBV photometry: 3 filter system (Johnson, 1956):

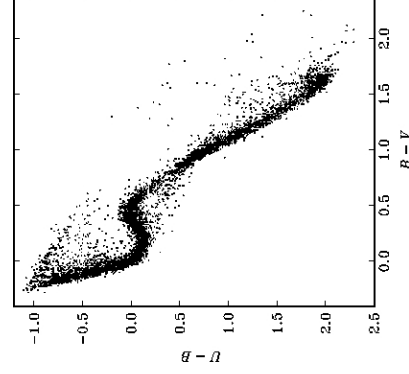
$m_U = U$ = ultraviolet $m_B = B$ = blue $m_V = V$ = visual

has been extended to red and infrared (R, I, J, H, K, ...) as these wavelength ranges became accessible

Brightness and Luminosity



Magnitudes



2-color diagram of the brightest stars ($V < 6^m.6$)

<http://images.astro.net.ru/pubd/2006/03/01/0001211924/img416.gif>

- Colors: compute magnitude difference:
e.g., $B - V$, $U - B$

- Colors are flux ratios in two wavebands

- Color-magnitude diagram (CMD): plot one color versus magnitude, often used (V vs. $B - V$)

- Two color diagram: e.g., $B - V$ vs. $U - B$.

Brightness and Luminosity



Luminosity (revisited)

The inverse square law links flux f at distance d to flux F measured at another distance D :

$$\frac{F}{f} = \frac{L/4\pi D^2}{L/4\pi d^2} = \left(\frac{d}{D}\right)^2$$

Define the absolute visual magnitude M_V as the visual magnitude measured at distance $D = 10$ pc:

$$m_V - M_V = 2.5 \log(F_V/f_V) = 2.5 \log(d/10 \text{ pc})^2 = 5 \log d - 5$$

$m_V - M_V$ is called the distance modulus, d is measured in pc.

absolute bolometric magnitude M_{bol} : magnitude corresponding to flux integrated over all wavelengths: $M_{\text{bol}} = 4.74 - 2.5 \log \frac{L}{L_{\odot}}$
bolometric correction B.C. = $M_{\text{bol}} - M_V$ from model atmospheres

Brightness and Luminosity

8



Introduction

Next fundamental parameter: Temperature

Obtained using spectroscopy

In the following: rough outline, as stellar spectroscopy is rather complicated
Outline:

1. spectral classification
2. Planck's Radiation Laws
3. Atomic line transitions
4. Spectral line formation

Stellar Spectra

1



Stellar spectra

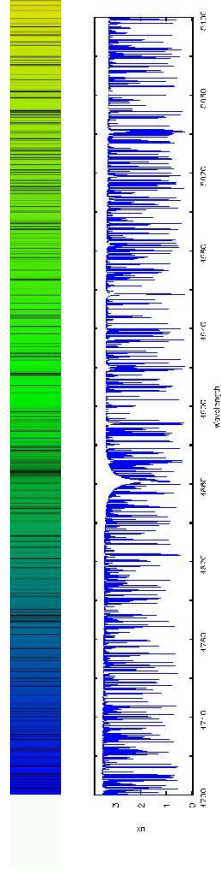
The spectrum of the sun:

Newton (1666): first solar spectrum obtained with a prism: contains all colors (wavelengths).

Fraunhofer (1814): more than 500 dark absorption lines:

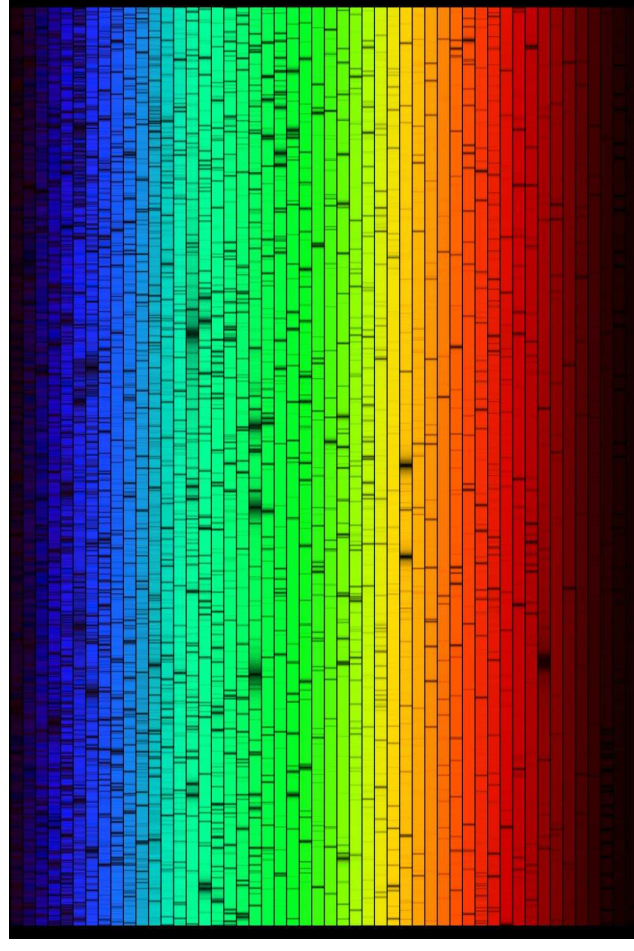
strongest marked A . . . L

Kirchhoff-Bunsen (1860): identify some Fraunhofer lines as atomic transition of neutral and ionised chemical elements ("fingerprints")



