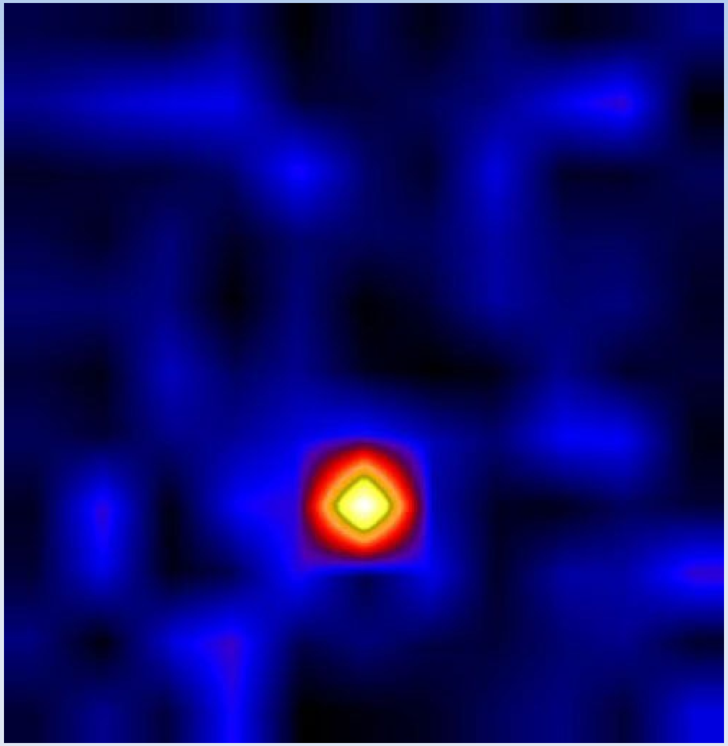
Compact Stars



Fall semester 2023/2024, Faculty of Physics UW

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Center for Theoretical Physics PAS

Compact Stars

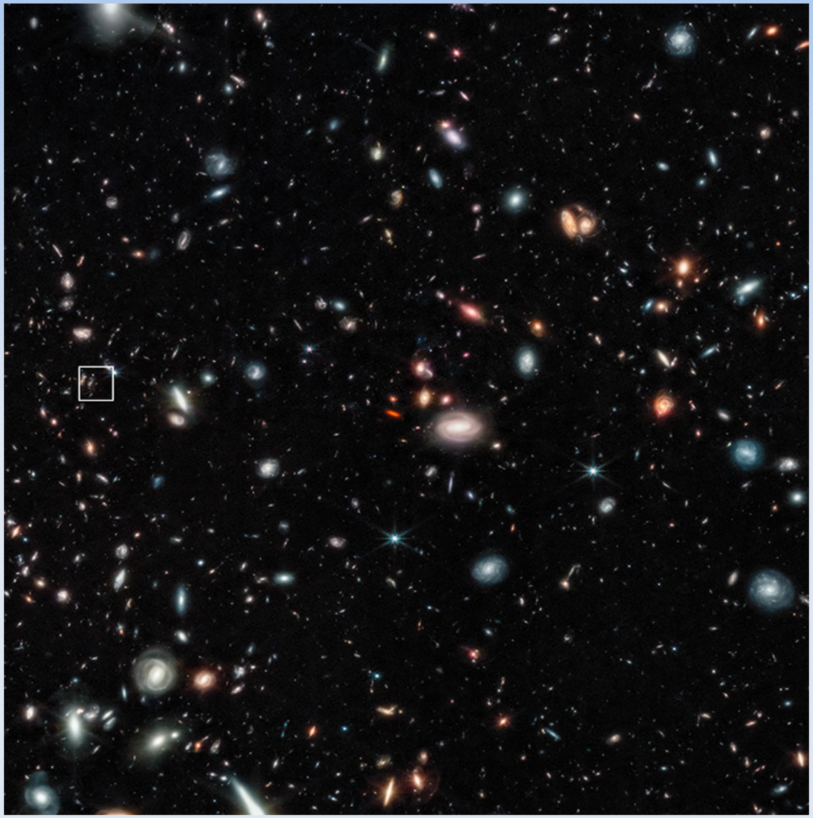
- Lectures on Monday, 13.15-15.00 pm
- Room 2.03
- 15 meetings until Jan 28.
- Final test: 01.29
- Scoring: test > 50% points
- Optional oral exam: to get a higher grade. Attendance on min. >10 lectures

Outline of the lectures

- Stellar evolution and compact object formation
- Binary stars
- Mass transfer and accretion disks
- Black hole and neutron star X-ray binaries
- X-ray astronomy, history, tools and methods
- Cataclysmic variables, white dwarfs, dwarf novae
- Structure and evolution of accretion disks
- Instabilities in black hole accretion
- Pulsars, magnetospheres, pulsar winds. Strange and quark stars.
- Gamma ray bursts, jets, progenitors
- Supermassive black holes
- Radiogalaxies, radioastronomy.
- Gravitational wave sources: binary compact systems

