Stars: Observations

What are stars?

Most important building blocks of the universe: stars

Proper definition:

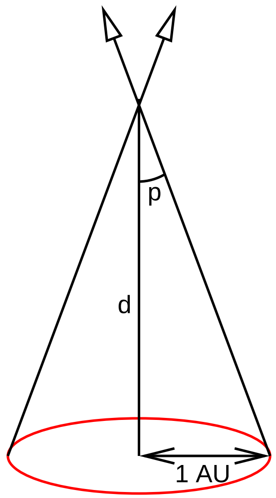
> Stars are gas balls consisting mainly of hydrogen and helium, which produce energy by fusion.

We will now look at observable properties of stars:

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

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

Distances



Direct distance measurements: parallax measurement:

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

Parallax angle (small angle approximation):

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

(p is measured in *radians*)

Typical values for p are arcseconds

$\Longrightarrow$ 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. . .

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:

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

Distances

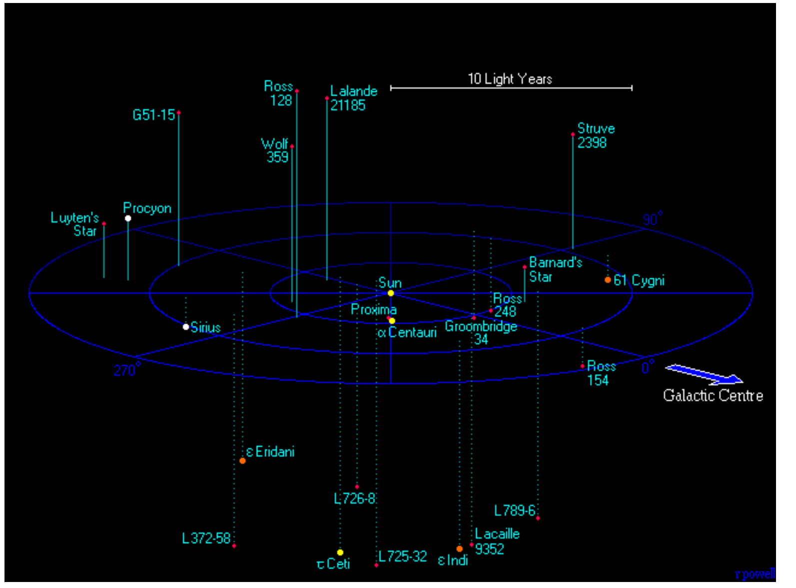
Best parallax measurements to date: ESA's Hipparcos satellite (with participation from Heidelberg and Tübingen).

- 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)

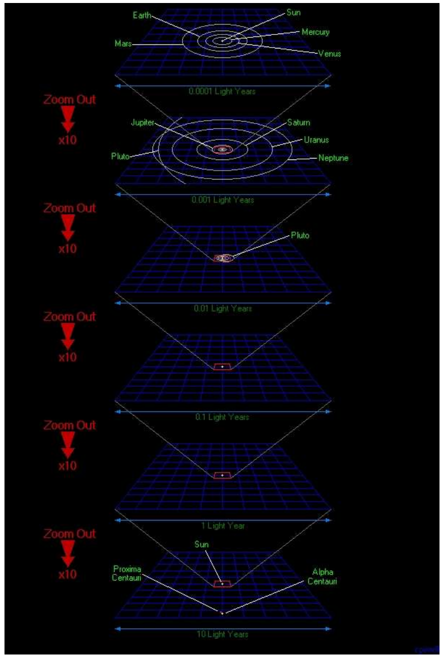
Results available at `http://astro.estec.esa.nl/Hipparcos/`:

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

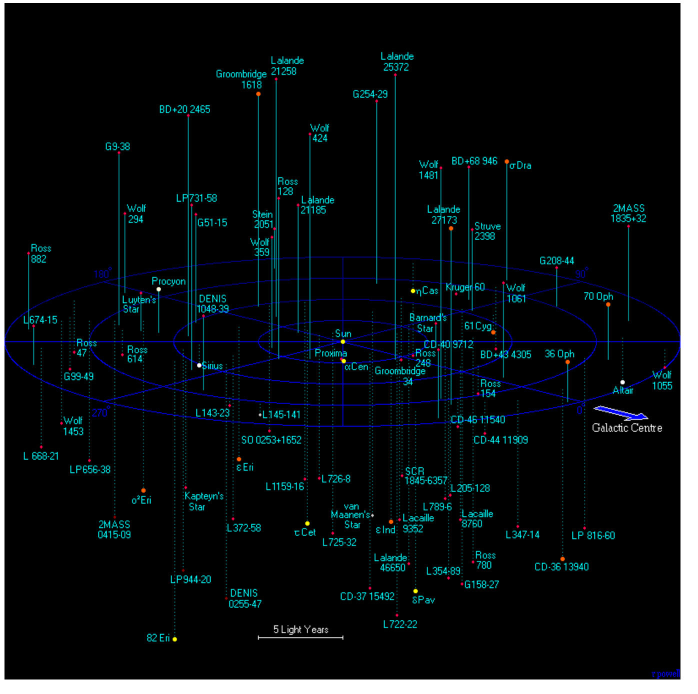
Tycho catalogue: 10^6 stars with 20–30 mas precision, two-band photometry



http://www.anzwers.org/free/universe/12lys.html
(12 ly = 3.7 pc)

