Stars: Observations

What are stars?

Most important building blocks of the universe: stars

Proper definition:

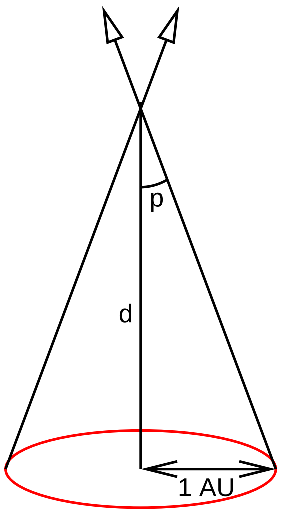
Stars are gas balls consisting mainly of hydrogen and helium, which produce energy by fusion.

We will now look at observable properties of stars:

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

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

Distances



Direct distance measurements: parallax measurement:

$\Longrightarrow$ Measure stellar position several times over year with respect to background stars.

Parallax angle (small angle approximation):

$$p = \frac{1\,\mathrm{AU}}{d}$$

(p is measured in *radians*)

Typical values for p are arcseconds

$\Longrightarrow$ define distance unit “Parsec” (“parallax second”) such that $d = 1\,\mathrm{pc}$ 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. . .

Distances

How far is one parsec?

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

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

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

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

Distances

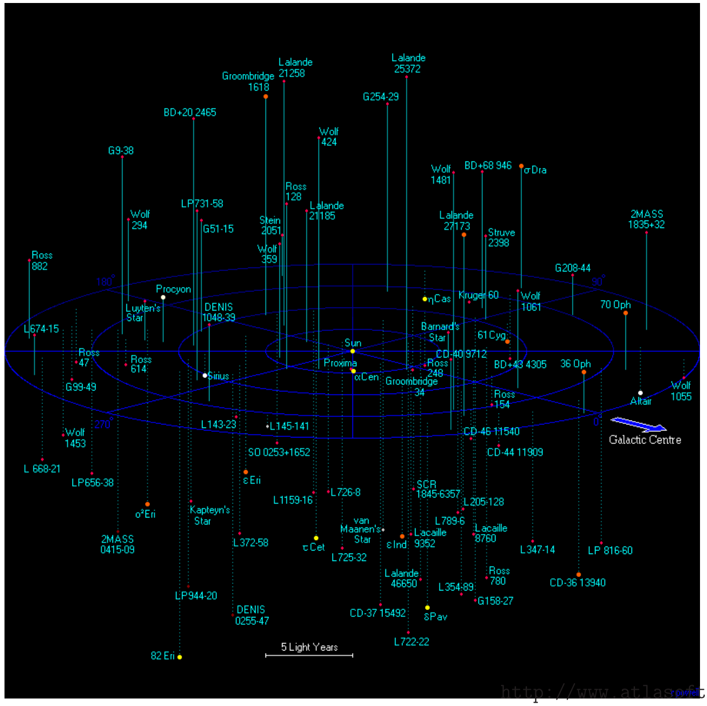
Best parallax measurements to date: ESA's Hipparcos satellite (with participation from Heidelberg and Tübingen).

- 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://www.rssd.esa.int/Hipparcos/`

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

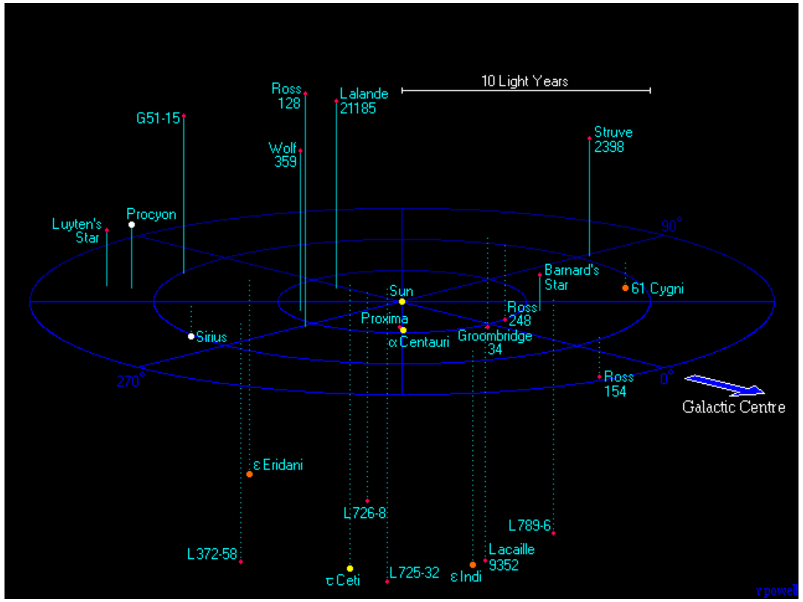
Tycho catalogue: 10^6 stars with 20–30 mas precision, two-band photometry



http://www.atlasoftheuniverse.com/20lys.html

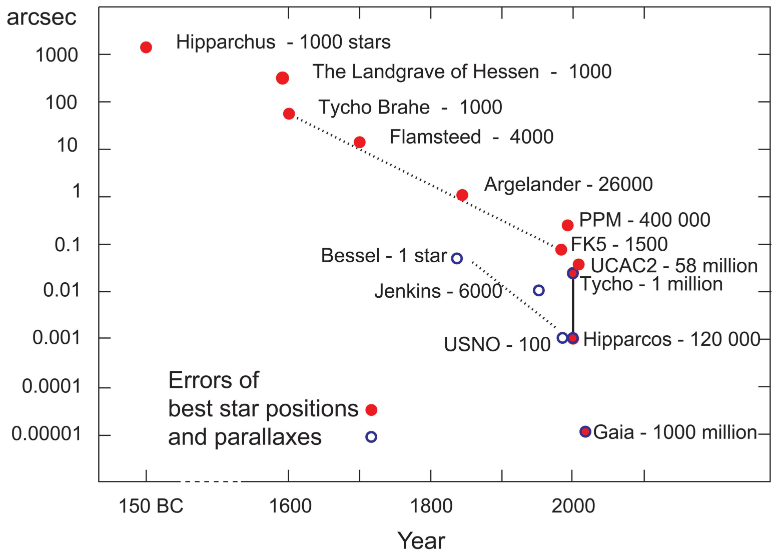
Known stars within 20 ly = 6.1 pc: 83 star systems with 109 stars and 8 brown dwarfs

Note: We are probably missing many faint stars already in this small volume!