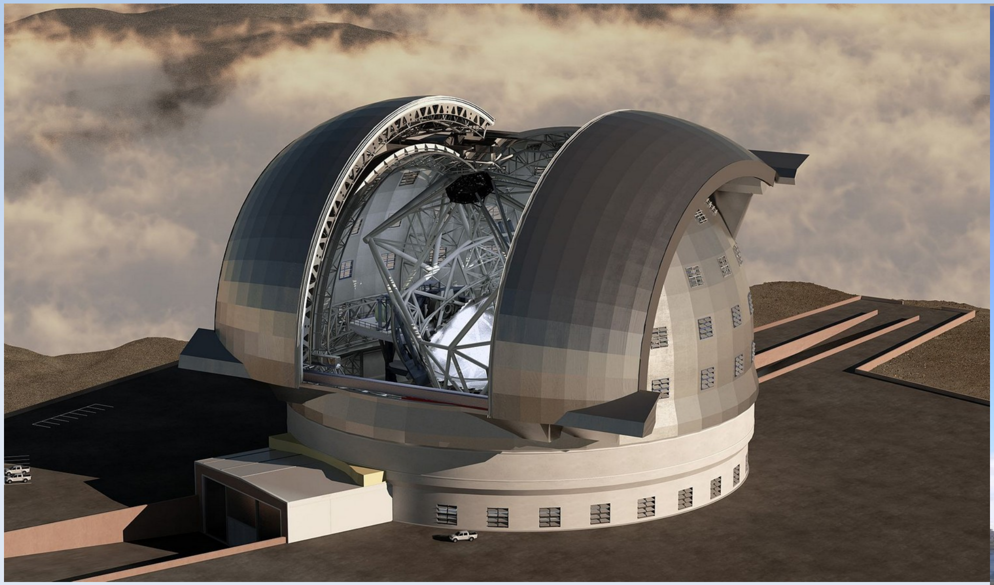
Starry night

Milky Way, Starry Night Sky Over Queenstown, New Zealand

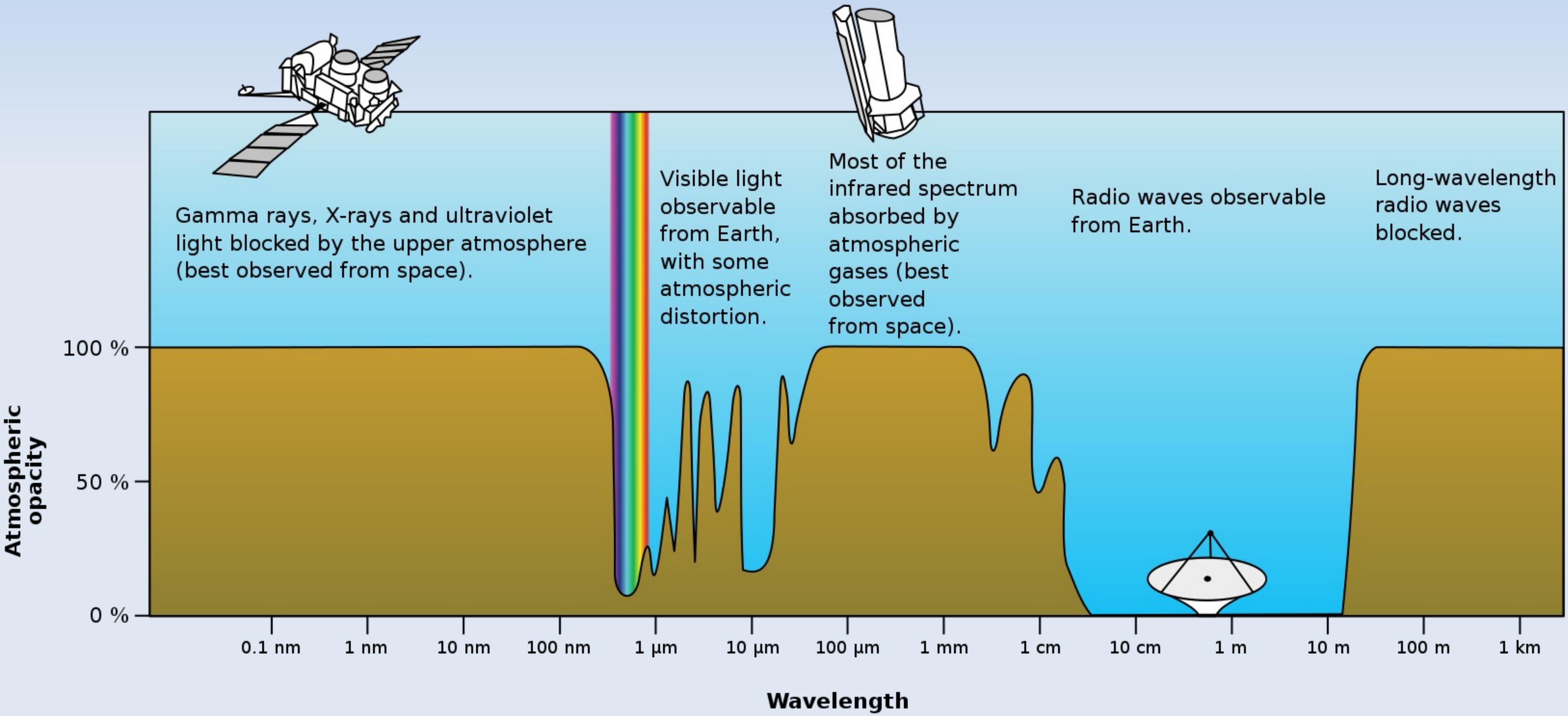


One of the first images from James Webb Telescope

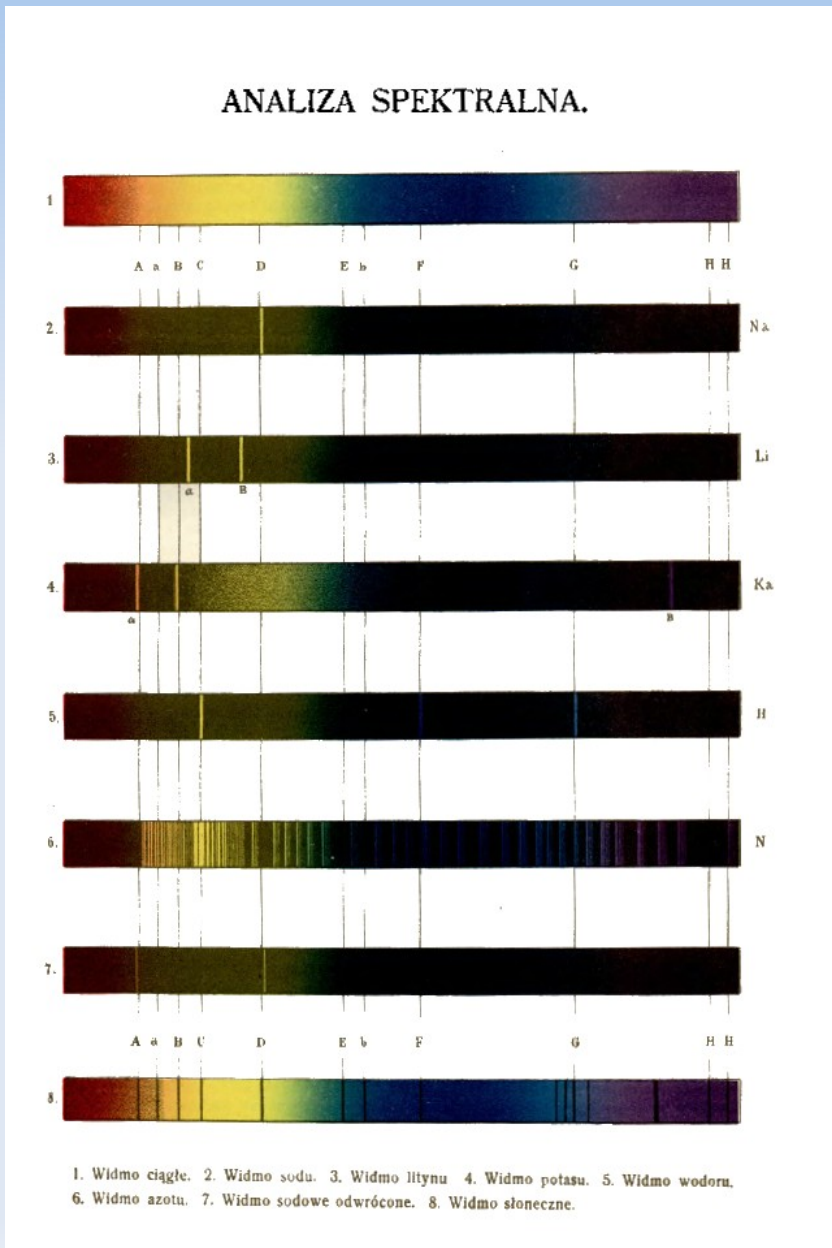
Observations, telescopes

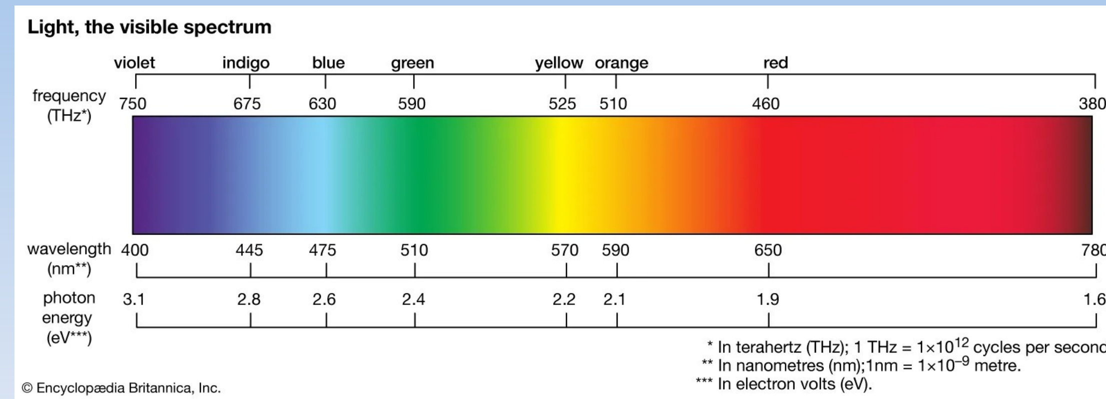


Observations



Spectrometry

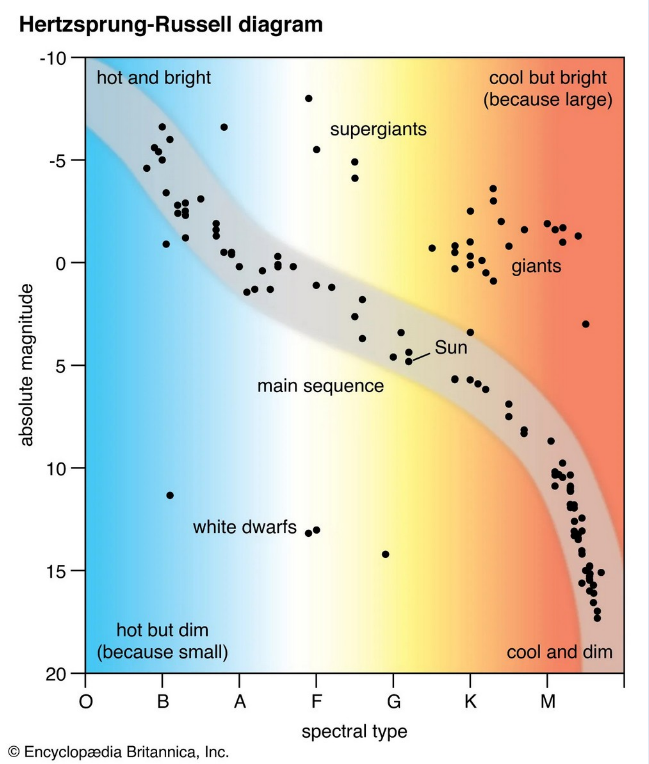




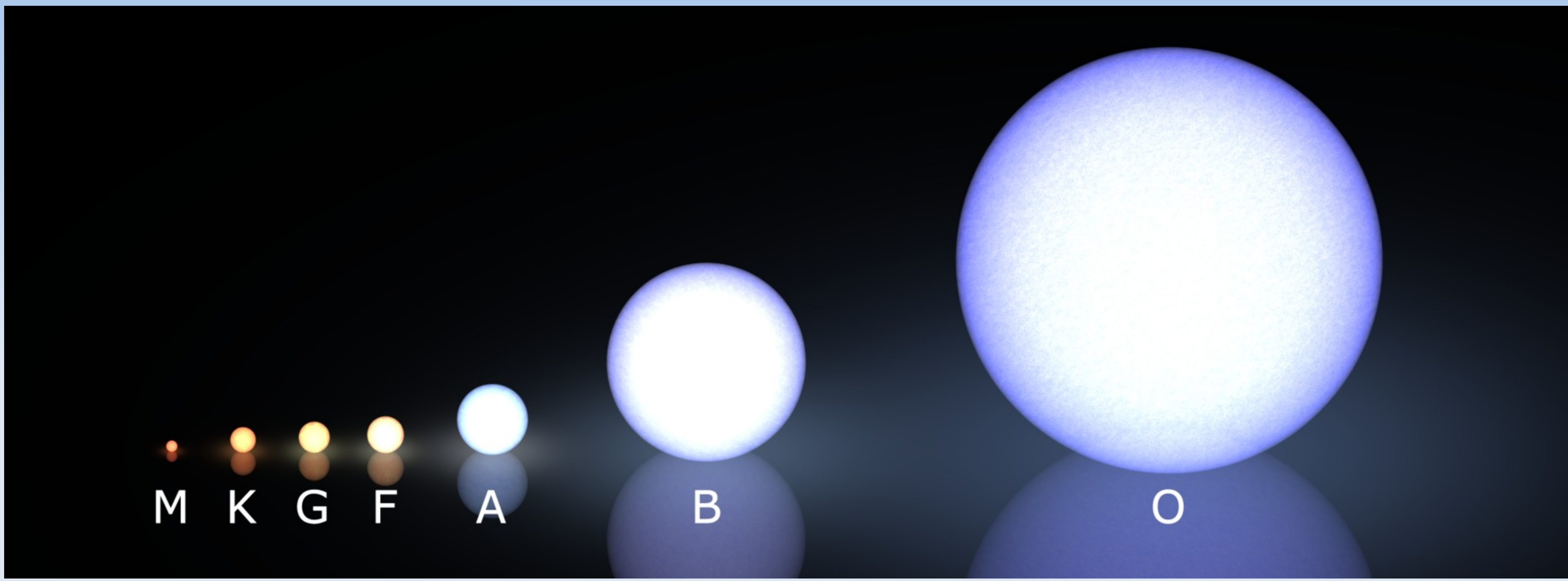
An instrument designed for visual observation of spectra is called a spectroscope, and an instrument that photographs or maps spectra is a spectrograph.

Spectral Classification