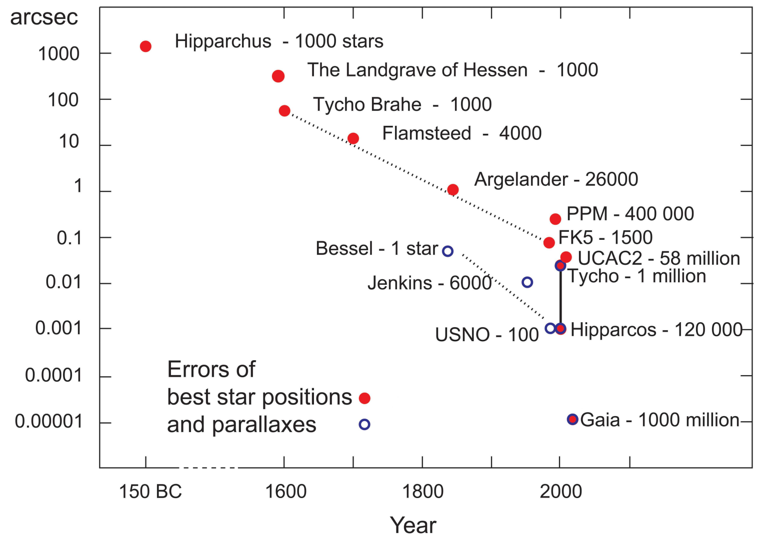


http://www.anzwers.org/free/universe/stardist.html



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/free/universe/20lys.html



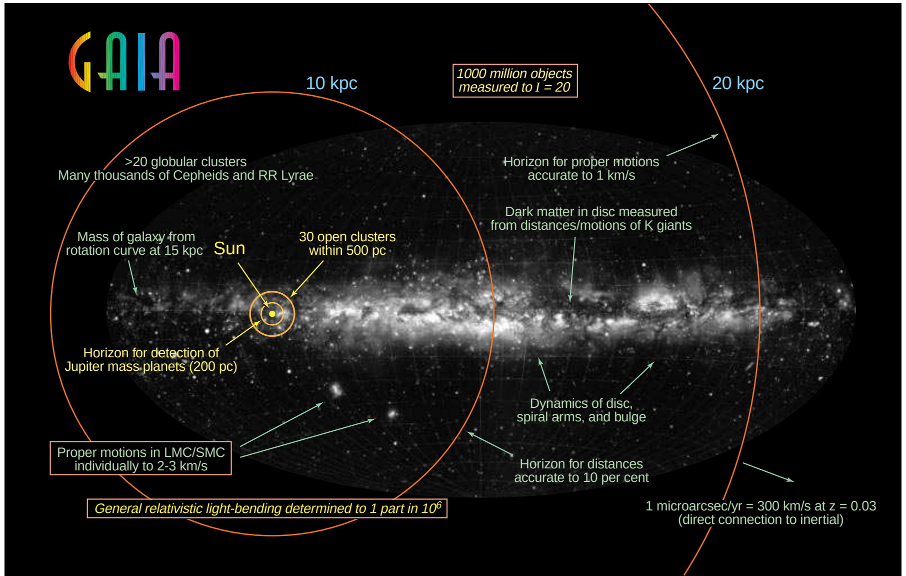
ESA/E. Høg

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

$\Longrightarrow$ can measure parallax out to $\sim$1 kpc

further out: "secondary distance estimators" $\Longrightarrow$ see later lectures

Plans for the future: GAIA (ESA mission, $\sim$2011–2012):



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

Luminosity

Definition: Luminosity of a star:

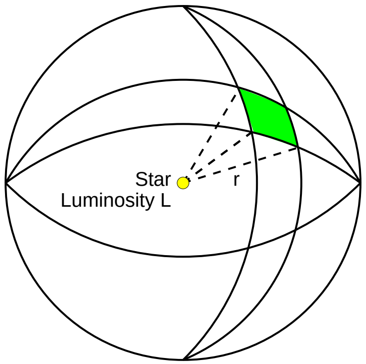
The total energy emitted by a star per second is called its luminosity.

(=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, I



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: $\mathrm{W\,m^{-2}}$ or $\mathrm{erg\,cm^{-2}\,s^{-1}}$).

Flux, IV

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 (4×10^{26} W).

$\Longrightarrow$ Flux arriving on Earth:

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

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

$\Longrightarrow$ your eye detects a power of

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

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

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

Magnitudes, I

Hipparchus
(??– ~127 BC)

First classification of stars:

- Stars of “magnitude 1”: brightest (visible) stars
- Stars of “magnitude 6”: faintest (visible) stars

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

Magnitudes, V

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)

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

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

Convention: to describe luminosity of a star, use the **absolute magnitude** M, defined as magnitude measured at distance $D = 10$ pc.

Therefore,

$$m - M = 2.5\log(F/f) = 2.5\log(d/10\,\mathrm{pc})^2 = 5\log d - 5$$

$m - M$ is called the **distance modulus**, d is measured in pc.

Introduction

Next observable: Temperature

Obtained using spectroscopy

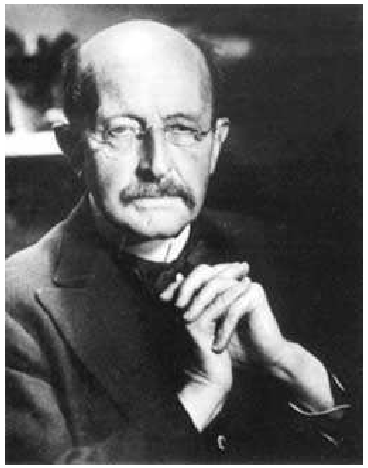
In the following: rough outline, as stellar spectroscopy is rather complicated

Outline:

1. Planck's Radiation Laws
2. Stellar Continuum Spectra
3. Spectral Classification

. . . unfortunately, need to be a little bit formal first

Planck's Radiation Law, I



Max Planck (1858–1947)

Stars are big glowing gas balls.

In zeroth order: thermodynamic equilibrium.

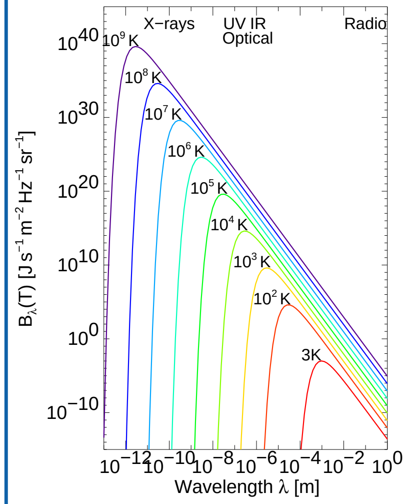
Max Planck: under these circumstances: emitted spectrum is blackbody radiation:

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

F_λ: Energy emitted per second and wavelength interval

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

Planck's Radiation Law, II



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

Stefan-Boltzmann law: Power emitted per square-meter surface of a blackbody:

$$P = \sigma T^4$$

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

"hotter bodies have a much higher luminosity"

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

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

"hotter bodies radiate higher energetic radiation"

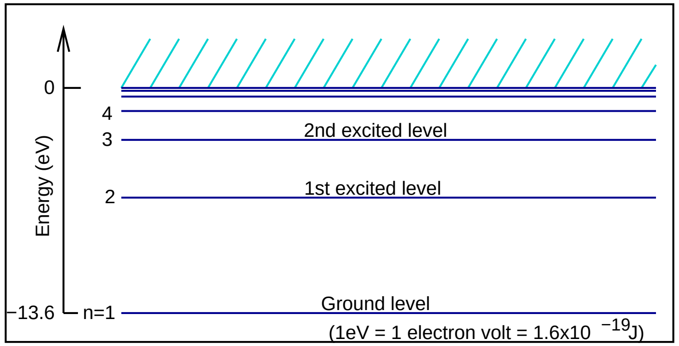
Spectroscopy, I

Quantum mechanics: atoms have discrete energy levels

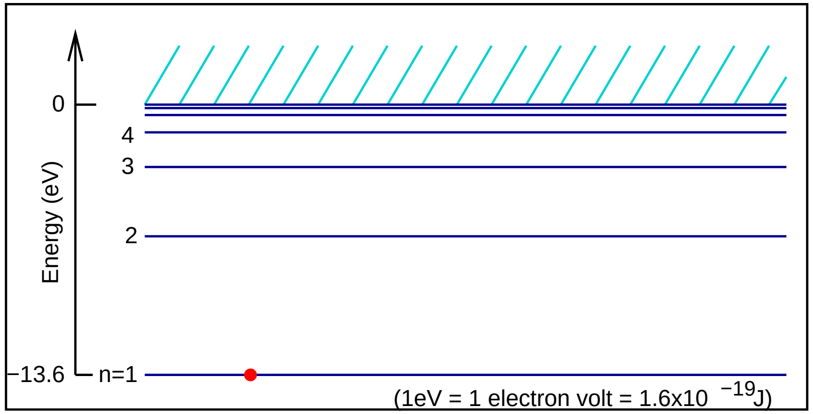
Energy levels in Hydrogen:

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

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



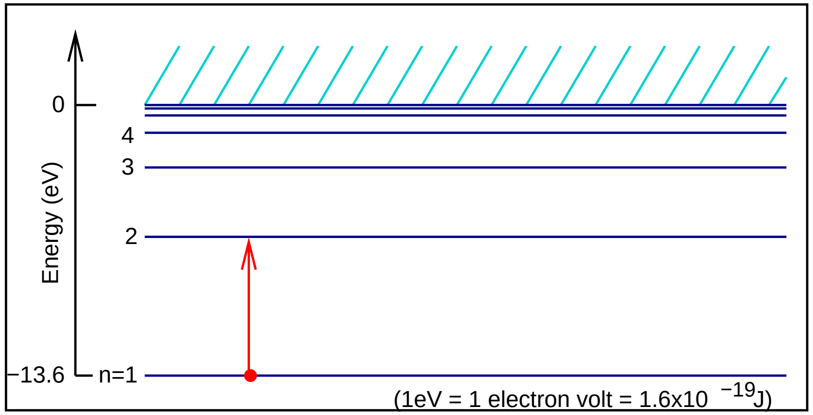
Spectroscopy, II



In hydrogen atom: electrons typically found in ground state.

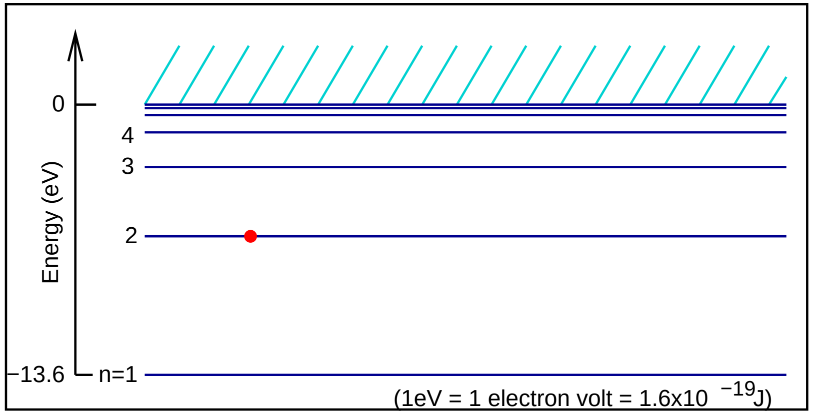
if temperature is higher, can also be in 1st excited state, but the physical principles following remain the same. . . .

Spectroscopy, IV



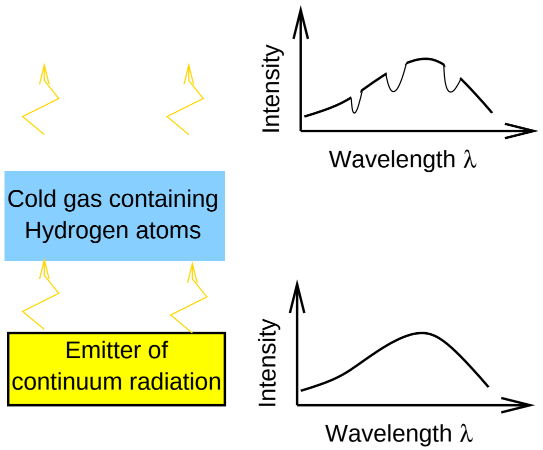
Photon hitting atom has energy $E_{\text{phot}} = h\nu = hc/\lambda$. If $E_{\text{phot}} = E_2 - E_1$, then photon can be absorbed. . . and electron has higher energy (is excited).

Spectroscopy, V



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

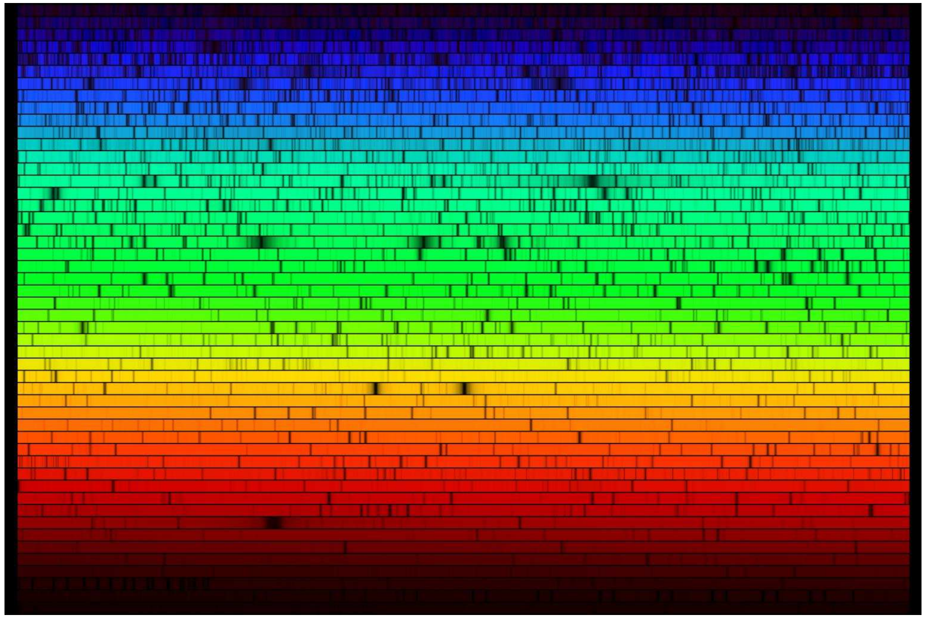
Spectroscopy, VIII



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.