`http://www.atlasoftheuniverse.com/12lys.html`

(12 ly = 3.7 pc)



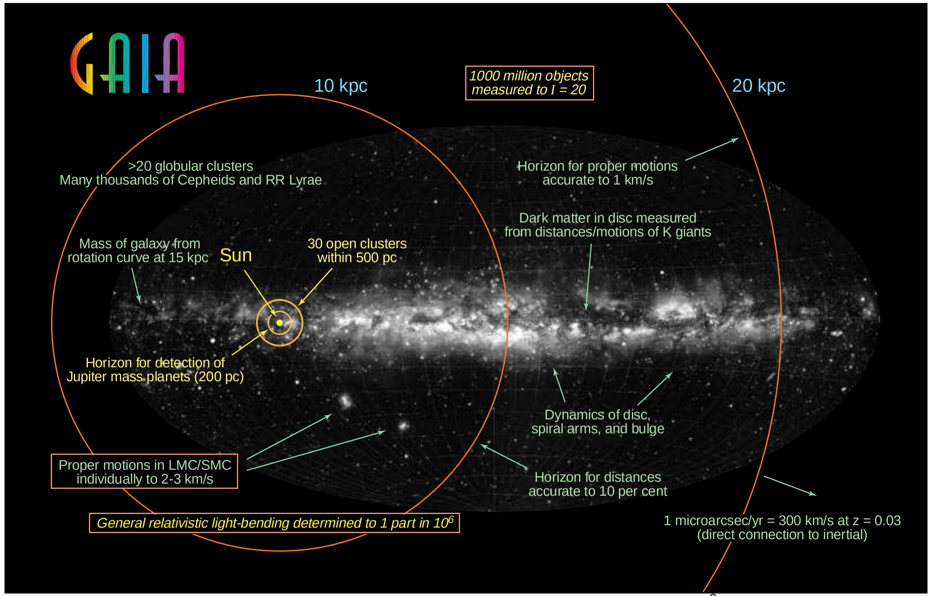
ESA/E. Høg

Today: positional accuracy ∼0.01″ from ground, and better than 1 mas (10^{-3}″) from space

⟹ can measure parallax out to ∼1 kpc

further out: "secondary distance estimators" ⟹ see later lectures

Plans for the future: GAIA (ESA mission, ∼End 2012):



GAIA: $\sim 20\mu$arcsec precision, 4 color to $V = 20$ mag, 10^9 objects.

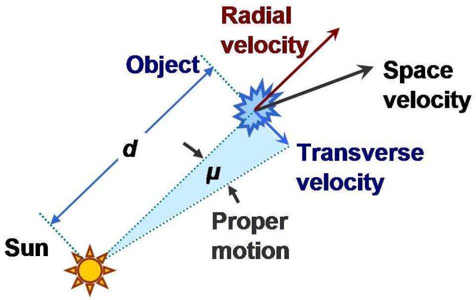
Proper Motions

Credit: Mortfield & Cancelli

Largest value for Barnard's star: μ=10.3 arcsec/yr

Proper Motions

Stars are not fixed to the sky



Wikipedia

three dimensional space motion:

Radial velocity: velocity along the line of sight (needs spectrum)

Tangential velocity: velocity perpendicular to the line of sight

Proper motion μ: Change of star's position with time.

(μ is measured in *arcsec/year*

Typical values for μ are mas/yr

Distance d needs to be known

Tangential velocity = $\mu \times d$

Luminosity

Definition: Luminosity of a star:

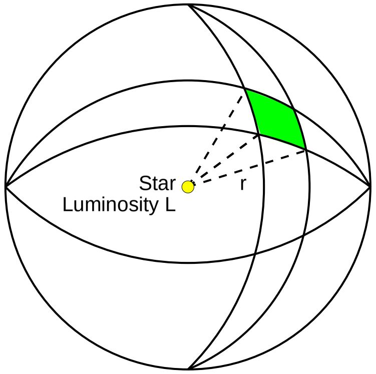
The total energy emitted by a star per second is called its luminosity.

(=luminosity is a power)

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

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

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 erg cm^{-2} s^{-1}).

Flux

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

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

- distance: 1.3 pc $\sim$ 4 $\times$ 10^{16} m
- luminosity: similar to the Sun (4 $\times$ 10^{26} W).

Flux arriving on Earth:

$$F = \frac{L}{4\pi r^2} = \frac{3.9\times10^{26}\,\mathrm{W}}{4\pi\cdot16\cdot10^{32}\,\mathrm{m}^2} = 2\times10^{-8}\,\mathrm{W\,m^{-2}}$$

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

$\Longrightarrow$ your eye detects a power of

$$P = A_{\mathrm{eye}}F = 5\times10^{-12}\,\mathrm{W}$$

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

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

Magnitudes

Hipparchus
($\sim$190 – $\sim$120 BC)

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

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): $^{\mathrm{m}}$
  examples: Castor (α Gem): $m_{\mathrm{V}} = 1^{\mathrm{m}}.59$

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

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 $D = 10\,\mathrm{pc}$:

$$m_\mathrm{V} - M_\mathrm{V} = 2.5\log(F_\mathrm{V}/f_\mathrm{V}) = 2.5\log(d/10\,\mathrm{pc})^2 = 5\log d - 5$$

$m_\mathrm{V} - M_\mathrm{V}$ is called the distance modulus, d is measured in pc.

absolute bolometric magnitude M_bol: magnitude corresponding to flux integrated over all wavelengths: $M_\mathrm{bol} = 4.74 - 2.5\log\frac{L}{L_\odot}$

bolometric correction B.C. $= M_\mathrm{bol} - M_\mathrm{V}$ from model atmospheres