- In 1880's, at Harvard Observatory, Charles Pickering and his assistant, Annie J. Cannon, compiled the Henry Draper Catalogue of stars.
- Their spectral types were identified, based on the strength of hydrogen lines, and then rearranged according to the surface temperatures.
- Stars are also classified according to their luminosity class

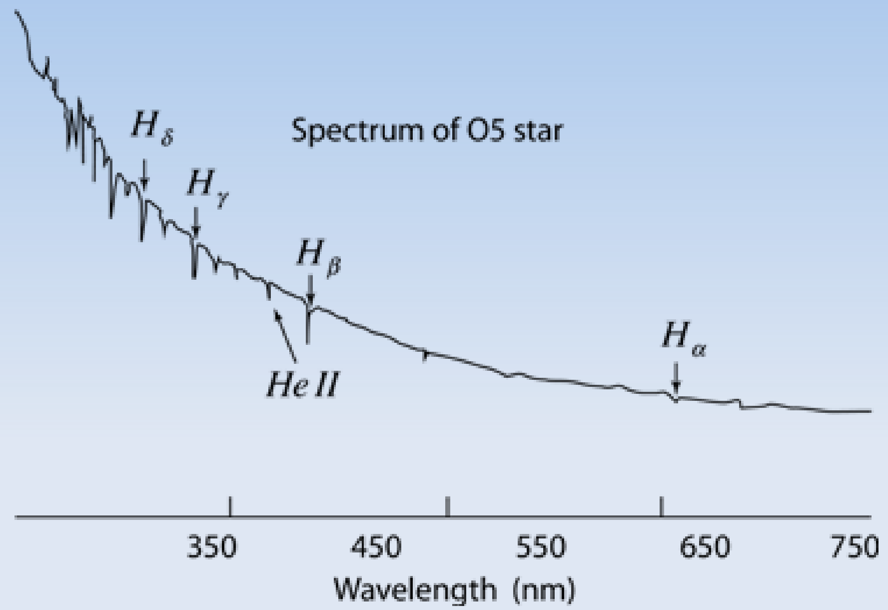


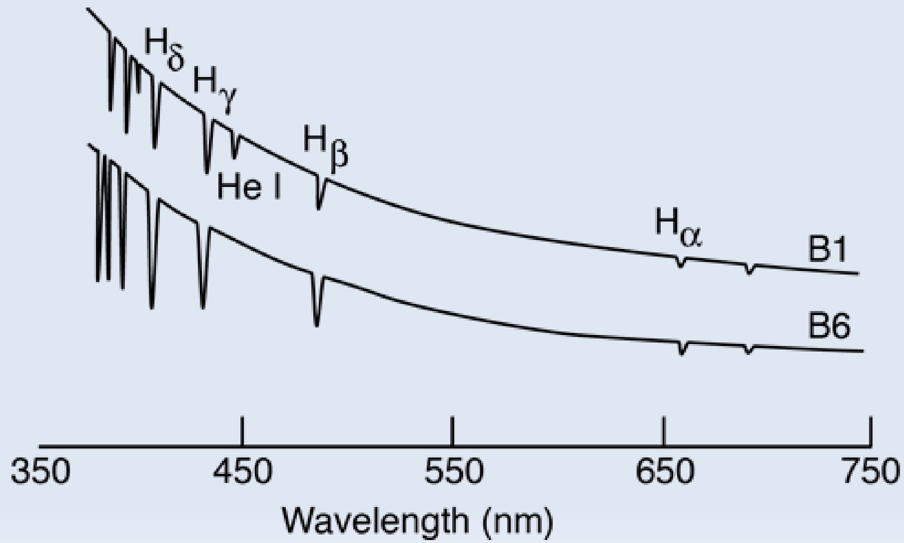
Spectral types of stars

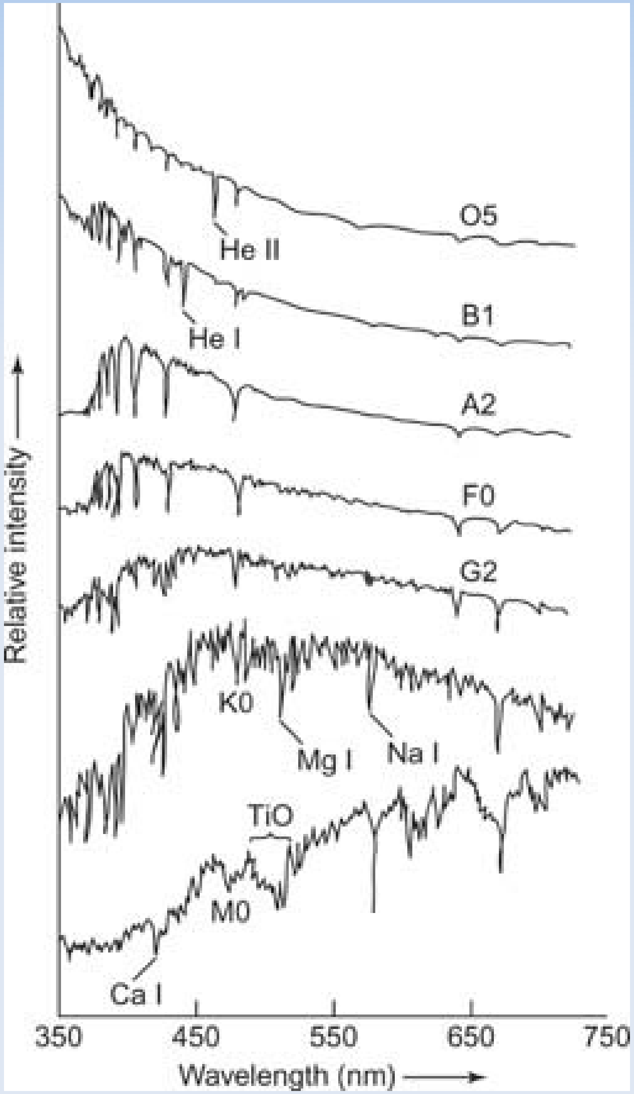


- Spectral type is determined by temperature, pressure and chemical composition
- Spectral lines in different type stars are due to Hydrogen, Helium, metals, and molecules