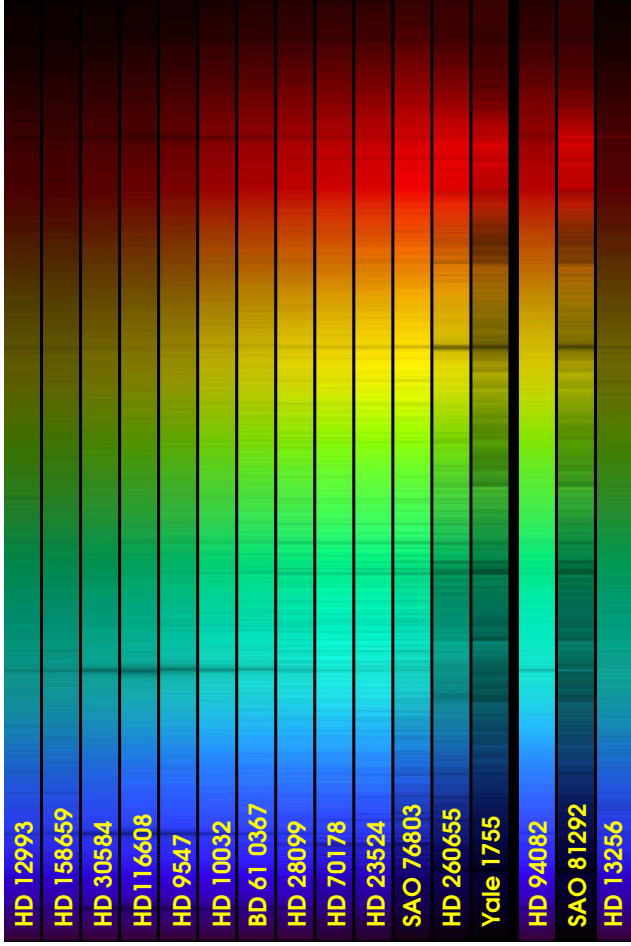
Stellar Spectra

2



N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Absorption line spectrum of the Sun: Fraunhofer Lines



Edward Pickering (around 1890): Stars have different spectra.

NOAO



11–22

Stellar spectra

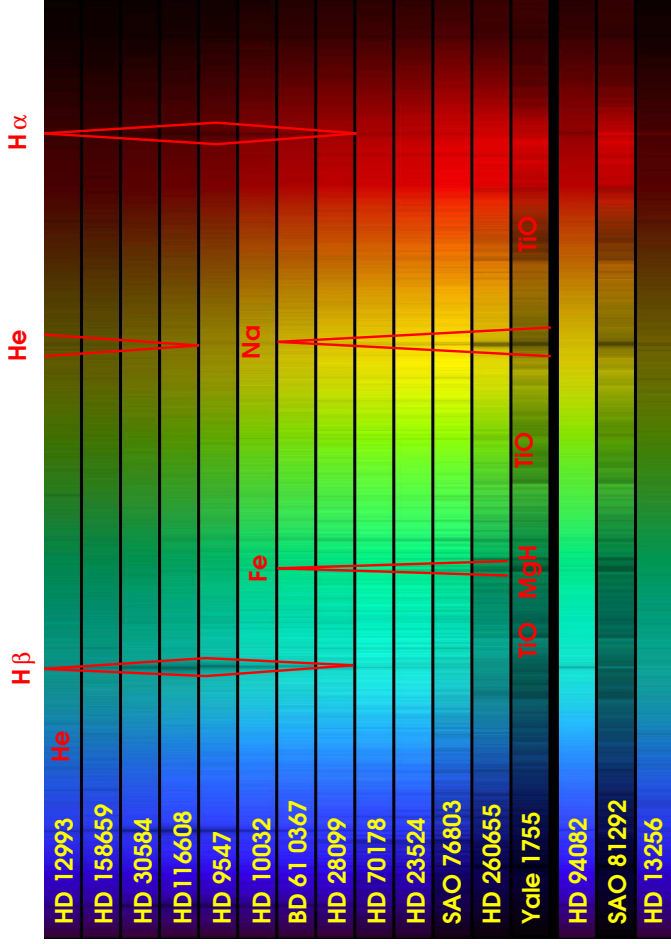


Annie Jump Cannon (1863–1941)

Biography:
<http://www.sdsc.edu/ScienceWomen/cannon.html>

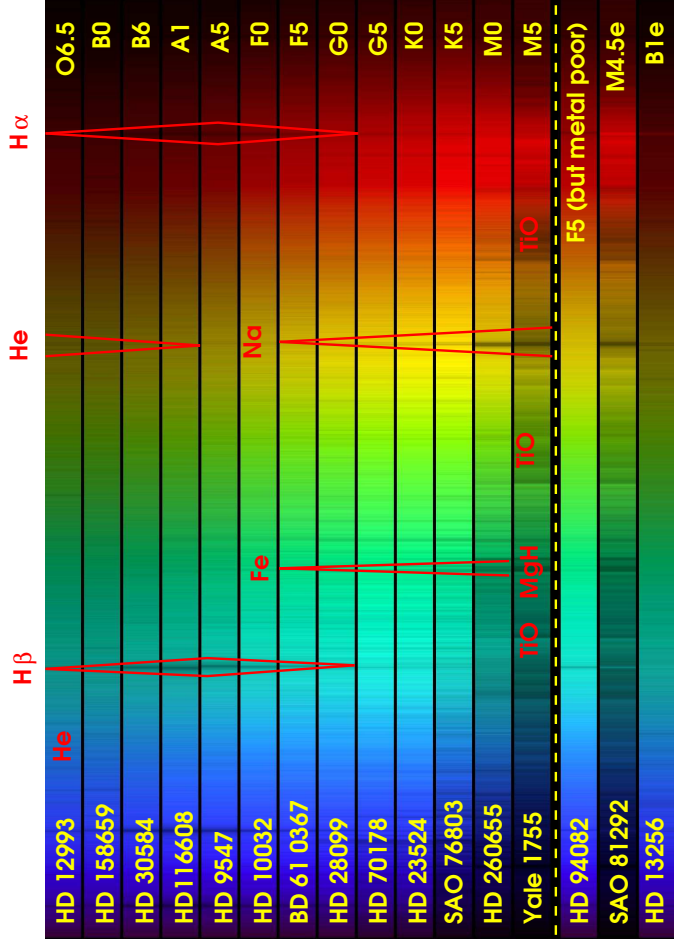
Annie Jump Cannon: There are spectral types.