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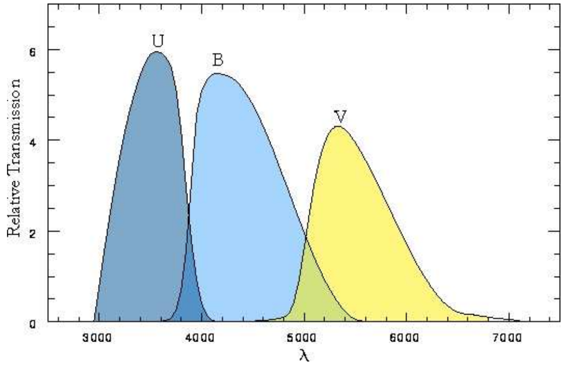
Colours



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

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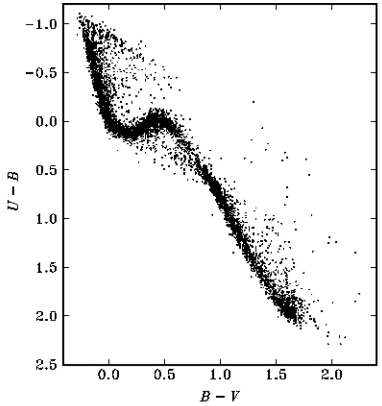
Colours



2-color diagram of the brighest stars
($V < 6^\mathrm{m}.6$)
`http://images.astronet.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.

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

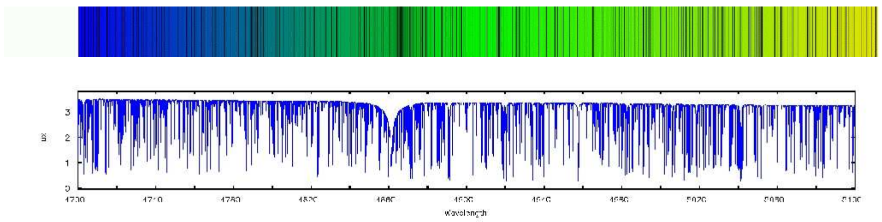
Stellar spectra

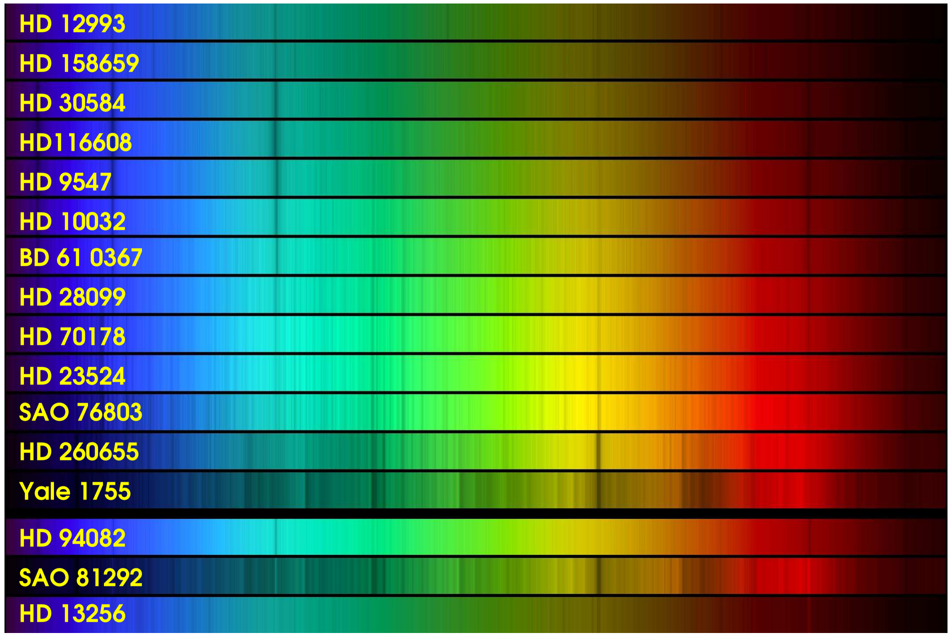
The spectrum of the Sun:

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”)





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

NOAO

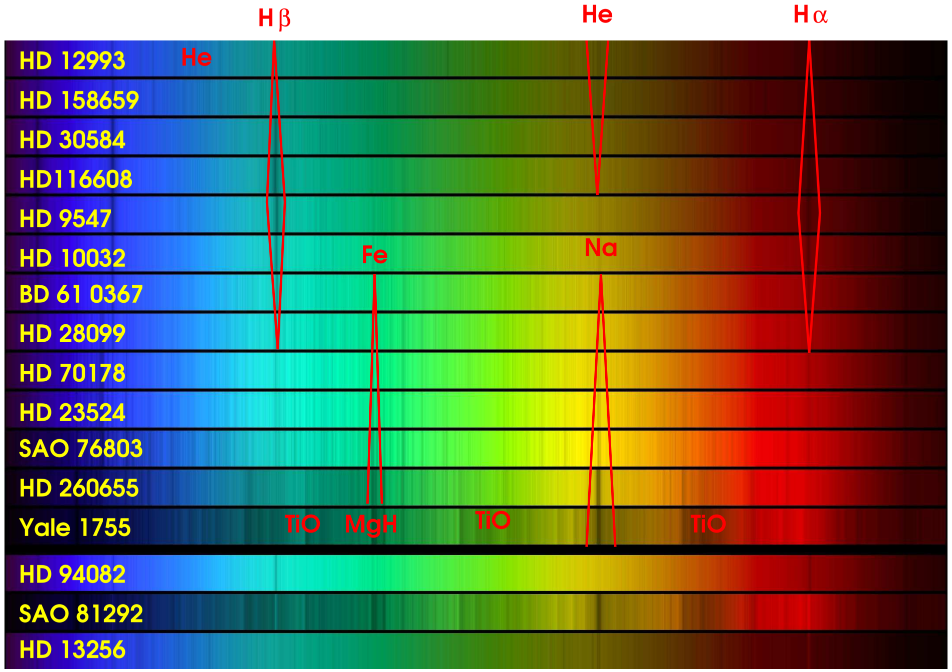
Stellar spectra

Annie Jump Cannon (1863–1941)