Spectral types: examples





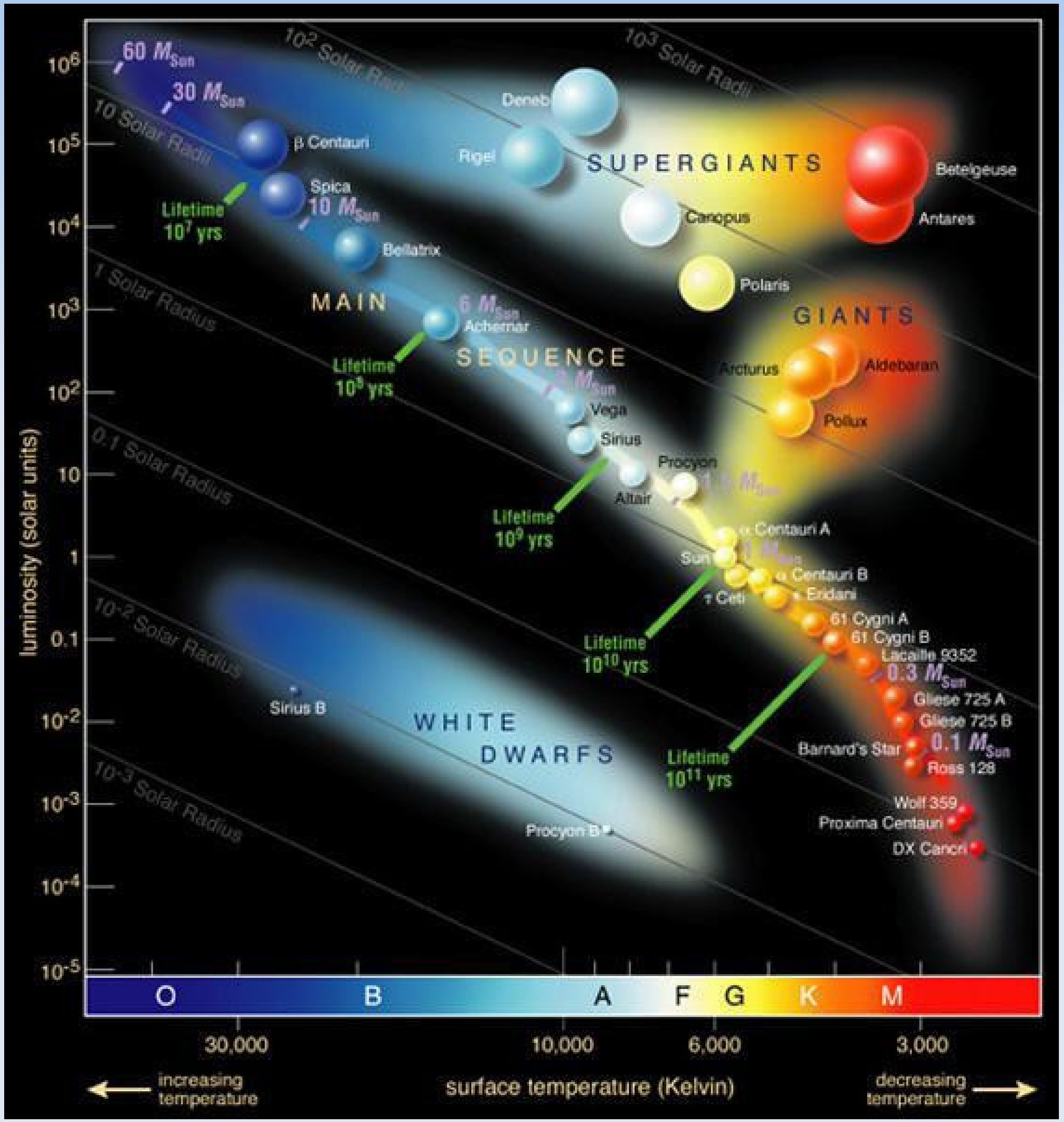


Normal star: Our Sun

- Sun: G2V yellow dwarf, mass=1.98×10^{33} g, M_V=4.83 mag, T_{eff}=5780 K
- Composition: 73% H, 25% He, 2% other: Ca, O, Ne, Fe
- Main sequence star generates energy from nuclear fussion of H atoms to He
- Outward thermal pressure balances gravity
- Luminosity and color (spectral type) determined by star's mass and composition

Stellar masses

- Mass of a single star is impossible to measure
- Mass-Luminosity relation, need to be calibrated
- Binary stars: mass from gravitational interactions

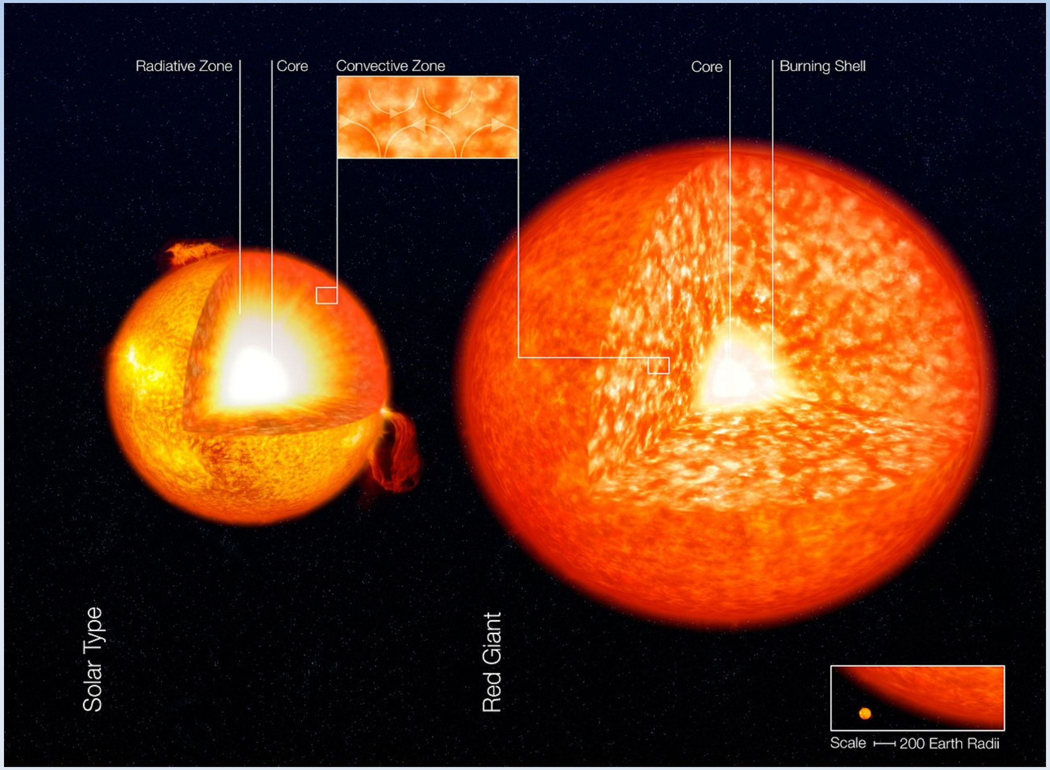


Mass-luminosity relation

- For main sequence stars
- Gravity balanced by pressure, $GM/R^2 \sim P \sim T$
- Luminosity scales with mass, $L \sim M^{\alpha}$
- Empirical relation, $\alpha=4$ for absolute magnitudes $M_{bol}<7.5$, $\alpha=2.8$ for $M_{bol} > 7.5$
- Spectral type of the star depends on temperature and chemical composition. For stars burning Hydrogen in the core, this forms the main sequence on the Herzsprung-Russel diagram

Evolved stars: giants

- Radius and luminosity much larger than Sun, for the same surface temperature
- Core depleted of Hydrogen, and contracted
- H burning in a shell. After He burning, core contraction and convective envelope expansion, more energy is transported to surface.
- Luminosity increases, because of the giant size



Evolutionary tracks

In 1969, BP wrote a computer code that solves differential equations of the static stellar structure:
- radiative temperature gradient, under gray atmosphere approx.
- pressure gradients for gas and radiation
- convective transport

Code solves 4 ODEs for density, temperature, optical thickness, and radius, as a function of mass enclosed in radius r. Boundary conditions are given by stellar mass and effective temperature.

An evolutionary code calculates time derivatives of all quantities, according to their space derivatives and rate of mass flow through the shells.