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

Absorption line spectrum of the Sun: Fraunhofer Lines

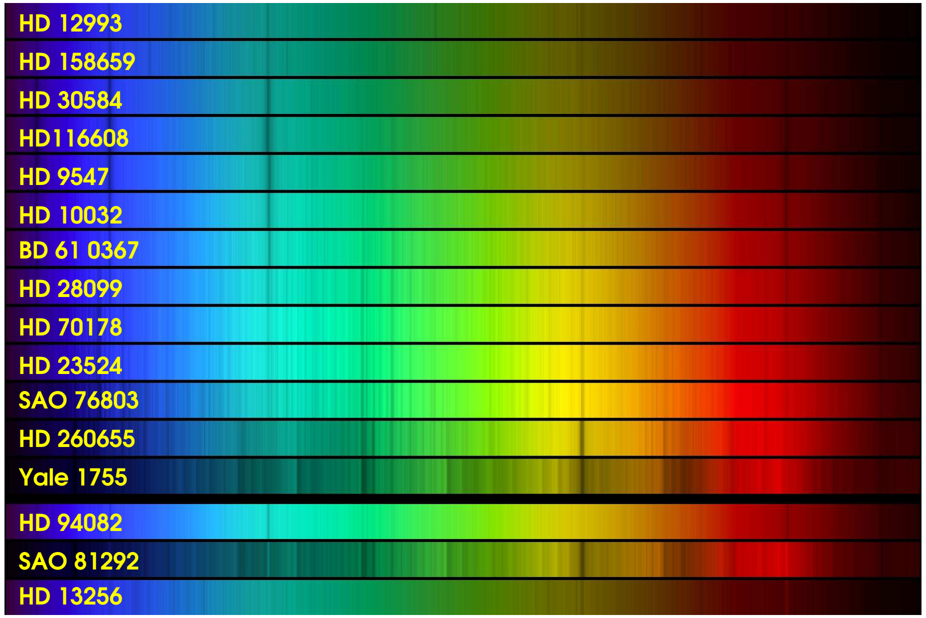
Spectroscopy, XII

Annie Jump Cannon (1863–1941)

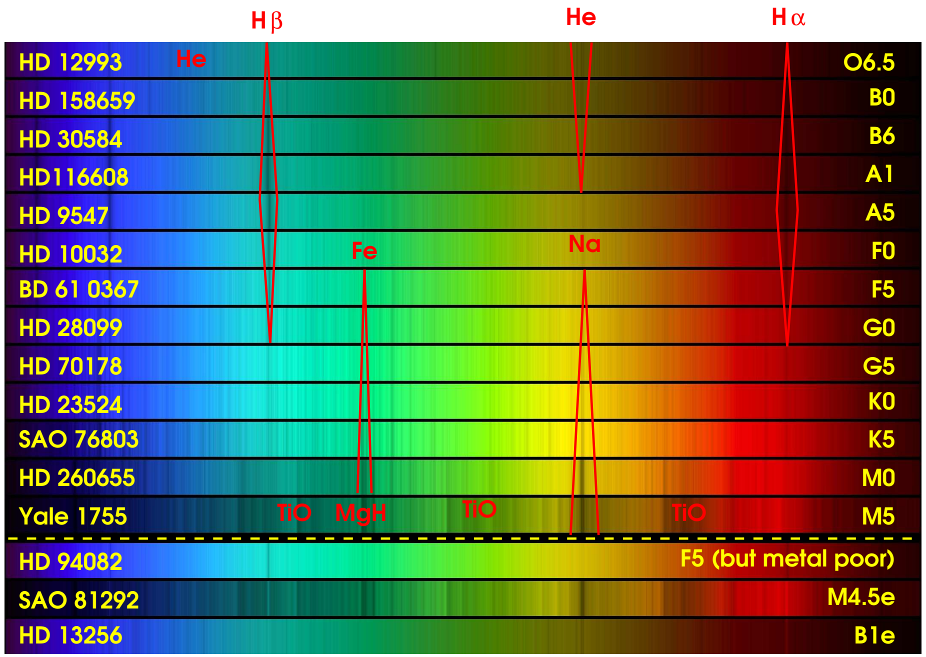
Biography: `http://www.sdsc.edu/ScienceWomen/cannon.html`

Annie Jump Cannon: There are spectral types.

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

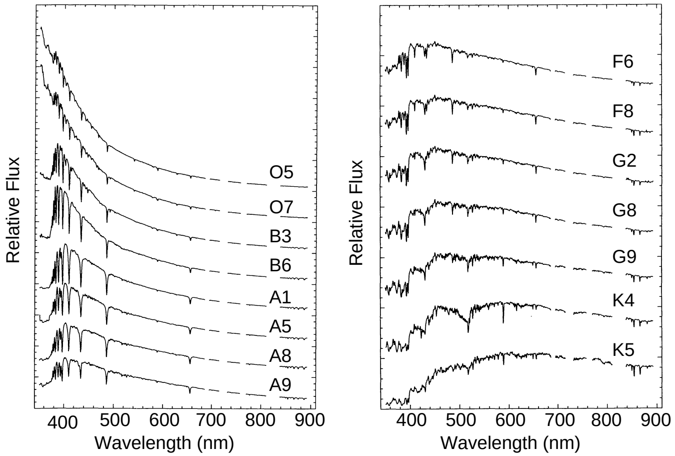


Annie Cannon (around 1890): Stars have different spectra. NOAO



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

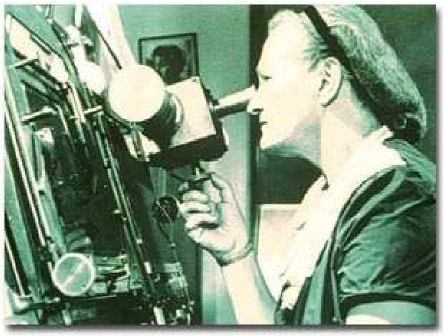
Spectroscopy, XV



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

Cecilia Payne-Gaposchkin: Spectral sequence is temperature sequence.

Spectroscopy, XVI



Cecilia Payne-Gaposchkin (1900–1979)

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

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.

later: 1st female full professor at Harvard

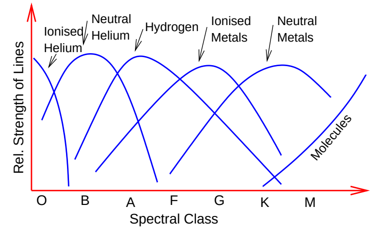
Spectroscopy, XXI

Summary spectral classes as a temperature sequence.