Henry Draper catalogues (Cannon plus ~10 female “computers”): 225000 spectral classifications.



Annie Cannon: Strength of absorption lines varies with spectral type.

NOAO



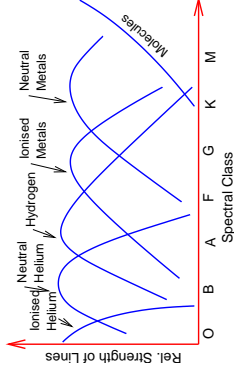
Annie Cannon: Strength of absorption lines varies with spectral type.

NOAO



11-25

Stellar spectra



O - B - A - F - G - K - M
 “early type” “late type”

plus subtypes: B0...B9, A0...A9, etc.

Sun is G2.

Note: “early” and “late” has *nothing* to do with age!

Mnemonics:

(<http://lheawww.gsfc.nasa.gov/users/allen/obafgkmrns.html>)

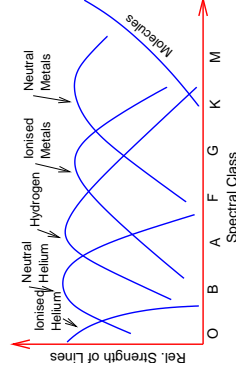
O Be A Fine Girl Kiss Me

Stellar Spectra



11-25

Stellar spectra



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O Be A Fine Girl Kiss Me

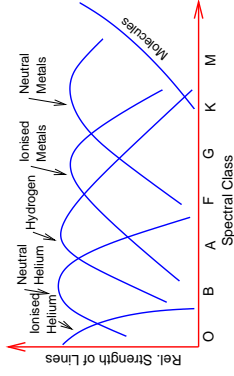
Stellar Spectra

9



11-25

Stellar spectra



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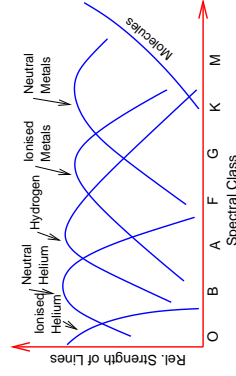
O Be A Fine Girl Kiss Me

Stellar Spectra



11-25

Stellar spectra



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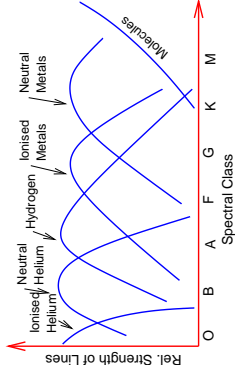
O Be A Fine Girl Kiss Me
 Only Boys Accepting Feminism Get Kissed Meaningfully

Stellar Spectra

11



Stellar spectra



O - B - A - F - G - K - M
 "early type" "late type"

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Mnemonics:

(<http://theawww.gsfc.nasa.gov/users/allen/obafgkmrns.html>)

O Be A Fine Girl Kiss Me Guy

Only Boys Accepting Feminism Get Kissed Meaningfully

Only Bold Astronomers Forge Great Knowledgeable Minds

Stellar Spectra

12



Stellar spectra

Tabelle 3.2: Die Spektralklassen

Klasse	charakteristische Spektren	Farbe	Farbenindex	Effektivtemperatur (K)	Beispiele
O	He I; He I	blau	-0,3	28000-50000	μPer, εOri
B	He I; H	blau-weiß	-0,2	9900-28000	Rigel, Spica
A	H	weiß	0,0	7400-9900	Wega, Sirius
F	Metalle; H	gelb-weiß	0,3	6000-7400	Procyon
G	Ca II; Metalle	gelb	0,7	4900-6000	Sonne, αCen A
K	Ca II; Ca I; andere Moleküle	orange	1,2	3500-4900	Arktur
M	TiO; andere Moleküle; Ca I	orange-rot	1,4	2000-3500	Beteigeuze
R ¹	CN; C ₂	orange-rot	1,7	3500-5400	...
S ²	ZrO; andere Moleküle	orange-rot	1,7	2000-3500	R Cyg
N ¹	C ₂	rot	>2	1900-3500	R Lep

¹ Kohlenstoffsterne

² Sterne mit etwas geringerer Kohlenstoffhäufigkeit als bei R- und N-Sternen; dafür treten Zirkoniumoxid-Molekülbänder auf.

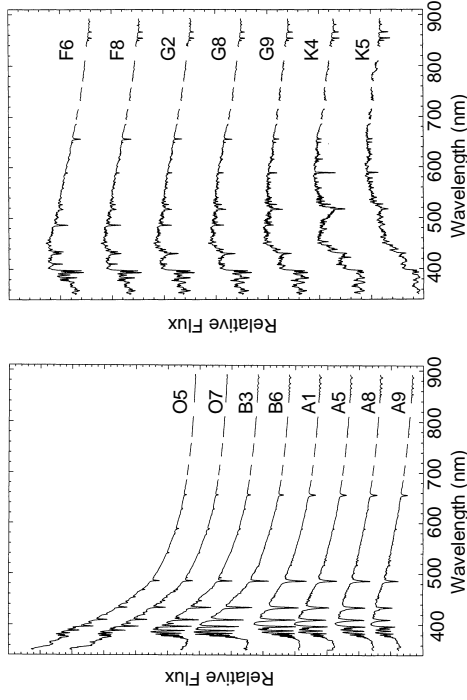
Kaler: Sterne (Spektrum Akademischer Verlag)

Stellar Spectra

13



Stellar spectra



Silva & Corneli, 1992, ApJ Suppl. 81, 865

Spectral Atlas for classification purposes.