Biography:
`http://www.sdsc.edu/ScienceWomen/cannon.html`

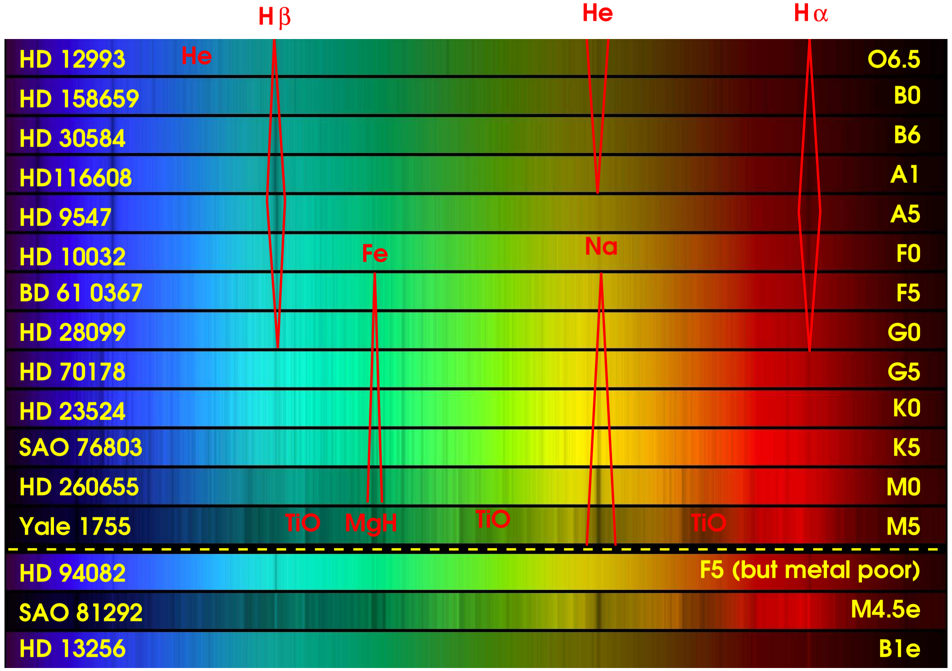
Annie Jump Cannon: There are spectral types.

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



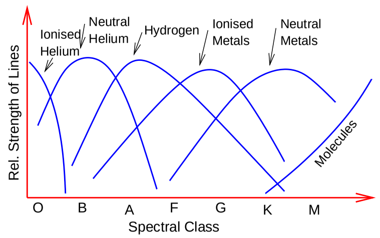
Annie Cannon: Strength of absorption lines varies with spectral type.

NOAO



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

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:

O Be A Fine Girl / Guy Kiss Me

Stellar spectra

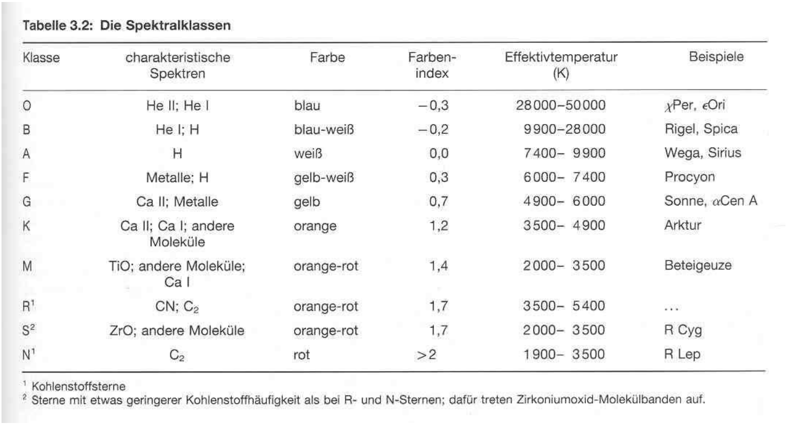


Tabelle 3.2: Die Spektralklassen

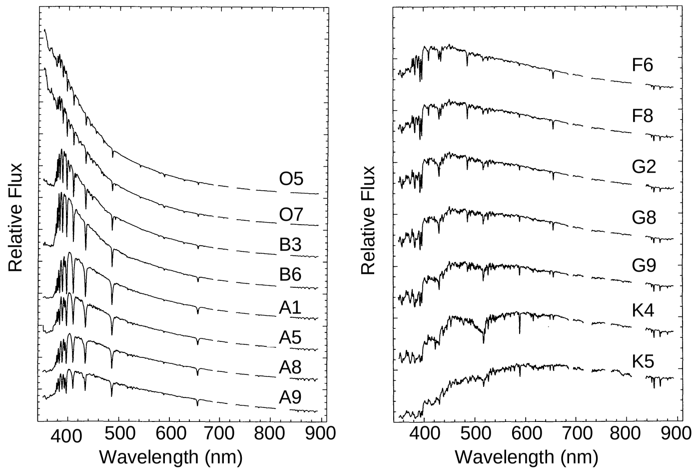
Klasse	charakteristische Spektren	Farbe	Farben-index	Effektivtemperatur (K)	Beispiele
O	He II; He I	blau	−0,3	28000–50000	χPer, ϵOri
B	He I; H	blau-weiß	−0,2	9900–28000	Rigel, Spica
A	H	weiß	0,0	7400– 9900	Wega, Sirius
F	Metalle; H	gelb-weiß	0,3	6000– 7400	Procyon
G	Ca II; Metalle	gelb	0,7	4900– 6000	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-Molekülbanden auf.

Kaler: Sterne (Spektrum Akademischer Verlag)

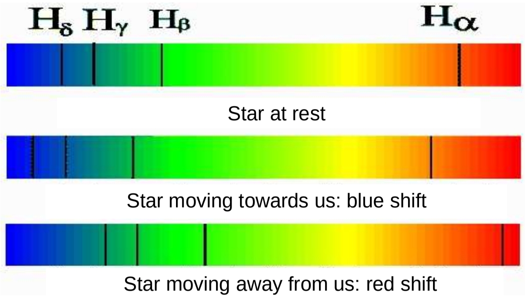
Stellar spectra



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

Spectral Atlas for classification purposes.