Our evolutionary calculations were started with homogeneous main sequence models having a metal content $Z = 0.03$, and a hydrogen content $X = 0.70$. The calculations were continued up to the helium flash (owing to the helium + nitrogen reaction) in the core for 0.8 and 1.5 $M_\odot$, and up to carbon ignition for 3, 5, 7, 10, and 15 $M_\odot$. In

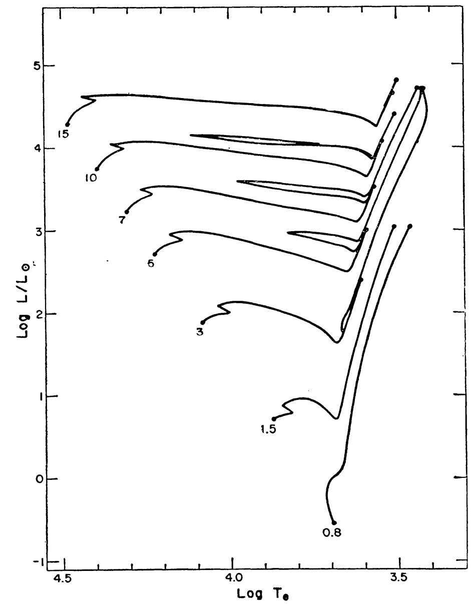
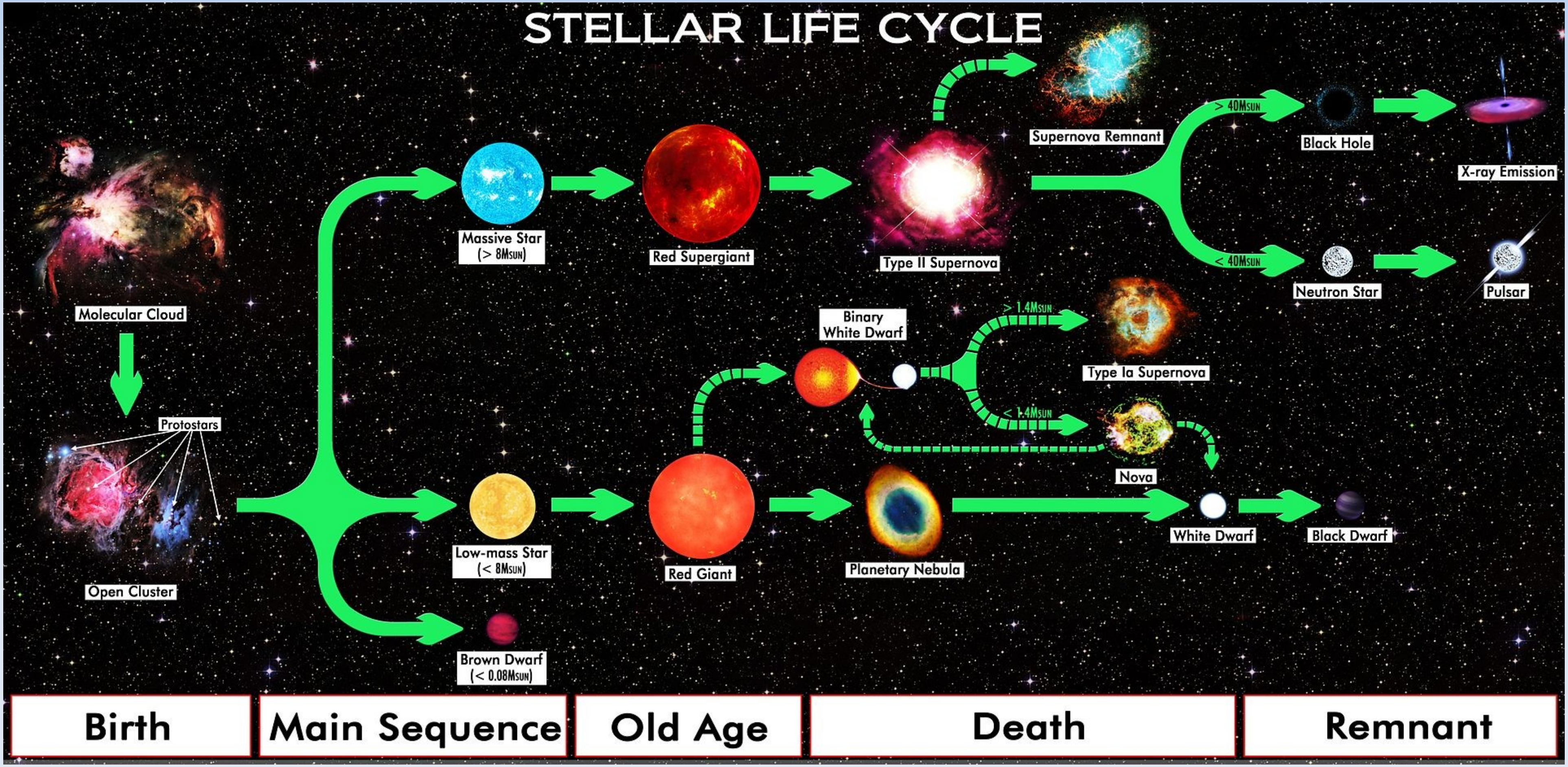


Fig. 1. Evolutionary tracks of Population I ($X = 0.7$, $Z = 0.03$) stars on the H—R diagram. The numbers at the beginning of each track give stellar mass in units of solar mass. Large dots indicate the position of the homogeneous main sequence models and the position of the models at the times of helium and carbon ignition in their cores.

the latter models the helium + nitrogen reaction was neglected. The evolution of those stars on the H—R diagram is shown in Figure 1. Large dots indicate the positions of models on the main sequence, and at the times of helium and carbon ignition. Evolutionary tracks for

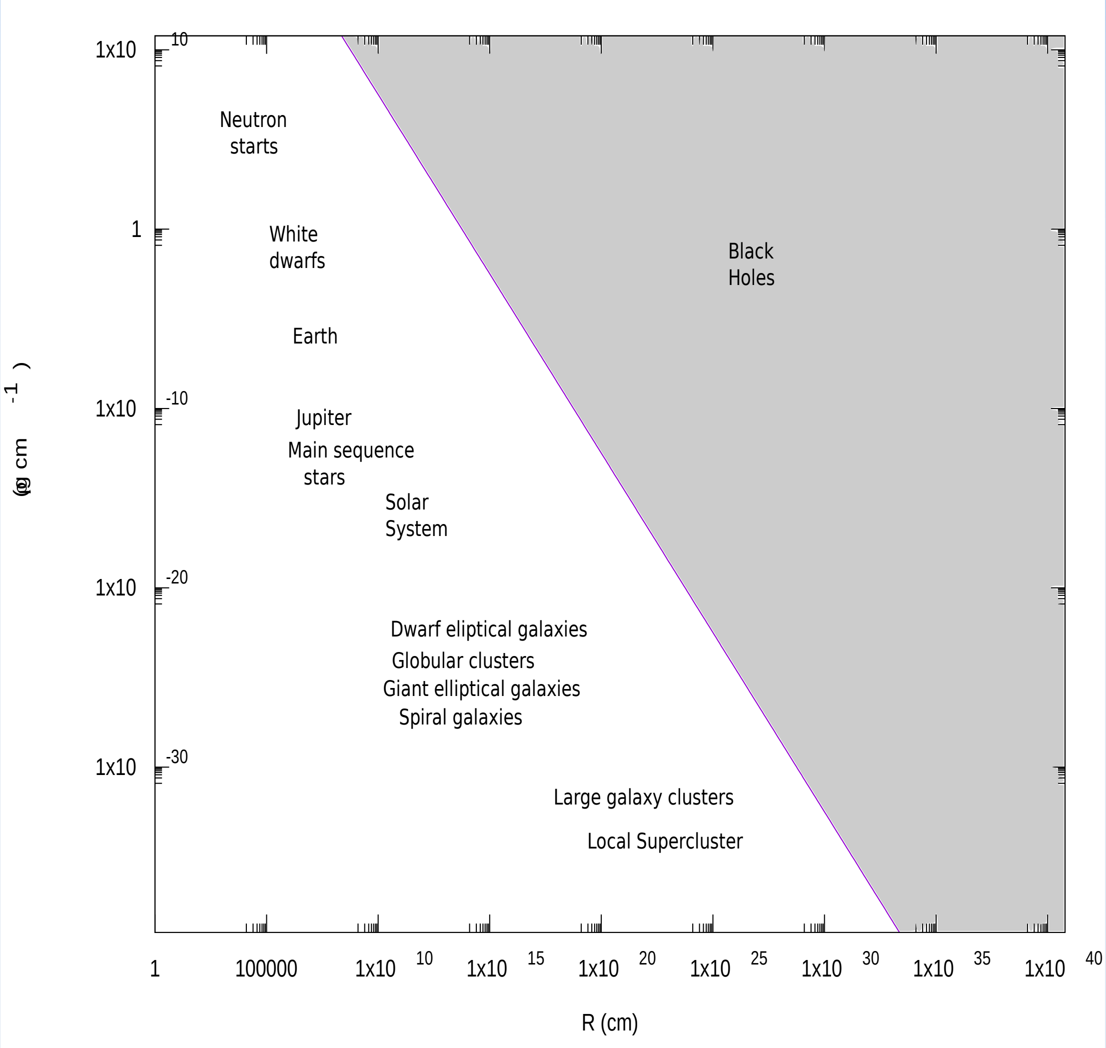
Illustration from B. Paczyński (1970, Acta Astronomica).

End products of stellar evolution



Why the star is unseen?