Stellar Spectra

14



Planck's Radiation Law

Stars are big glowing gas balls.

In zeroth order: thermodynamic equilibrium.

Max Planck: under these circumstances: emitted flux spectrum is blackbody radiation:

$$B_{\lambda} = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda kT) - 1} \quad (11.1)$$

B_{λ} : Energy emitted per second and wavelength interval and unit area into 1 sr.

- $h = 6.623 \times 10^{-34}$ J s: Planck's constant
- $k = 1.38 \times 10^{-23}$ J K⁻¹: Boltzmann constant



Max Planck (1858-1947)

Stellar Spectra

15



Planck's Radiation Law

Without proof, the following two important relationships hold for blackbody radiation:

Stefan-Boltzmann law: Flux (power emitted per square-meter surface) of a blackbody:

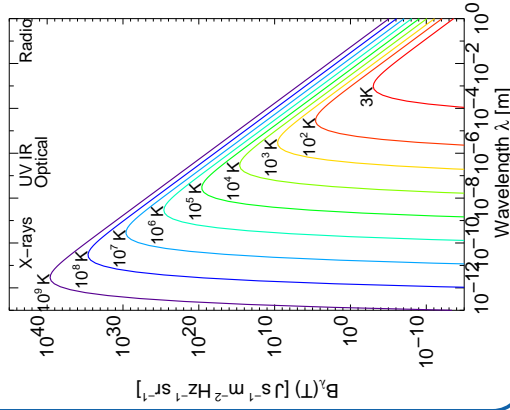
$$F = B = \int_0^{\infty} B_{\lambda}(\lambda) d\lambda = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
"hotter bodies have a much higher luminosity"

Wien's displacement law: Wavelength of maximum blackbody emission:

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m K}$$

"hotter bodies radiate higher energetic radiation"

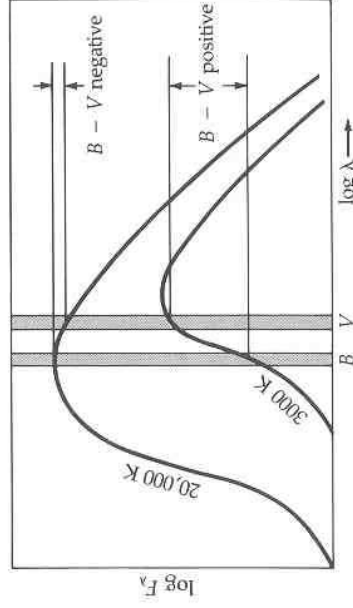


Stellar Spectra

16



Planck's Radiation Law



(Zeilik & Gregory)

Colors are temperature indicators: U - B, B - V, ...

Stellar Spectra

17



Spectroscopy

BSc, Cambridge, left UK because of situation of women in astronomy

1st person to obtain PhD in Astronomy at Harvard: "Stellar Atmospheres, A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars"

Otto Struve: "undoubtedly the most brilliant Ph.D. thesis ever written in astronomy."

Spectral types are a temperature sequence.

Cecilia Payne-Gaposchkin (1900-1979) later: 1st female full professor at Harvard

Biography: <http://www.harvardsquarelibrary.org/unitarians/payne2.html>



Stellar Spectra

18



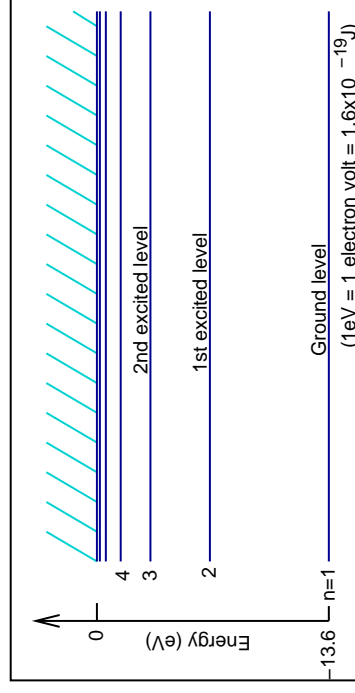
Spectroscopy

Quantum mechanics: atoms have discrete energy levels

Energy levels in Hydrogen:

$$E_n = -\frac{2\pi^2 \mu e^4}{\hbar^2} \cdot \frac{1}{n^2} \propto -\frac{1}{n^2}$$

($n \in \mathbb{N}$; Balmer formula)



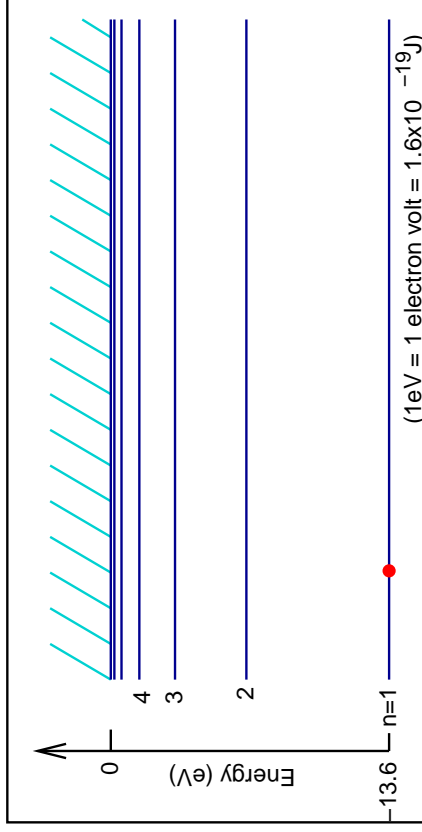
Stellar Spectra

19



11-33

Spectroscopy



In hydrogen atom: electrons typically found in ground state.

if temperature is higher, can also be in 1st excited state, but the physical principles following remain the same....