Radial velocity



Star at rest

Star moving towards us: blue shift

Star moving away from us: red shift

Doppler formula:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_\text{rad}}{c} \qquad (10.1)$$

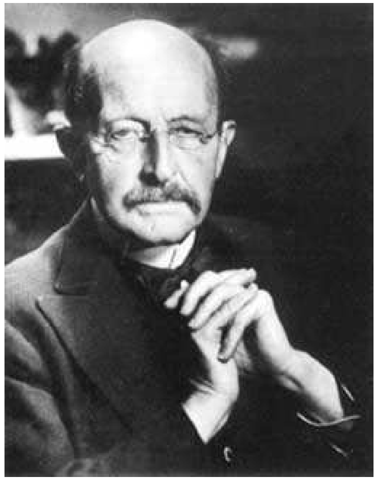
allows to measure the radial velocity v_rad from line shifts

plus tangential velocity (from distance and proper motion)

3D space motion

c: speed of light

Planck's Radiation Law



Max Planck (1858–1947)

Stars are big glowing gas balls.

In zeroth order: thermodynamic equilibrium.

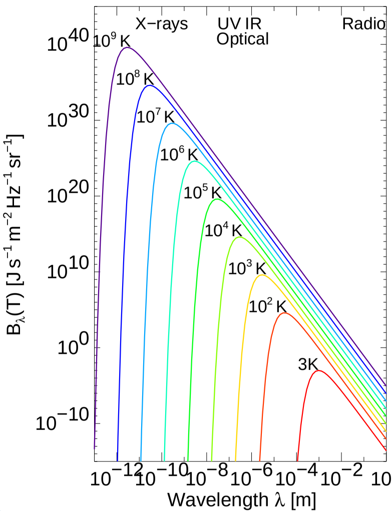
Max Planck: under these circumstances: emitted flux spectrum is blackbody radiation:

$$B_\lambda = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda kT) - 1} \qquad (10.2)$$

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

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:

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

where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$

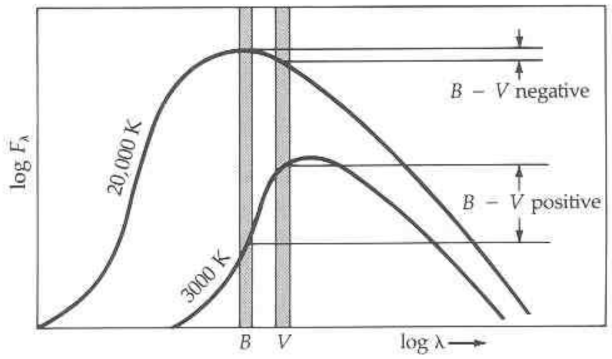
"hotter bodies have a much higher luminosity"

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

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

"hotter bodies radiate higher energetic radiation"

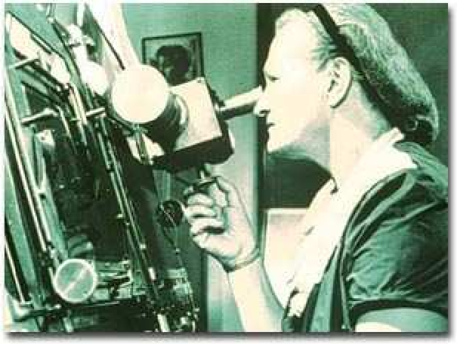
Planck's Radiation Law



(Zeilik & Gregory)

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

Spectroscopy



Cecilia Payne-Gaposchkin (1900–1979)

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

1^{st} 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.

later: 1st female full professor at Harvard

Biography: `http://www.harvardsquarelibrary.org/unitarians/payne2.html`

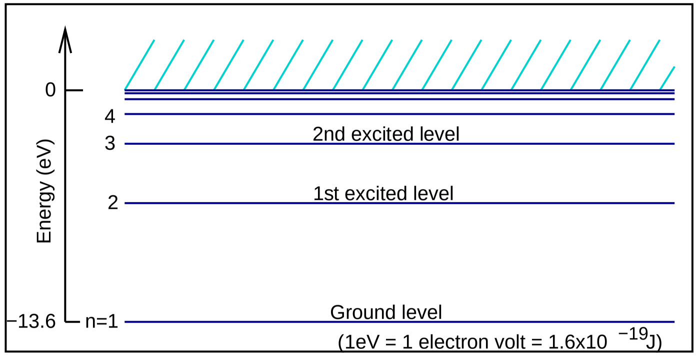
Spectroscopy

Quantum mechanics: atoms have discrete energy levels

Energy levels in Hydrogen:

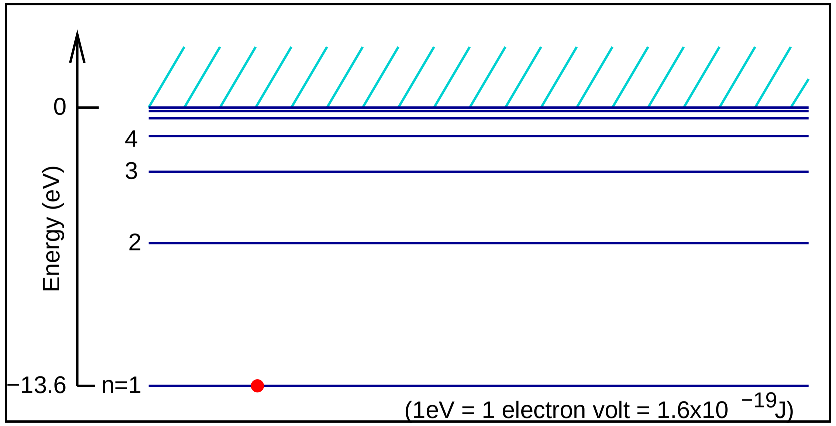
$$E_n = -\frac{2\pi^2\mu e^4}{\hbar^2} \cdot \frac{1}{n^2} \propto -\frac{1}{n^2}$$

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



(1eV = 1 electron volt = 1.6x10 $^{-19}$J)

Spectroscopy

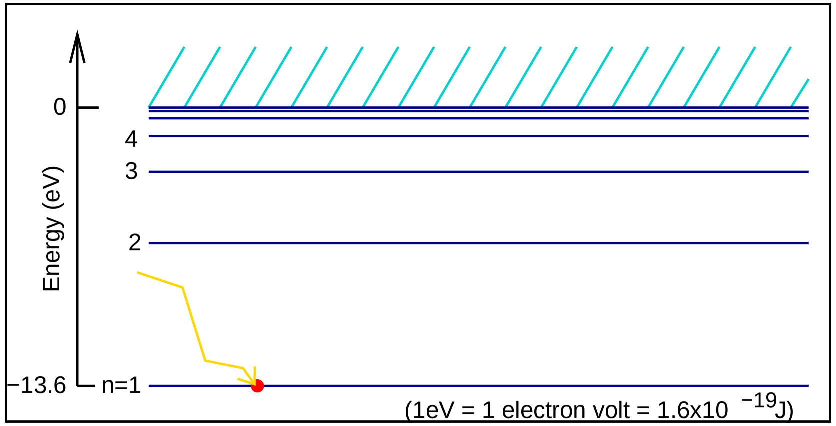


(1eV = 1 electron volt = 1.6x10 $^{-19}$J)

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. . . .