- Compact star: mass to radius ratio is very large
- Black holes
- Neutron stars
- White dwarfs
- They are final stages of stellar evolution
- Astrophysical BHs have wide range of masses and radii



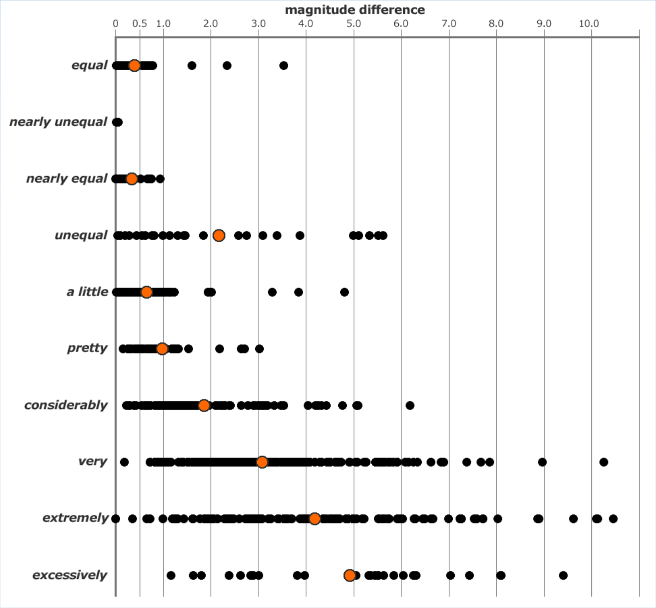
Milestones in history of compact stars

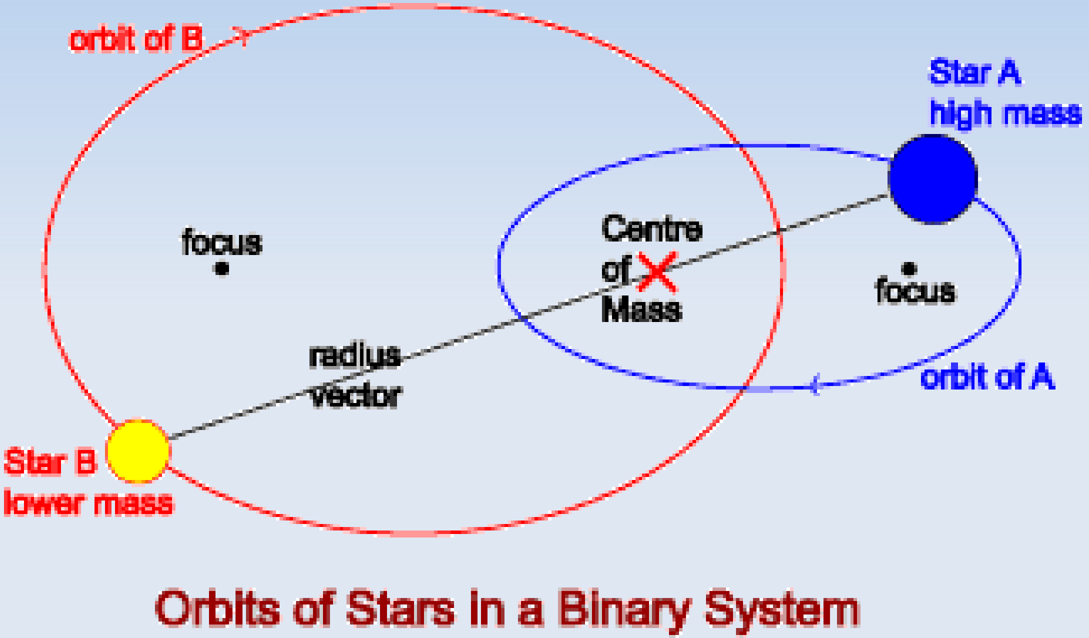
- 1783: discovery of a white dwarf, 40Eri B (W. Hershel)
- 1950’s: discovery of quasars, sources that must contain supermassive black holes
- 1963: beginning of X-ray astronomy (Riccardo Giacconi). Discovery of systems which must contain a compact star component (neutron star or black hole)
- 1967: discovery of pulsars, definite proof of existence of neutron stars
- 2015: discovery of gravitational waves, definite proof of existence of black holes

Break

Binary stars

William Herschel (1738-1822) compiled first catalogue of pairs of stars, with separation of a few arcseconds. The catalogue consisted of over 700 stars



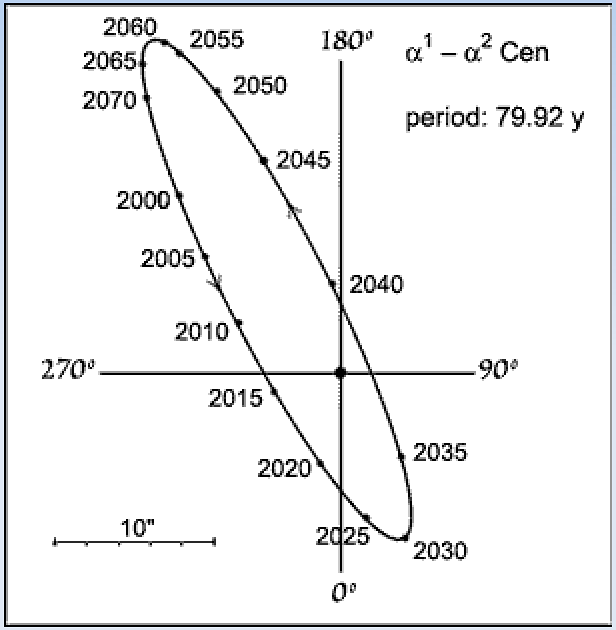


Each of the the two stars in a binary system have an elliptical orbit (can be almost circular in some cases). They share a common focus which is the centre of mass or barycenter of the system and orbit around this point. The radius vector joining the two stars always cuts through the barycenter.

Binary stars

- 50-80% of stars are in binary or multiple systems
- This is caused by the process of star formation
- **Visual binaries:** separation > 0.2 arcsec.
- **Astrometric binaries**: motion of visible star around the center of mass
- **Spectroscopic binaries**: the spectrum of visible star shows periodic blueshifts and redshifts from Doppler effect
- **Eclipsing binaries:** periodic variations of intensity due to star's eclipses

Visual binaries



α Centauri, 1.338 pc distant is in fact a visual binary with the two stars labelled α Cen A (*Rigil*)

and α Cen B (*Toliman*)

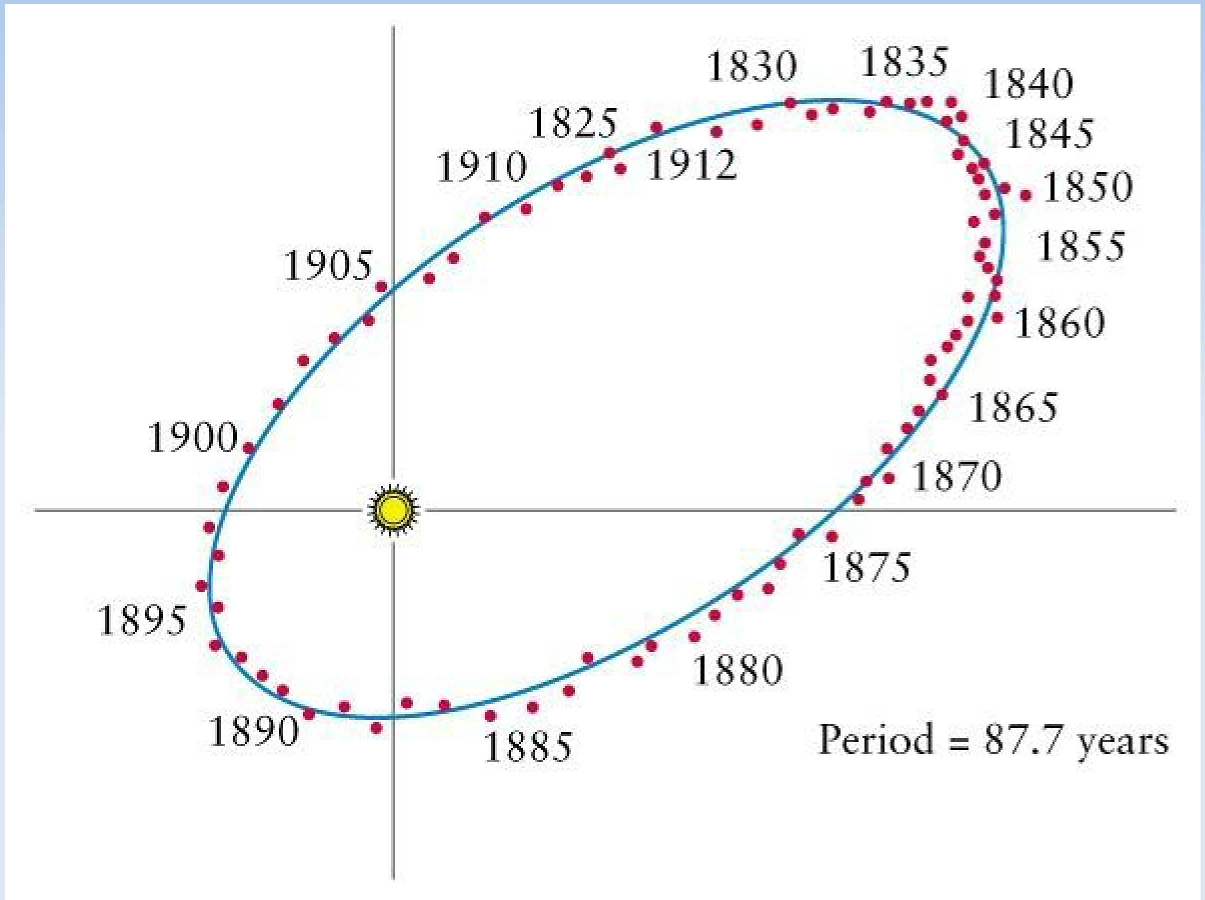
separated by a distance of about 23 Astronomical Units.