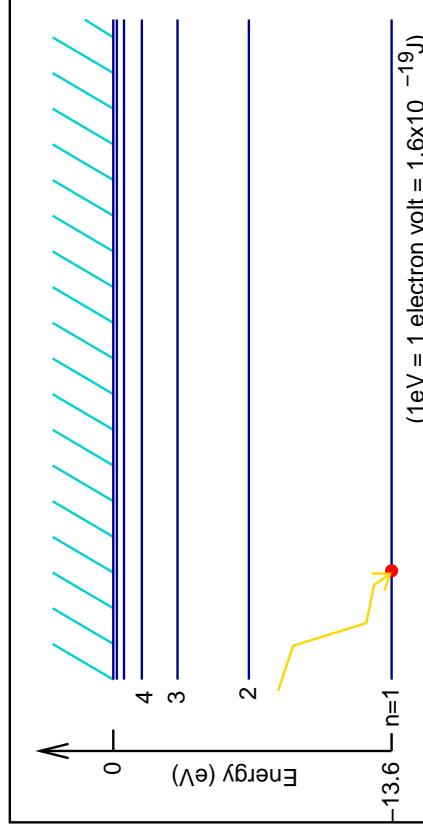
Stellar Spectra

20



11-34

Spectroscopy



Photon hitting atom has energy $E_{\text{photon}} = h\nu = hc/\lambda$. If $E_{\text{photon}} = E_2 - E_1$, then photon can be absorbed...

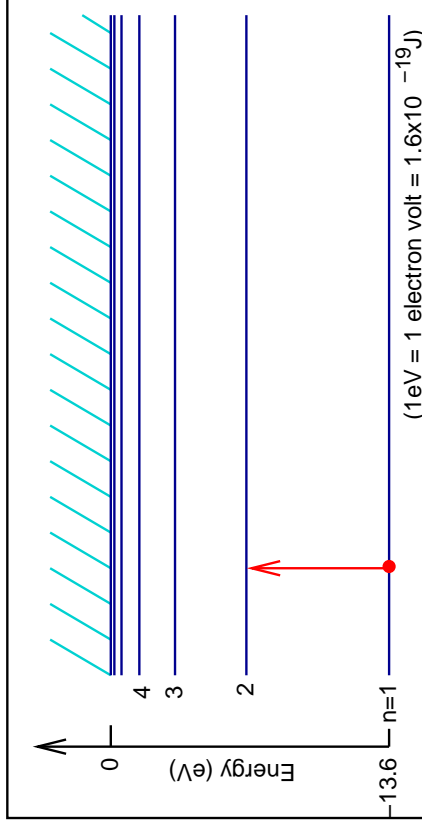
Stellar Spectra

21



11-34

Spectroscopy



Photon hitting atom has energy $E_{\text{photon}} = h\nu = hc/\lambda$. If $E_{\text{photon}} = E_2 - E_1$, then photon can be absorbed... and electron has higher energy (is excited).

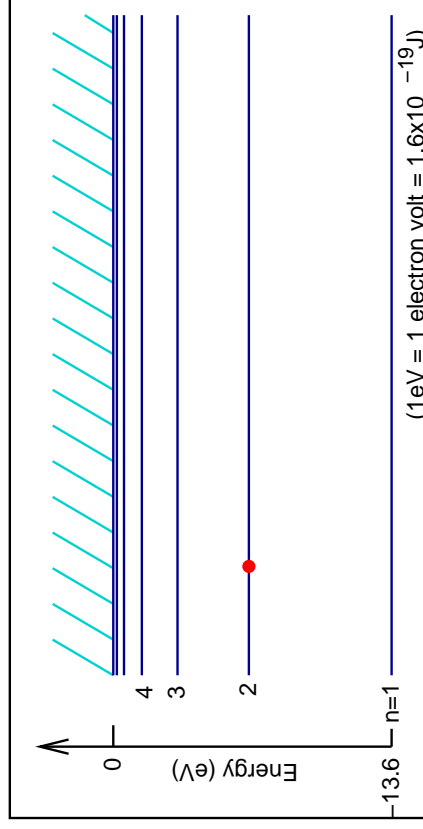
Stellar Spectra

22



11-35

Spectroscopy



After absorption event, absorbing photon has disappeared and hydrogen atom remains in excited state.

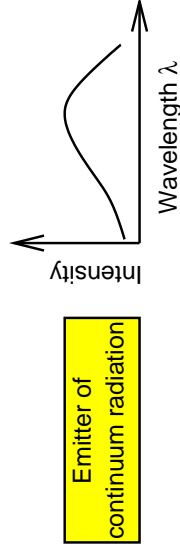
Stellar Spectra

23



Spectroscopy

1. Assume stellar surface has continuum spectrum (Planck).



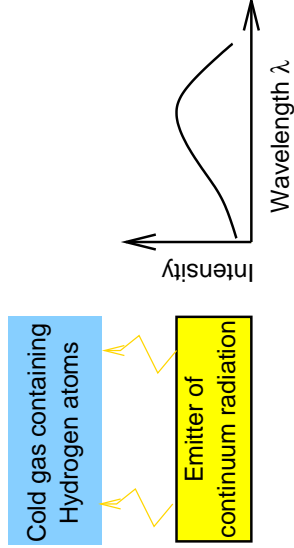
Stellar Spectra

24



Spectroscopy

1. Assume stellar surface has continuum spectrum (Planck).
2. Assume surface is below atmosphere of colder gas.



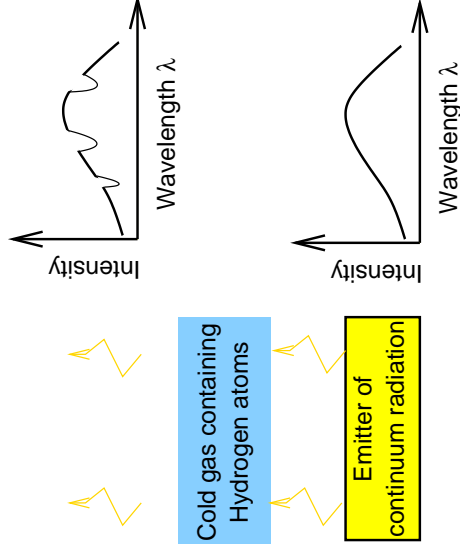
Stellar Spectra

25



Spectroscopy

1. Assume stellar surface has continuum spectrum (Planck).
2. Assume surface is below atmosphere of colder gas.
 - ⇒ Atmosphere absorbs photons at wavelengths characteristic for the elements present in stellar atmosphere.
 - ⇒ Formation of absorption line spectrum.