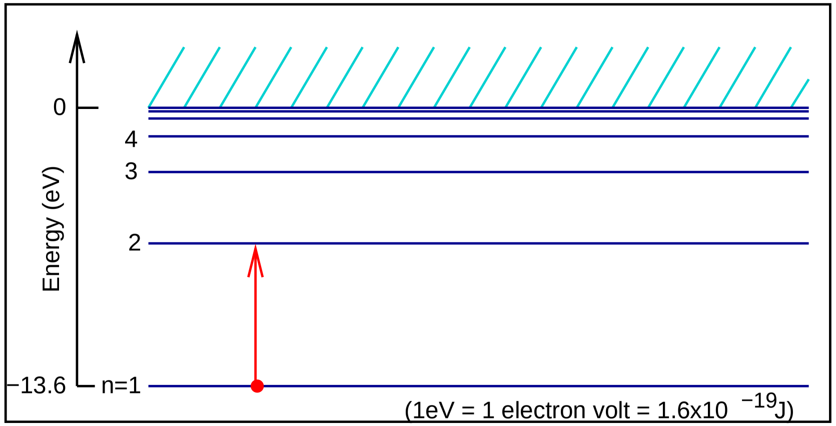
Spectroscopy



(1eV = 1 electron volt = 1.6x10 $^{-19}$J)

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

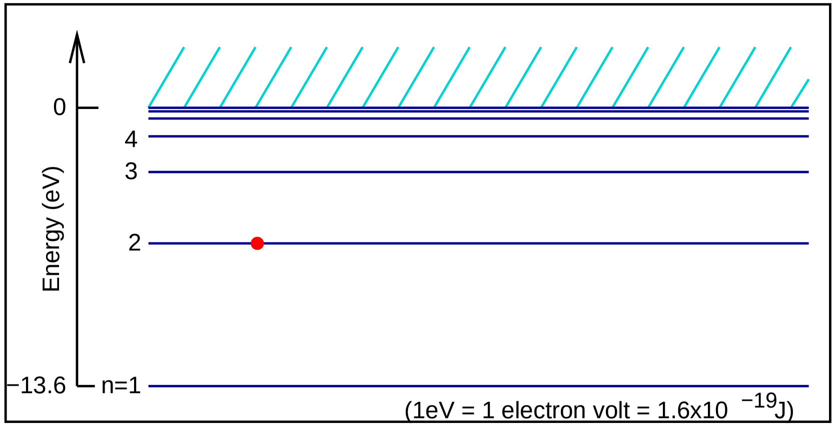
Spectroscopy



(1eV = 1 electron volt = 1.6x10^{-19}J)

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

Spectroscopy

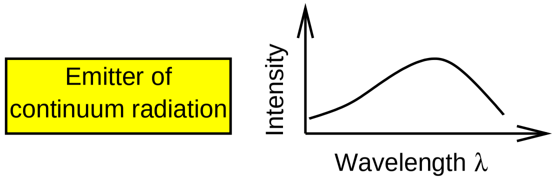


(1eV = 1 electron volt = 1.6x10^{-19}J)

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

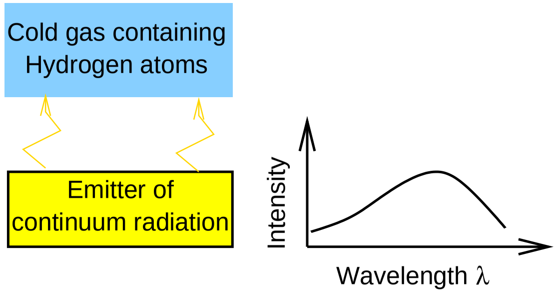
Spectroscopy

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


Emitter of continuum radiation

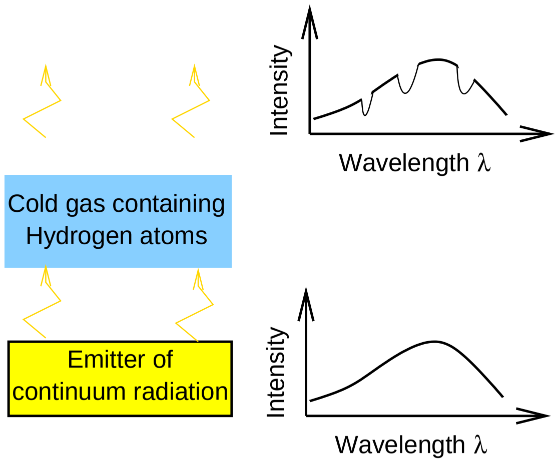
Spectroscopy

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


Cold gas containing Hydrogen atoms

Emitter of continuum radiation

Spectroscopy



Cold gas containing Hydrogen atoms

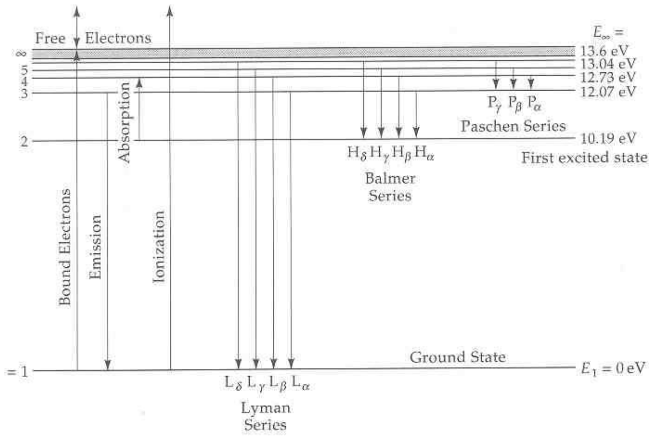
Emitter of continuum radiation

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

$\Longrightarrow$ Atmosphere absorbs photons at wavelengths characteristic for the elements present in stellar atmosphere.