O - B - A - F - G - K - M

30000 K — 3000 K

"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:

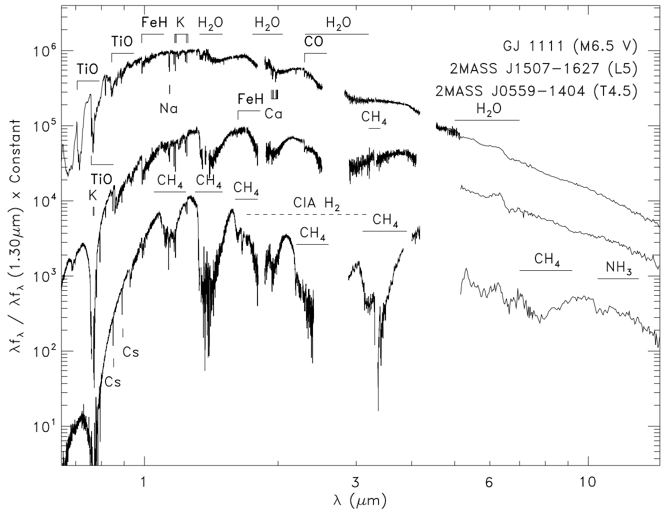
(http://lheawww.gsfc.nasa.gov/users/allen/obafgkmrns.html)

O Be A Fine Girl/Guy Kiss Me

Only Boys Accepting Feminism Get Kissed Meaningfully

Only Bold Astronomers Forge Great Knowledgeable Minds

L- and T-Stars



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

Cushing et al., 2006

L- and T-Stars

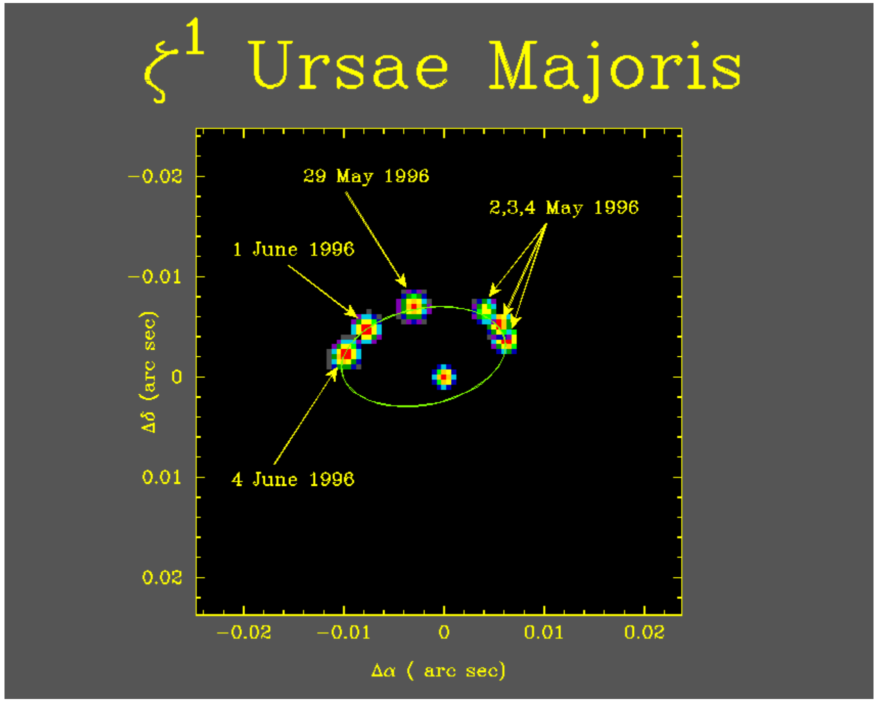
Brown Dwarfs $\Longrightarrow$ extension of spectral types to lower temperature objects

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 $\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.



V. van Gogh: Starry Night over the Rhône (1888)

The WebMuseum (`http://www.ibiblio.org/wm/`; original: Paris, Musée d'Orsay)

Masses, XIII

Mizar A and B are rather typical stars:

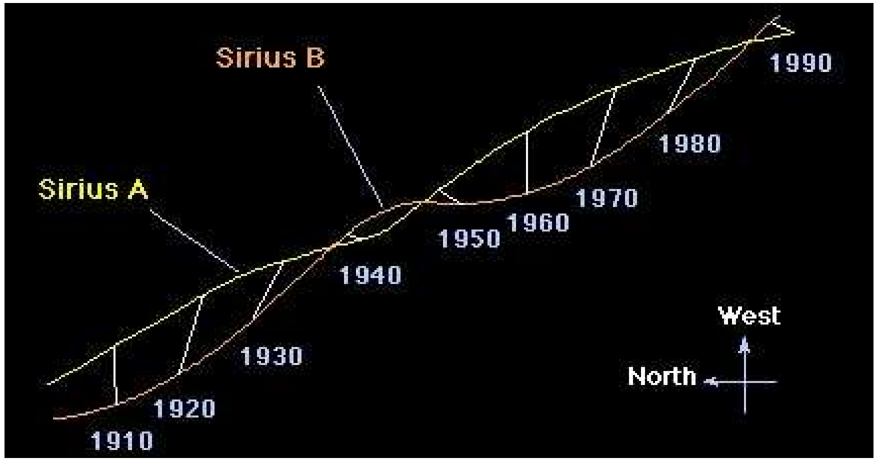
50% – 80% of all stars in the solar neighbourhood belong to multiple systems.

Rough classification:

apparent binaries: stars are *not* physically associated, just happen to lie along same line of sight (“optical doubles”).

visual binaries: bound system that can be resolved into multiple stars (e.g., Mizar); can image orbital motion, periods typically 1 year to several 1000 years.

spectroscopic binaries: bound systems, cannot resolve image into multiple stars, but see Doppler effect in stellar spectrum; often short periods (hours. . . months).



http://csep10.phys.utk.edu/astr162/lect/binaries/astrometric.html

Astrometric binaries: Motion of stars around common center of mass results in a "wobble" around the CM (since CM is moving along a straight line).

Masses, XVII

To determine stellar masses, use Kepler's 3rd law:

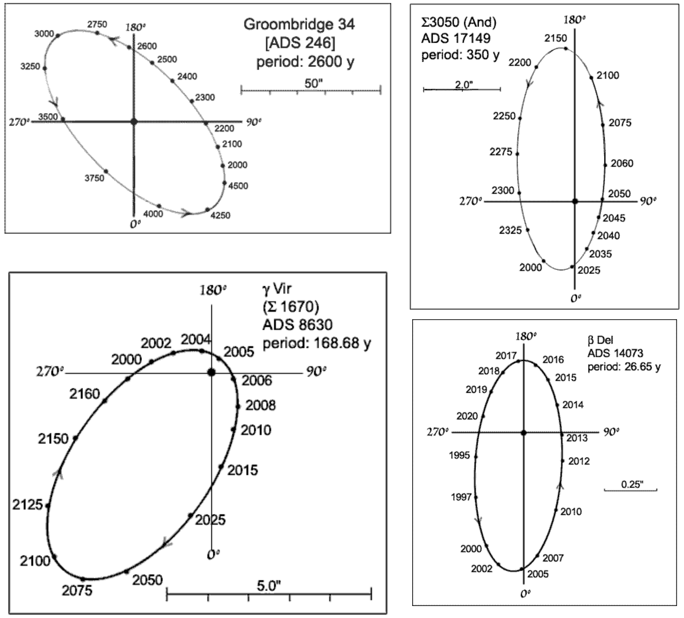
$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(m_1 + m_2)$$

where

- $M_{1,2}$: masses
- P: period
- a semimajor axis

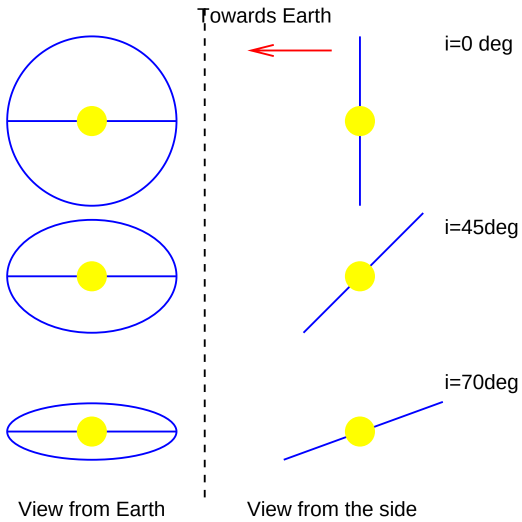
Observational quantities:

- P – directly measurable
- a – measurable from image *if and only if* distance to binary and the inclination are known



Taking out proper motion leaves us with binary star orbits.

Masses, XVIII



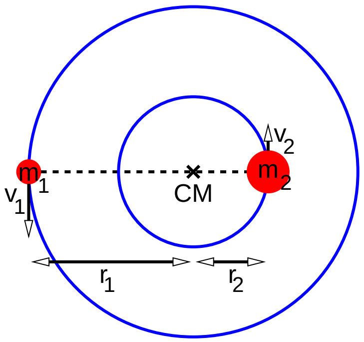
Problem when analysing orbits: orientation of orbit in space: "inclination"

In simplest case: real semimajor axis:

$$a_{\text{observed}} = a_{\text{real}} \cos i$$

Inclination typically found using Kepler's 2nd law plus geometry...

Masses, XIX



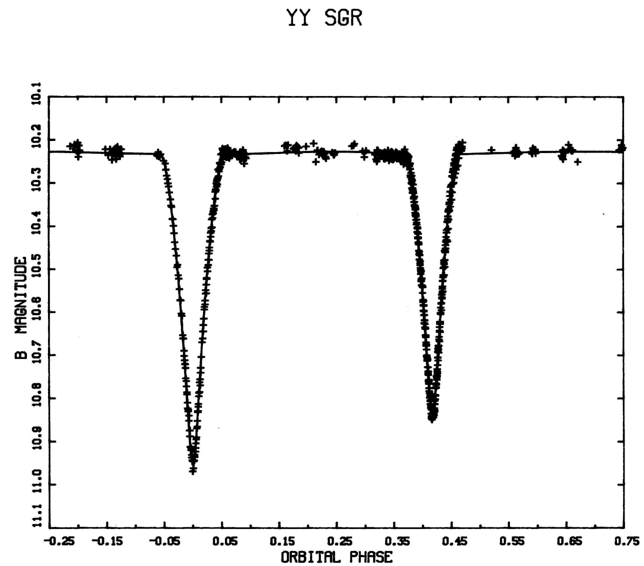
Kepler's 3rd law gives $M_1 + M_2$.

To determine individual masses, M_1 and M_2, we make use of the fact that the stars move around their common center of mass (CM):

$$M_1 a_1 = M_2 a_2 \quad \text{such that} \quad \frac{M_1}{M_2} = \frac{a_2}{a_1}$$

where a_1, a_2: semi-major axes of orbits around CM (observable from imaging).

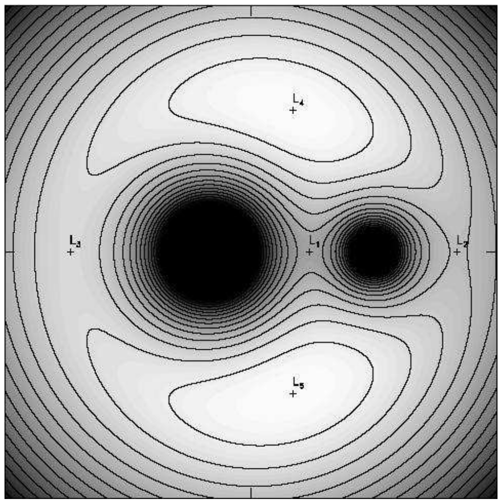
MOVIE TIME: vbin0.mpg, vbin4.mpg



(YY Sgr, $M_1/M_2 = 0.95$, $P = 2.6285372(8)$ d; Lacy, 1993, AJ 106, 738; B5/B6 stars)

Eclipsing binaries: photometric binaries where the orbital plane is perpendicular to the celestial plane.

Photometric Binaries, I



R. Hynes

In a close binary system: Gravitational potential described by the Roche potential:

$$\Phi_R(\boldsymbol{r}) = -\frac{GM_1}{|\boldsymbol{r}-\boldsymbol{r}_1|} - \frac{GM_2}{|\boldsymbol{r}-\boldsymbol{r}_2|} - \frac{1}{2}(\boldsymbol{\omega}\times\boldsymbol{r})^2$$

and where

$$\boldsymbol{\omega} = \left(\frac{GM}{a^3}\right)^{1/2} \hat{e}$$

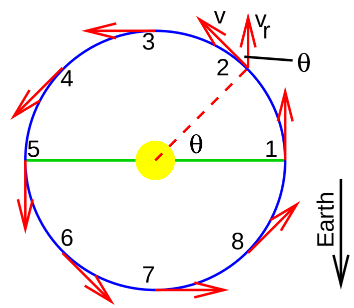
Stellar surfaces are isosurfaces of this potential

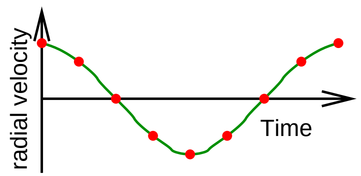
$\Longrightarrow$ stars are non-spherical

$\Longrightarrow$ Stellar magnitude changes with orbit.

MOVIE TIME: output.mpg

Spectroscopic Binaries, I





For spectroscopic binaries: can only measure radial velocity along line of sight

For circular orbit, angle θ on orbit:

$$\theta = \omega t$$

where $\omega = 2\pi/P$.

Observed radial velocity:

$$v_r = v\cos(\omega t)$$

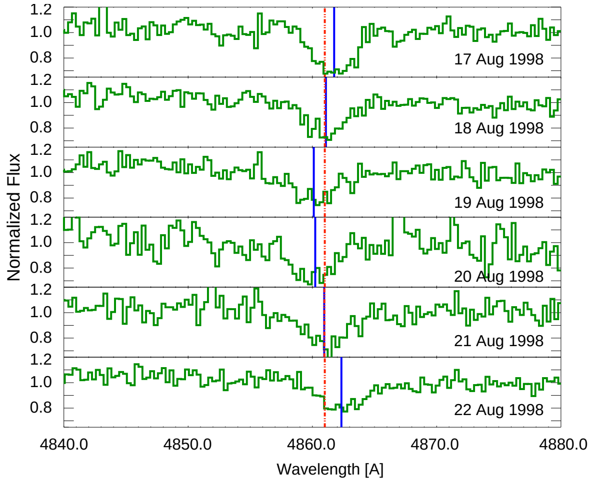
If orbit has inclination i, then

$$v_r(t) = v \sin i \cos(\omega t)$$

From observation of $v_r(t) \Longrightarrow v\sin i$.