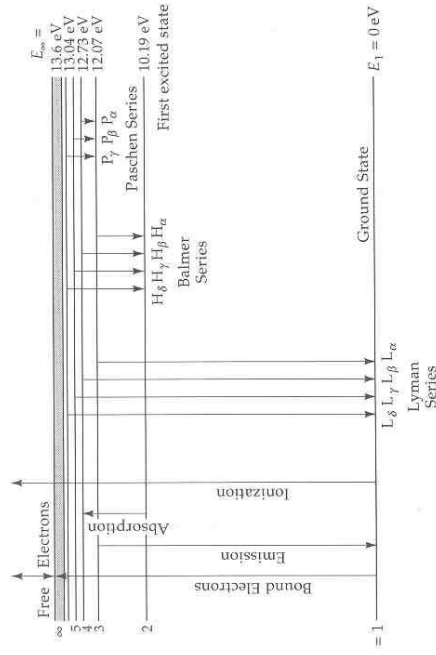


Stellar Spectra

26



Spectroscopy



Hydrogen lines in the visual (Balmer lines) arise from absorbing photons by atoms in the first excited state.

Stellar Spectra

27



Spectroscopy

Excitation: relative population of 2 energy levels in thermodynamical equilibrium (Boltzmann):

$$\frac{n_i}{n_j} = \frac{g_i}{g_j} e^{-\frac{E_i - E_j}{kT}}$$

g_i, g_j = statistical weights (Quantum mechanics).

Population of excited levels relative to ground state increase with increasing T .

Ionization: Electron removed from atom. In classical Physics the statistical weight of the free electron would be infinite.

Quantum mechanics gives Saha's equation:

$$\frac{n_{\text{up}}}{n_{\text{low}}} = \frac{1}{n_e} 2 \left(\frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} \frac{g_{\text{up}}}{g_{\text{low}}} e^{-\frac{E_{\text{up}} - E_{\text{low}}}{kT}}$$

statistical weight of electron from Heisenberg's principle of uncertainty and the Pauli prescription.

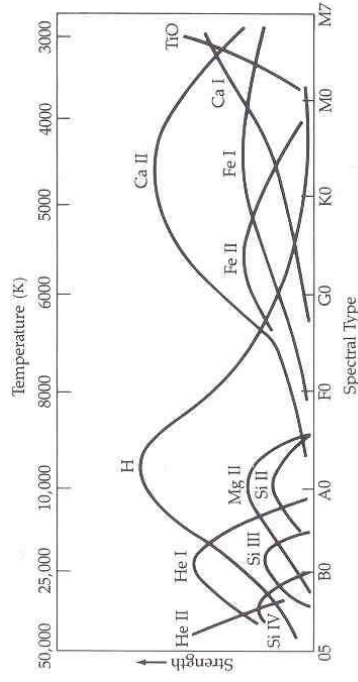
Degree of ionization increases with increasing T and decreasing n_e

Stellar Spectra

28



Spectroscopy



(Zeilik & Gregory)

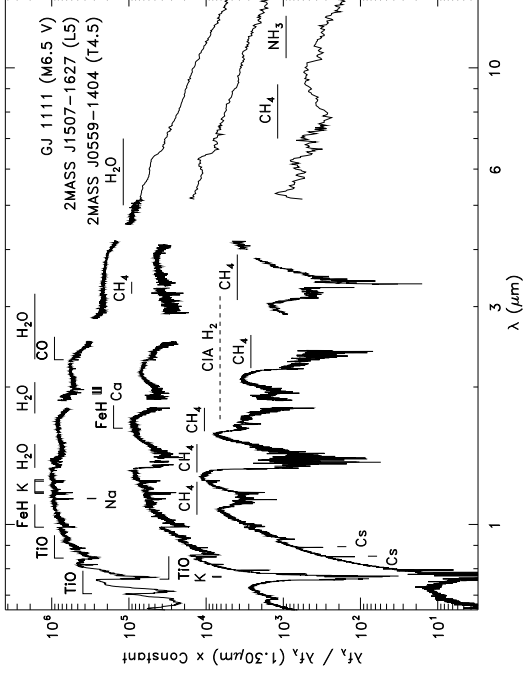
Hydrogen Balmer line strength increases from spectral type M to A due to excitation and decreases from A to O due to ionization.

Stellar Spectra

29



L- and T-Stars



1995 ff.: discovery of brown dwarfs (low mass, low temperature objects, see later).

Cushing et al., 2006

Stellar Spectra

30



L- and T-Stars

Brown Dwarfs \implies extension of spectral types to lower temperature objects

L dwarfs: objects with temperatures of 1200–2500 K, low mass, some do not support fusion. Spectra peak in IR, optical spectra contain prominent lines from metal hydrides and alkali metals.

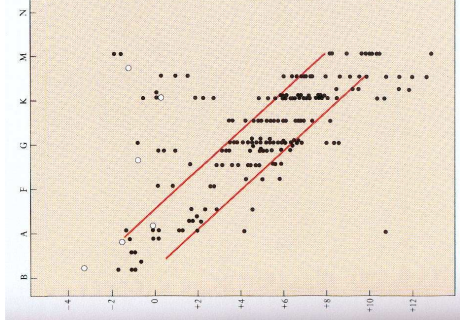
Designation: L is character closest to M that was still available.