$\Longrightarrow$ Formation of absorption line spectrum.

Spectroscopy



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

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.

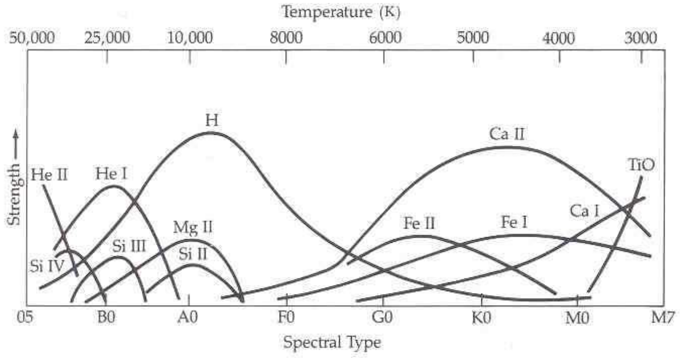
Quantum mechanics gives Saha's equation:

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

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

Degree of ionization increases with increasing T and decreasing n_{e}

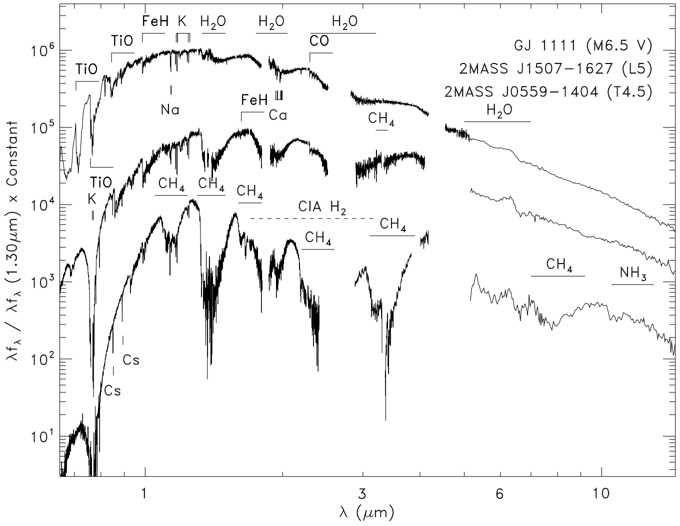
Spectroscopy



(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.

L- and T-Stars



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

Cushing et al., 2006

L- and T-Stars

Brown Dwarfs $\Longrightarrow$ extension of spectral types to lower temperature objects

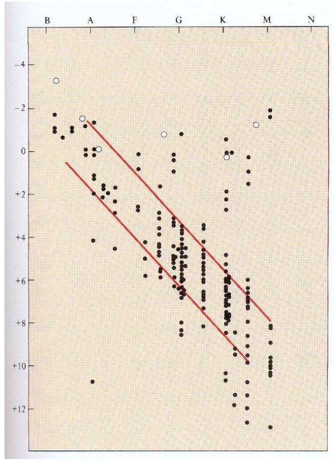
L dwarfs: objects with temperatures of 1200–2500 K, low mass, some do not support fusion. Spectra peak in IR, optical spectra contain prominent lines from metal hydrides and alkali metals.

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

T dwarfs: brown dwarfs with temperatures of ∼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.

Hertzsprung Russell Diagram

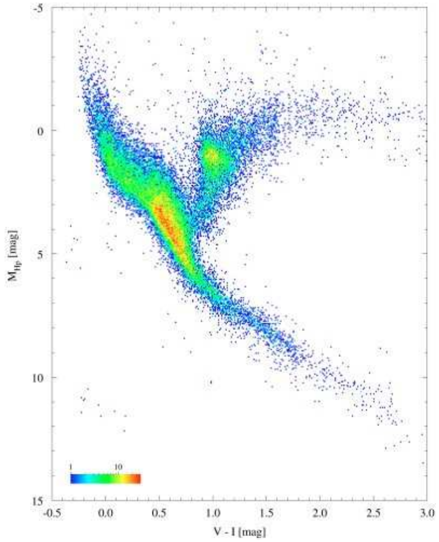


Kaler: Sterne (Spektrum Akademischer Verlag)

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

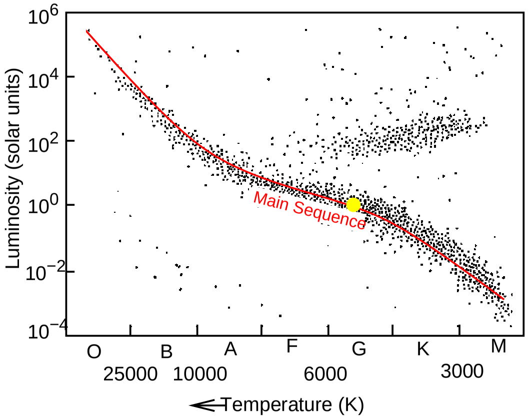
Most important phase diagram in stellar astrophysics

Hertzsprung Russell Diagram



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

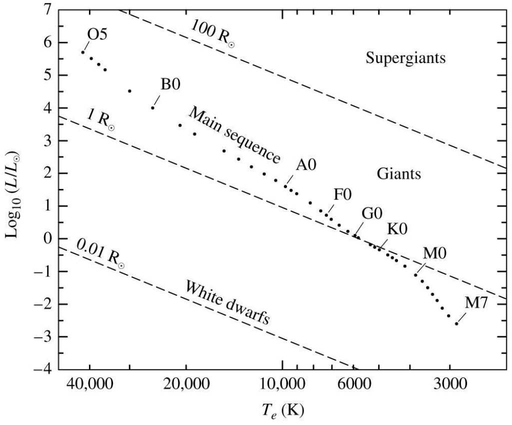
Hertzsprung Russell Diagram



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

- Most stars on Main Sequence (“dwarfs”)