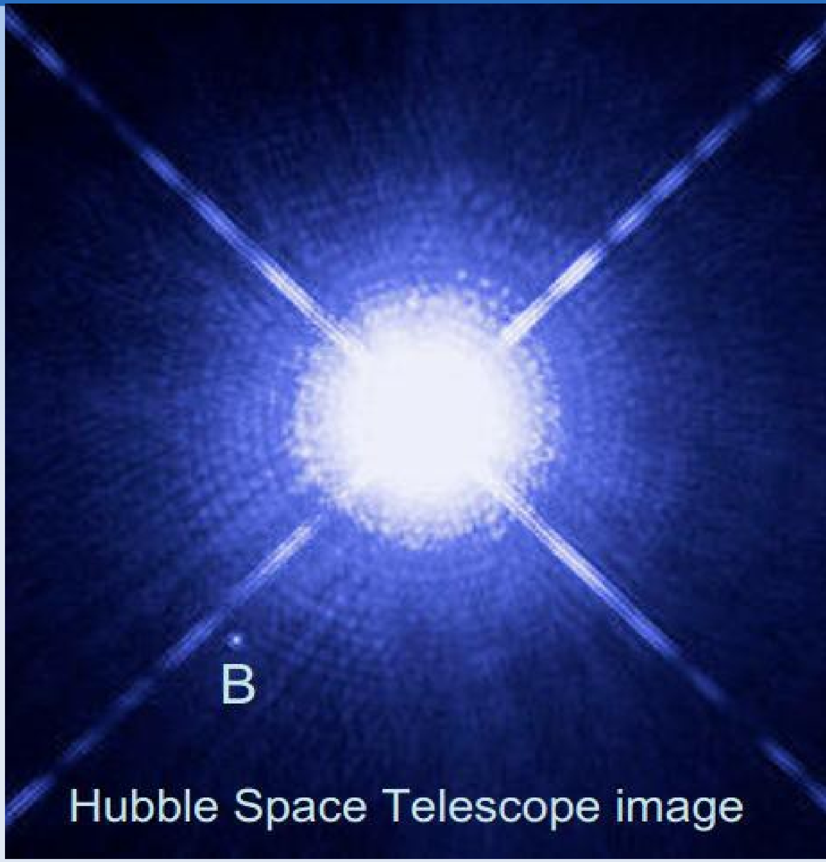
A third star, *Proxima Cen*, currently the closest star to us at a distance of 4.22 ly or 1.295 pc is also called α Cen C.

For many years since its discovery in 1915 it was thought to be a third member of the system at a much greater distance from the system's centre of mass.

Recent observations, however, suggest it may not be gravitationally bound to the other two.

Visual binaries





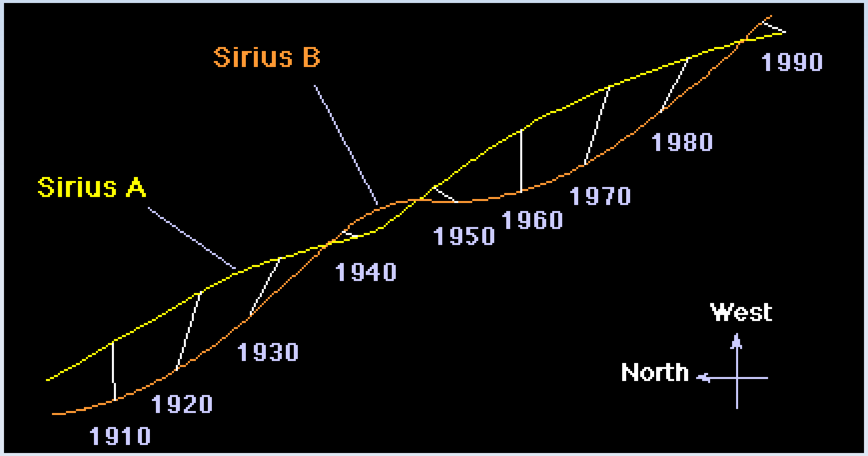
- 70 Oph: visual binary
- Sirius: astrometric binary, until HST

Astrometric binaries

Stars show a perturbation or "wobble" in proper motion. From the periodicity we can infer that the perturbation occurs due to the gravitational influence of an unseen companion.

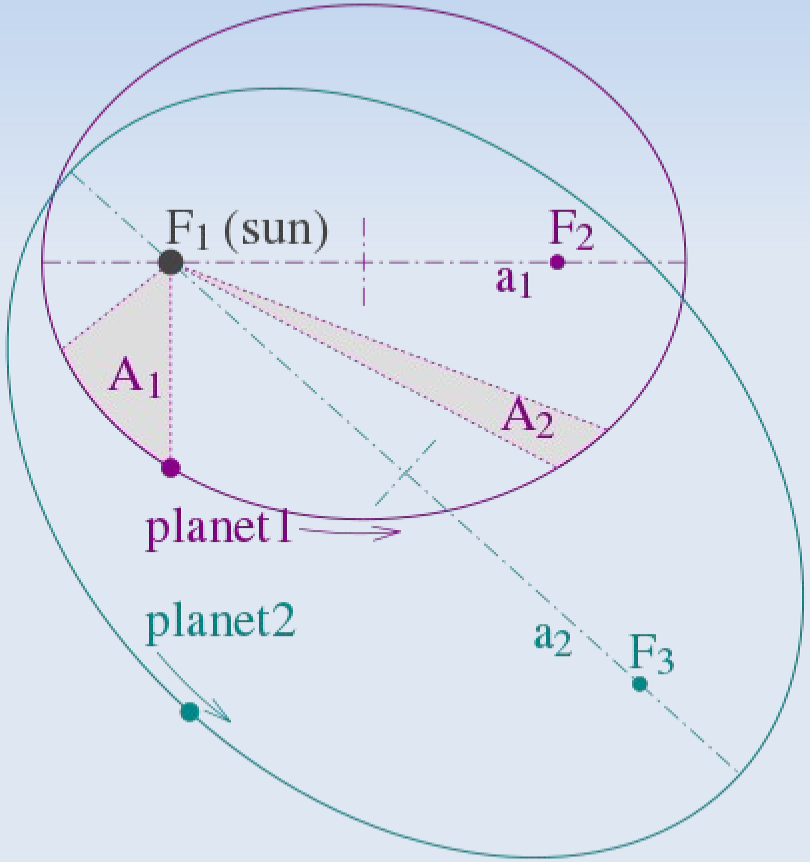
We have a system in which a visible star and a dimmer companion orbit a common centre of mass.

Binary systems detected by such astrometric means are called astrometric binaries.