T dwarfs: brown dwarfs with temperatures of \sim 1000 K, strong lines from molecules such as methane in the spectrum.

See Kirkpatrick (2005, Ann. Rev. Astron. Astrophys., 43, 195) for an overview and the formal definition of these spectral types.

Stellar Spectra

31

**Hertzsprung Russell Diagram**

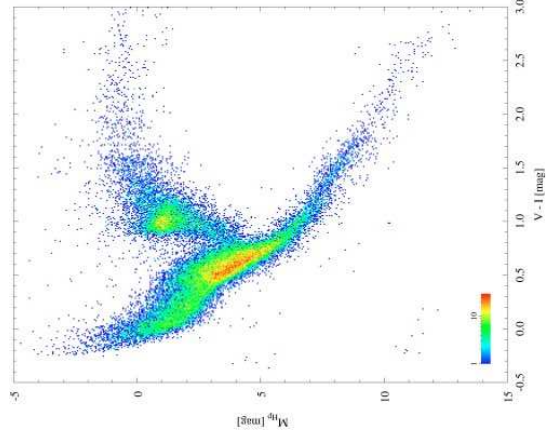
Hertzsprung Russell Diagram (HRD)
Einar Hertzsprung & Henry Norris Russell (1913):
plot absolute visual magnitude versus spectral type

Most important phase diagram in stellar astrophysics

Kaler: Sterne (Spektrum Akademischer Verlag)

Hertzsprung Russell Diagram

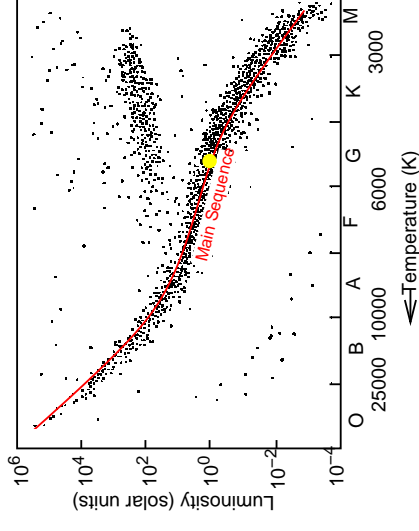
1

**Hertzsprung Russell Diagram**

The photometric HRD:
plot absolute visual magnitude versus B-V color
HRD from Hipparcos mission

Hertzsprung Russell Diagram

2

**Hertzsprung Russell Diagram**

Hertzsprung-Russell Diagram (HRD):
Spectral type versus stellar luminosity

- Most stars on Main Sequence ("dwarfs")

Hertzsprung Russell Diagram

3

**Yerkes classification**

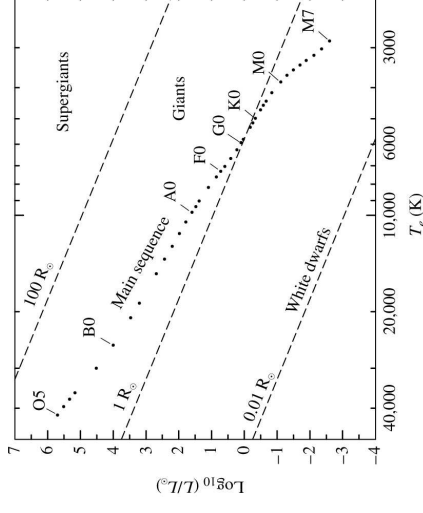
Stellar Luminosity:

$$L = 4\pi R^2 \sigma T_{\text{eff}}^4 \propto R^2 T_{\text{eff}}^4 \quad (11.2)$$

Lines of constant radius:

$$\log \frac{L}{L_{\odot}} = 2 \log \frac{R}{R_{\odot}} + 4 \log \frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \quad (11.3)$$

- ⇒ hot (early type) main sequence stars are larger than the sun
- ⇒ cool (late type) main sequence stars are smaller than the sun



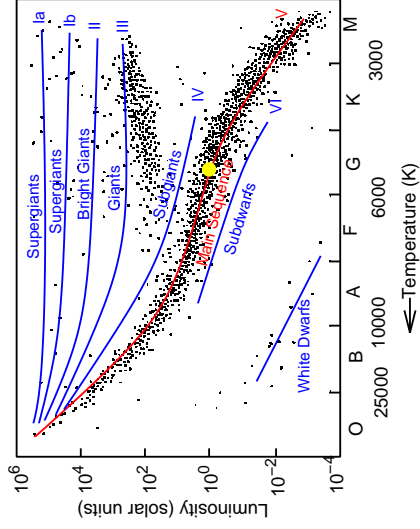
Carroll & Ostlie

Hertzsprung Russell Diagram

4



Yerkes classification



Size of stars influences spectral lines (see next slide): "Morgan-Keenan classes" or "luminosity classes":

- Ia = hypergiant,
- Ib = supergiant,
- II = bright giant,
- III = giant,
- IV = subgiant,
- V = dwarf,
- VI = subdwarf

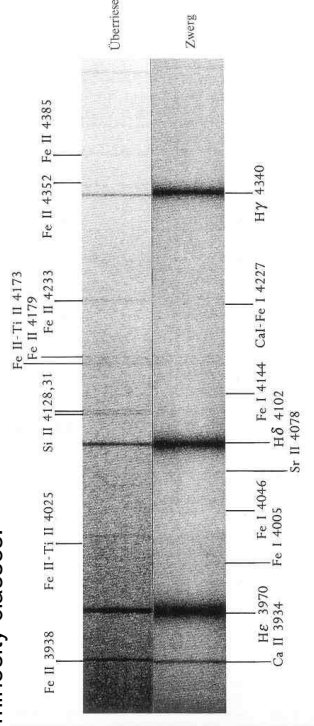
Notation: Append "Morgan-Keenan classes" to spectral class: Sun: G2 V, Betelgeuse: M2 Ib