("velocity amplitude")

Spectroscopic Binaries, II



HDE 226868/Cyg X-1; Pottschmidt (2001)

Motion of star visible through Doppler shift in stellar spectrum:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c} = \frac{v}{c}\sin i \cos\omega t$$

For virtually all stars, classical Doppler effect is enough; once $v \gtrsim 0.1c$, however, use relativistic Doppler effect,

$$\nu_{\text{obs}} = \nu_{\text{em}}\sqrt{\frac{1+v/c}{1-v/c}}$$

To derive the mass function, we start as usual with Kepler's 3rd law,

$$\frac{G}{4\pi^2}(M_1+M_2) = \frac{R^3}{P^2}$$

In the following, we will assume that we observe the spectral lines from star number 1 only.

Because of the center of mass definition,

$$M_1 r_1 = M_2 r_2$$

such that

$$R = r_1 + r_2 = r_1\left(1+\frac{r_2}{r_1}\right) = r_1\left(1+\frac{M_1}{M_2}\right)$$

In the case that the orbits are circular, the velocity of the star whose spectrum we see is

$$v_1 = \frac{2\pi r_1^2}{P}$$

However, due to the unknown inclination, we only observe the radial velocity component, that is

$$v_{\text{obs}} = v_1 \sin i$$

In terms of the observables, r_1 is

$$r_1 = \frac{P}{2\pi}v_1 = \frac{P}{2\pi}\frac{v_{\text{obs}}}{\sin i}$$

such that finally

$$R = r_1\left(1+\frac{M_1}{M_2}\right) = \frac{P}{2\pi}\frac{v_{\text{obs}}}{\sin i}\left(1+\frac{M_1}{M_2}\right)$$

We can now insert R into Kepler's 3rd law:

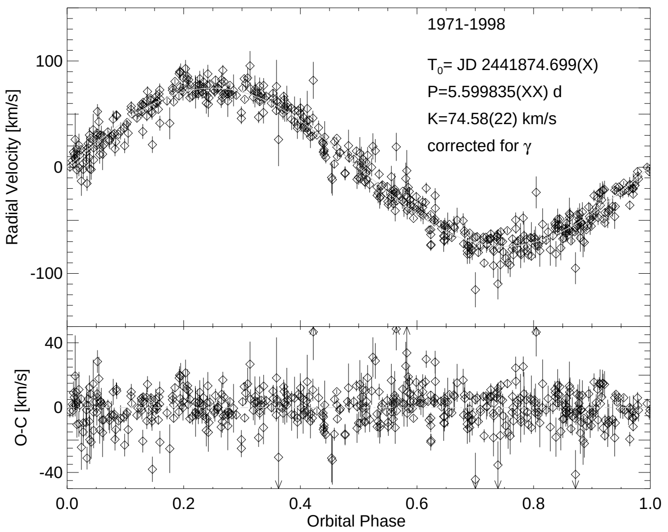
$$\frac{G}{4\pi^2}(M_1+M_2) = \frac{1}{P^2}\frac{P^3}{(2\pi)^3}\frac{v_{\text{obs}}^3}{\sin^3 i}\left(1+\frac{M_1}{M_2}\right)^3$$

and obtain after some straightforward algebra

$$\frac{M_2^3}{(M_1+M_2)^2}\sin^3 i = \frac{P v_{\text{obs}}^3}{2\pi G}$$

the mass function. On the right side are the observables P and v_{obs}, on the left hand side the unknowns i, M_1, and M_2.

Spectroscopic Binaries, III



Best fit radial velocity curve of HDE 226868/Cyg X-1 using data spanning more than 30 years.

Pottschmidt et al. (2001)

Mass Function

If only one star visible: can only determine limits for mass: mass function

$$\frac{P v_{\text{obs}}^3}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2} =: f_{\text{M}}$$

with observables:

- v_{obs}: (velocity amplitude of M_1)
- P: period

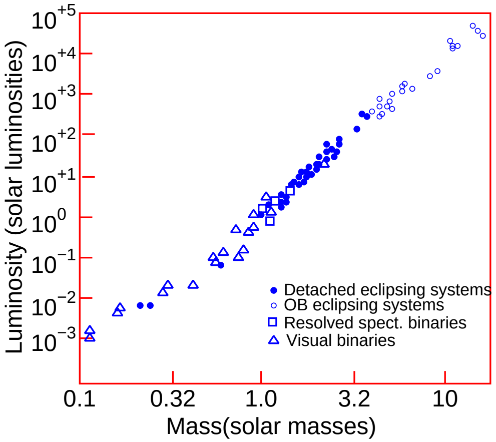
and unknowns:

- M_1: mass of "primary star"
- M_2: mass of (unseen) "secondary star"
- i: inclination

$\Longrightarrow$ f_{M} is lower limit for M_2, since for $M_1 = 0$, $M_2 = f_{\text{M}}/\sin^3 i \geq f_{\text{M}}$

Often used for neutron star and black hole binaries. . .

Application: Mass-Luminosity Relation



Empirical result:

$$\frac{L}{L_\odot} = \begin{cases} 0.23 \left(\frac{M}{M_\odot}\right)^{2.3} & (M < 0.43\,M_\odot) \\ \left(\frac{M}{M_\odot}\right)^{4.0} & (M \geq 0.43\,M_\odot) \end{cases}$$

$\Longrightarrow$ more massive stars have extremely higher luminosities!

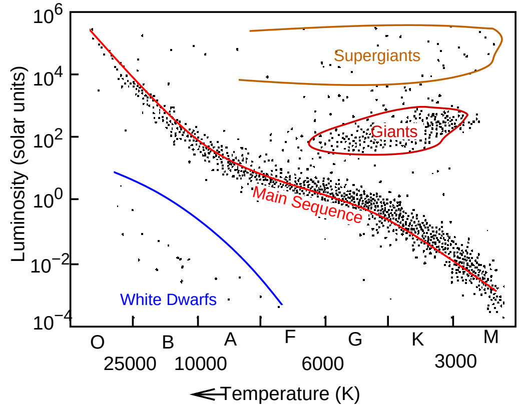
(factor 2 in $M \rightarrow$ factor 8 in L).

Direct consequence:

More massive stars live much shorter lives

sometimes, one also sees $L \propto M^{3.3}$...