Yerkes classification



Carroll & Ostlie

Stellar Luminosity:

$$L = 4\pi R^2 \sigma T_{\text{eff}}^4 \propto R^2 T_{\text{eff}}^4 \quad (10.3)$$

Lines of constant radius:

$$\log \frac{L}{L_\odot} = 2 \log \frac{R}{R_\odot} + 4 \log \frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \quad (10.4)$$

$\Longrightarrow$ hot (early type) main sequence stars are larger than the Sun

$\Longrightarrow$ cool (late type) main sequence stars are smaller than the Sun

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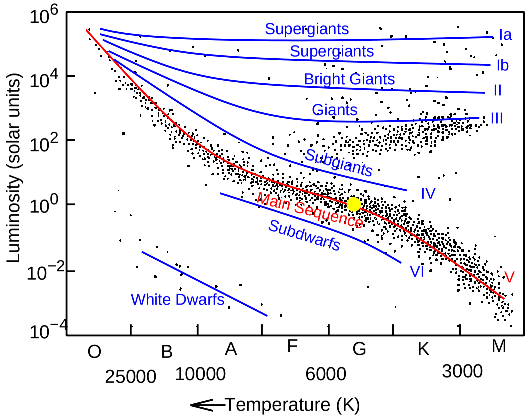
Yerkes classification



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 Iab

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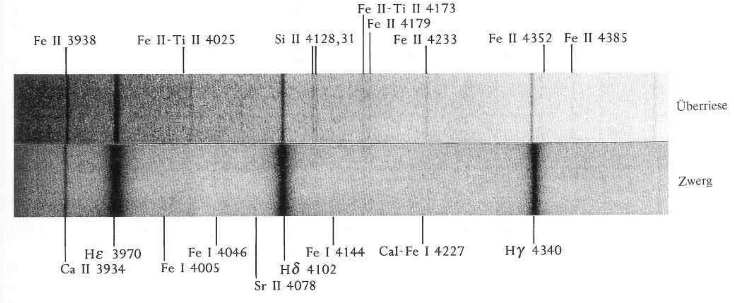
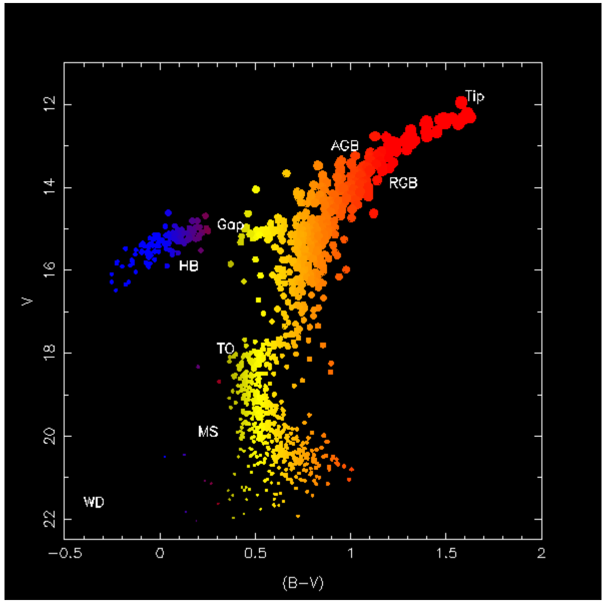
Yerkes classification

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

Globular Cluster NGC 6903 STScI



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

Globular Clusters: HRD is *very* different of solar neighbourhood

MS: Main Sequence

TO: Turn-Off point

HB: Horizontal Branch

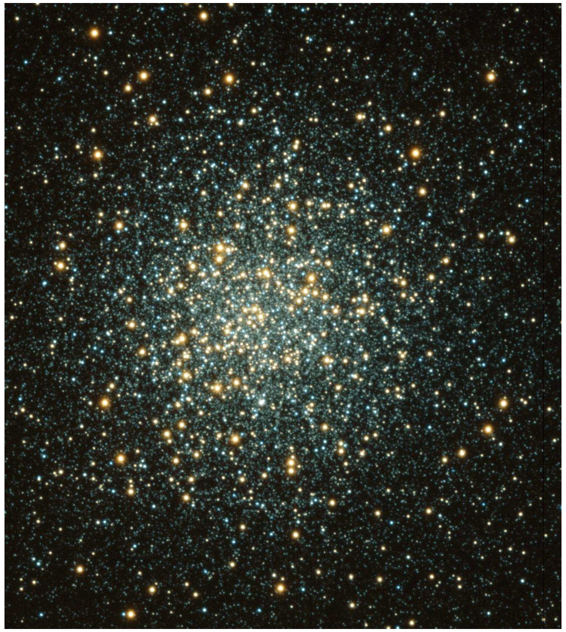
RGB: Red Giant Branch

AGB: Asymptotic Giant Branch

WD: White Dwarfs

All stars in globular cluster born at the same time

$\Longrightarrow$ HRD shows evidence for stellar evolution



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

Terms to know

- Astrometry:
  parallax mesurements yield distances: $p = \frac{1\,\mathrm{AU}}{d}$ (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: $\frac{f_{\mathrm{V},1}}{f_{\mathrm{V},2}} = 100^{(m_{\mathrm{V},2}-m_{\mathrm{V},1})/5}$
    - $*$ absolute visual magnitude M_V = magnitude at $D = 10\,\mathrm{pc}$
    - $*$ distance modulus: $m_\mathrm{V} - M_\mathrm{V} = 2.5\log(F_\mathrm{V}/f_\mathrm{V}) = 2.5\log(d/10\,\mathrm{pc})^2 = 5\log d - 5$
    - $*$ bolometric absolute magnitude $M_\mathrm{bol} = -2.5\log\frac{L}{L_\odot} + 4.74$
    - $*$ bolometric correction: B.C. $= M_\mathrm{bol} - M_\mathrm{V}$
    - $*$ color indices, e.g., UBV: B $-$ V $= m_\mathrm{B} - m_\mathrm{V}$, U $-$ B $= m_\mathrm{U} - m_\mathrm{B}$
- Planck's law:
  - Effective temperature: $T_\mathrm{eff}^4 = F/\sigma = L/(4\pi R^2\sigma)$
  - color indices are temperature indicators

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 $\Longrightarrow$ 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