Hertzsprung Russell Diagram



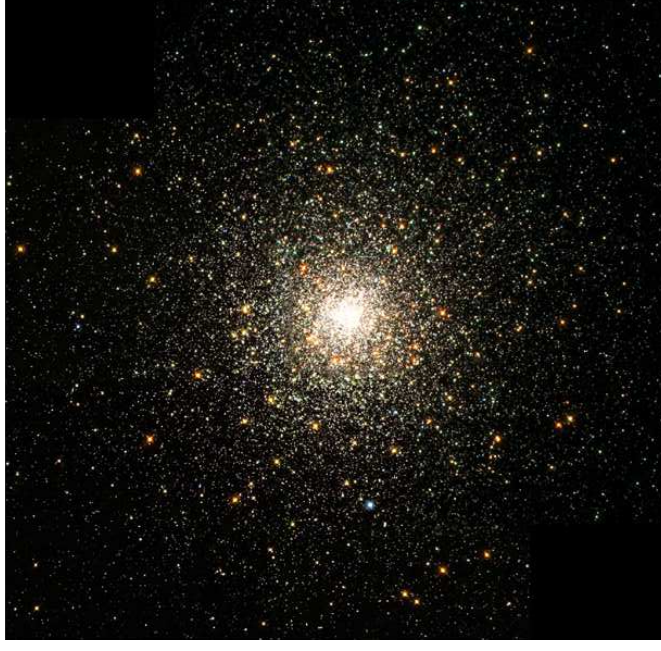
Yerkes classification

Spectral classification can be refined to include line widths and shapes in so called luminosity classes:



luminosity effect for spectral type A: the Balmer lines are much narrower in the supergiant than in the dwarf star

Hertzsprung Russell Diagram



Globular Cluster NGC 6903



M3, S. Kafka and K. Honeycutt, Indiana University/WIYN/NOAO/NSF
note many red giants!

Terms to know

- Spectroscopy: two dimensional classification scheme
 - 1. Harvard: spectral types: O, B, A, F, G, K, M
 - 2. Yerkes (Morgan-Keenan): luminosity classes Ia, Ib, II, III, IV, V, VI
- Spectral sequence is caused by excitation (Boltzmann equation) and ionization (Saha equation) of atoms \implies temperature sequence
- luminosity classes are density indicators (without proof)
- Hertzsprung-Russell-Diagram: Three versions:
 - classical: M_V vs. spectral type
 - photometric: Color-magnitude diagram (CMD): V vs. (B-V), M_V vs. color index (usually B-V)
 - physical: Luminosity vs. effective temperature: L vs. T_{eff}
 - * most stars are on the main sequence
 - * various types of giants above the main sequence
 - * white dwarfs below the main sequence

Globular Clusters: HRD is very different of solar neighbourhood

MS: Main Sequence

TO: Turn-Over point

HB: Horizontal Branch

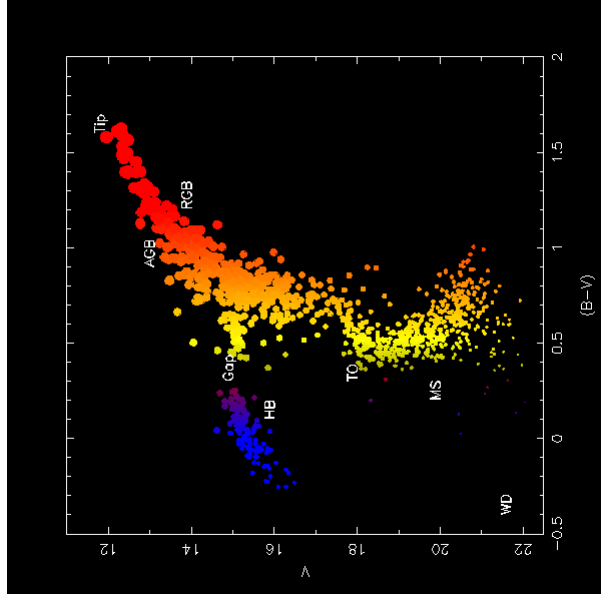
RGB: Red Giant Branch

AGB: Asymptotic Giant Branch

WD: White Dwarfs

All stars in globular cluster born at the same time \implies HRD shows evidence for stellar evolution

\implies HRD shows evidence for stellar evolution



HRD of Globular Cluster M5 (UNSW, Sydney)
(B-V: \sim spectral class; V: is a magnitude)

Terms to know

- Astrometry:
 - parallax measurements yield distances: $p = \frac{1\text{AU}}{d}$ (unit: pc)
- Photometry:
 - Flux, luminosity and the inverse square law: $F = \frac{L}{4\pi r^2}$
 - The magnitude scale:
 - * apparent visual magnitude $m_V = \frac{f_{V,1}}{f_{V,2}} = 100^{(m_{V,2} - m_{V,1})/5}$
 - * absolute visual magnitude $M_V = \text{magnitude at } D = 10\text{ pc}$
 - * distance modulus: $m_V - M_V = 2.5 \log(F_V/f_v) = 2.5 \log(d/10\text{ pc})^2 = 5 \log d - 5$
 - * bolometric absolute magnitude $M_{\text{bol}} = -2.5 \log \frac{L}{L_{\odot}} + 4.74$
 - * bolometric correction: B.C. = $M_{\text{bol}} - M_V$
 - * color indices, e.g., UBV: B - V = $m_B - m_V$, U - B = $m_U - m_B$
- Planck's law:
 - Effective temperature: $T_{\text{eff}}^4 = F/\sigma = L/(4\pi R^2\sigma)$
 - color indices are temperature indicators