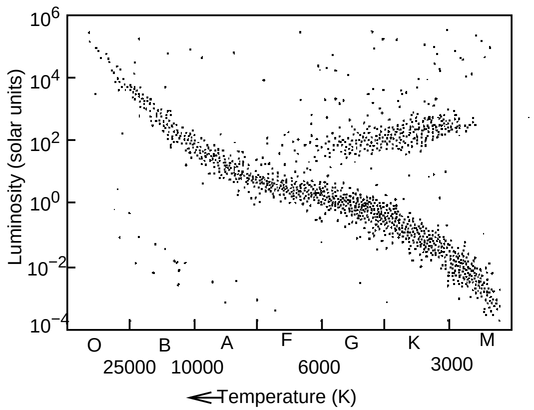
HRD



- Most stars on Main Sequence (“dwarfs”)
- Stellar Luminosity: $L = 4\pi R^2 \sigma T^4 \propto R^2 T^4$
  $\Longrightarrow$ cold, luminous stars are *BIG*
  $\Longrightarrow$ “giants”
- Hot, underluminous stars are small: “white dwarfs”

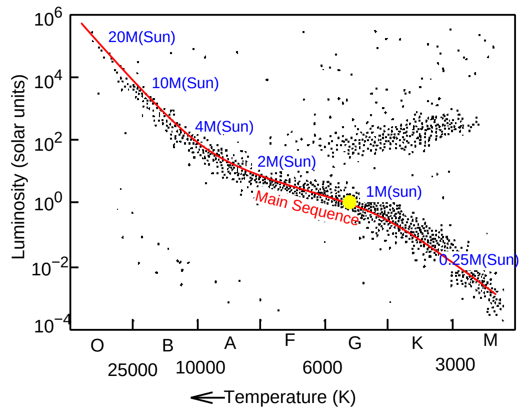
Hertzsprung - Russell Diagram (HRD): Stellar temperature versus stellar luminosity

HRD



Hertzsprung - Russell Diagram (HRD): Stellar temperature versus stellar luminosity

HRD

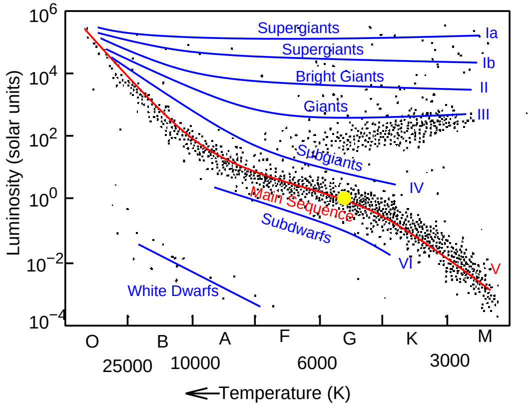


Combining Mass-Luminosity Relationship and HRD:

Main Sequence is a Mass Sequence

- M-Dwarfs have $M \lesssim 0.25 M_\odot$
- G-Stars are similar to Sun and have $M \sim M_\odot$
- O- and B-Stars are very massive ($M \gtrsim 20 M_\odot$)

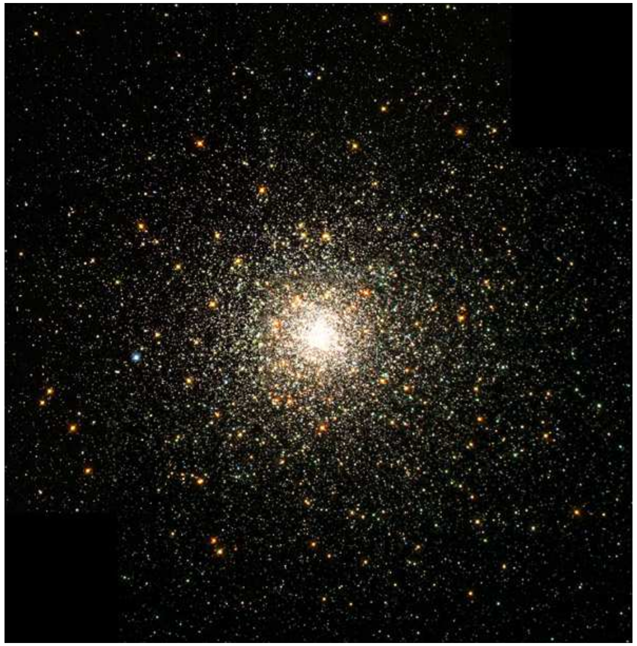
HRD



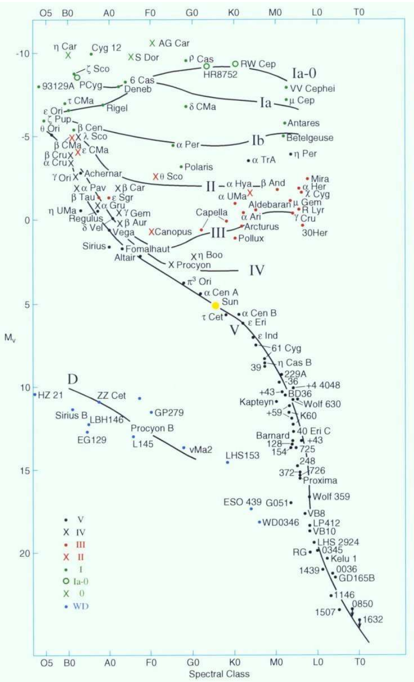
Finally, stars also classified in luminosity classes Ia, Ib, II, III, IV, V, VI

"Morgan-Keenan classes"

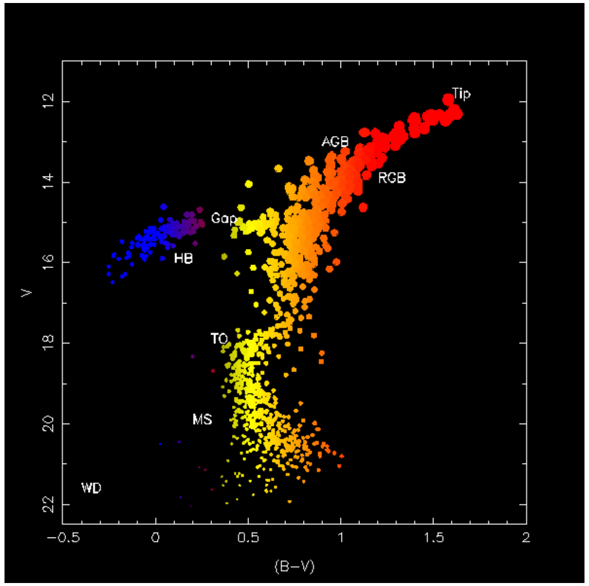
M-K class is appended to spectral class: Sun: G2 V, Beteigeuze: M2 Iab



Globular Cluster NGC 6903 STScI



Kaler, 2005, Cambridge Encyclopedia of Stars, CUP



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-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

$\Longrightarrow$ HRD shows evidence for stellar evolution