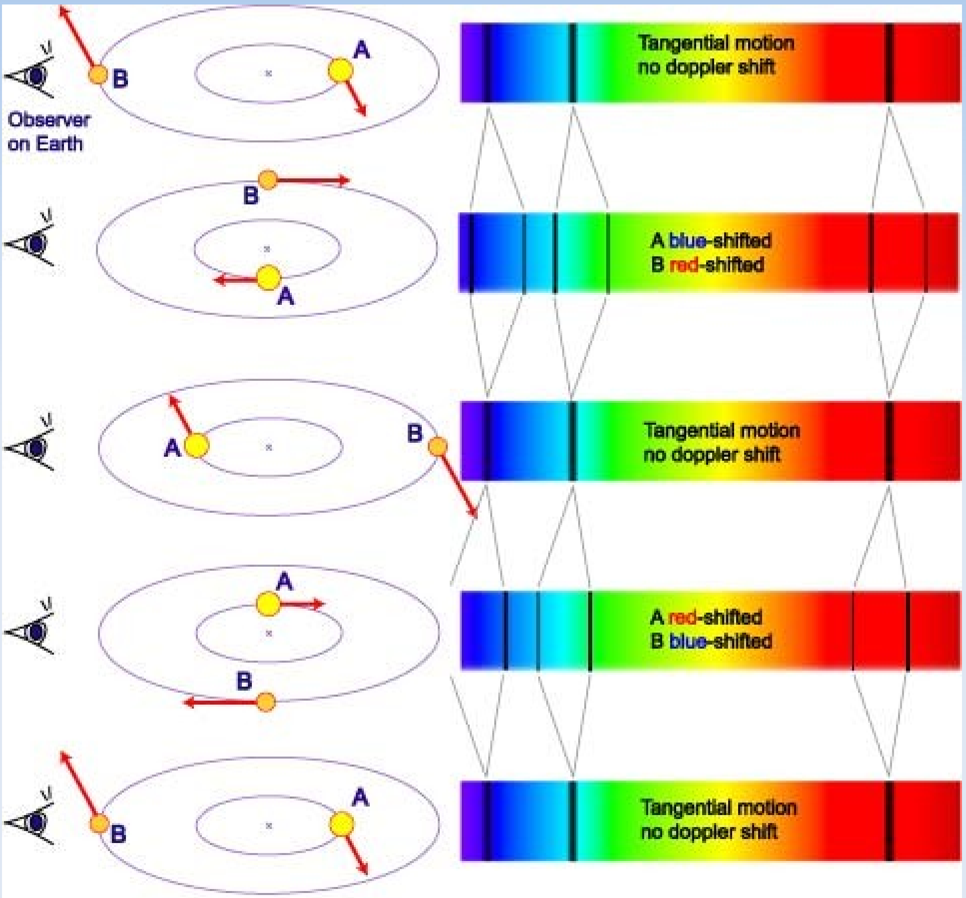
Kepler's laws

- Isolated system of two massive bodies
- Empirical laws, understood later in the frame of Newton's gravity theory
- Constants of motion: position and velocity of the center of mass, angular momentum vector, energy.
- Orbit: perihelion angular distance, time at perihelion



$$\frac{a^3}{P^2} = \frac{G(m_1 + m_2)}{4\pi^2} \qquad r = \frac{p}{1 + e\cos(\phi - \omega)}$$

Spectroscopic binaries

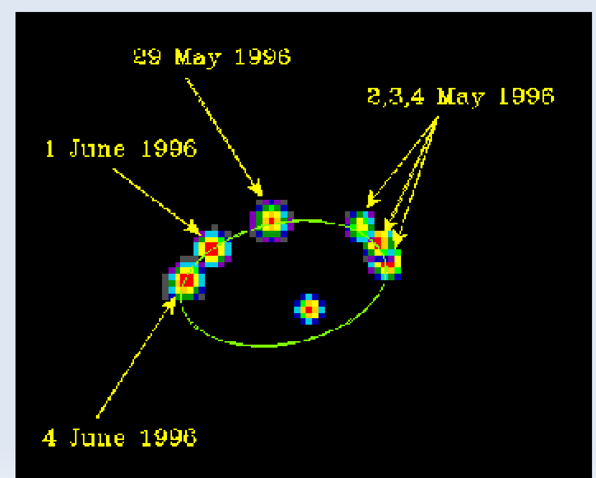


A Spectroscopic Binary System
High-mass star A and lower-mass B orbit around a common centre of mass. The observed combined spectrum shows periodic splitting and shifting of spectral lines. The amount of shift is a function of the alignment of the system relative to us and the orbital speed of the stars.

The majority of binary systems have been detected by Doppler shifts in their spectral lines. Such systems are called spectroscopic binaries.

The spectrum obtained from the system will actually be a combination of the spectra from each of the component stars.

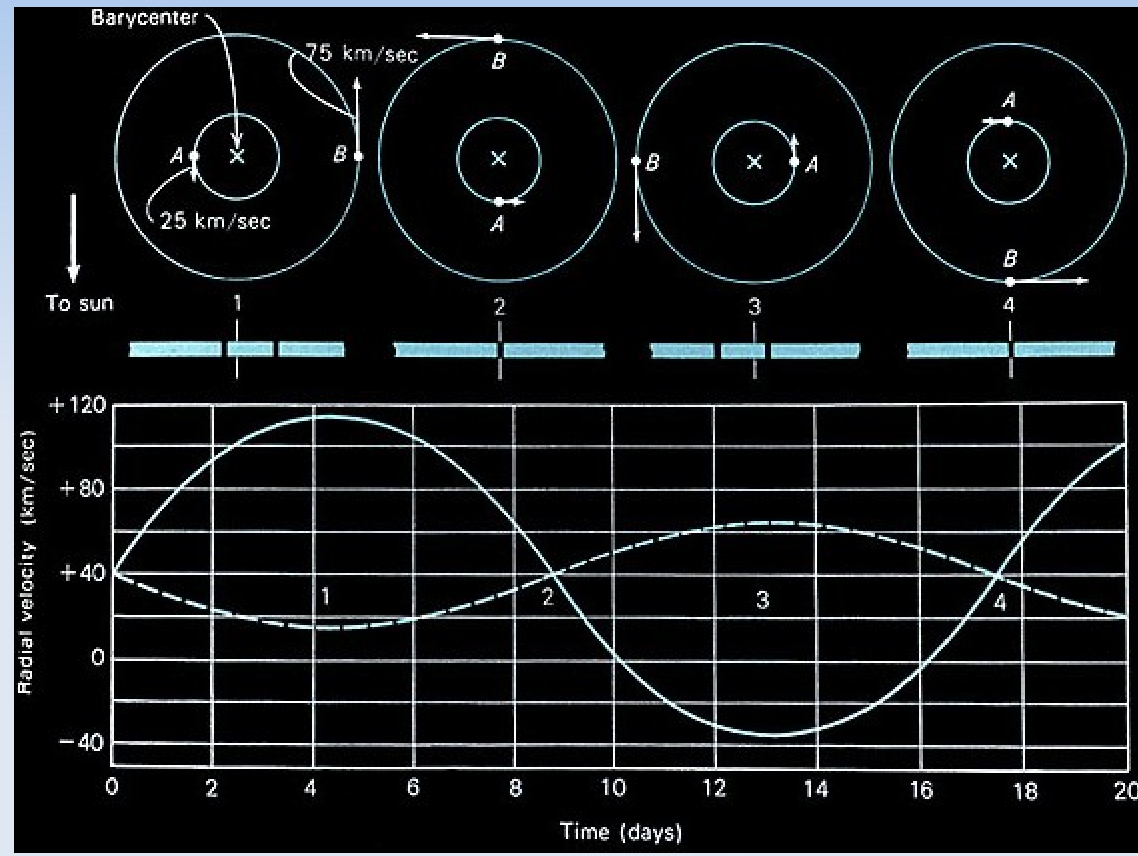
Analysis of the spectral line shifts versus time reveals information about the radial velocities of the component stars.

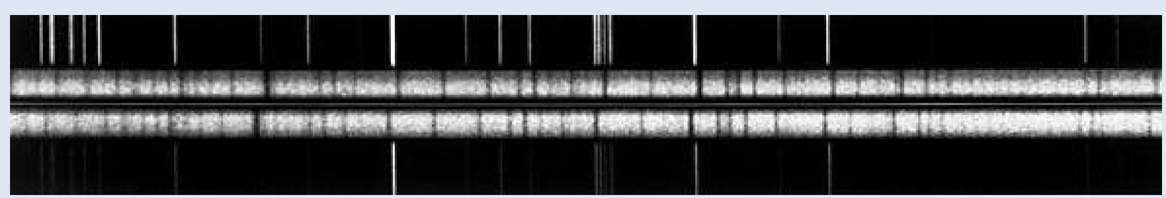


Mizar system

Spectroscopic binaries

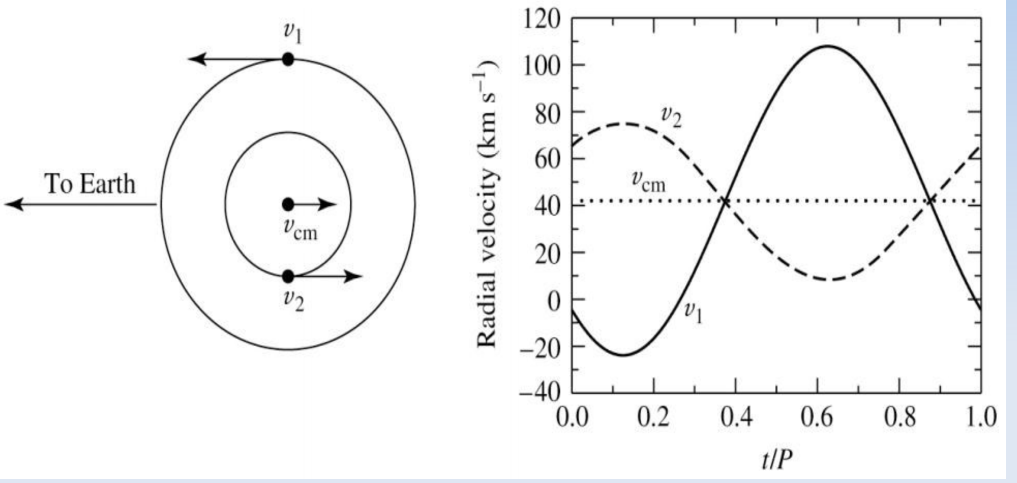
- Periods about hours-months. Separations may be smaller than 1 AU
- Detected spectra from 1 or 2 stars
- Radial velocity curves for inclined orbits
- Velocities are known if the inclination is known

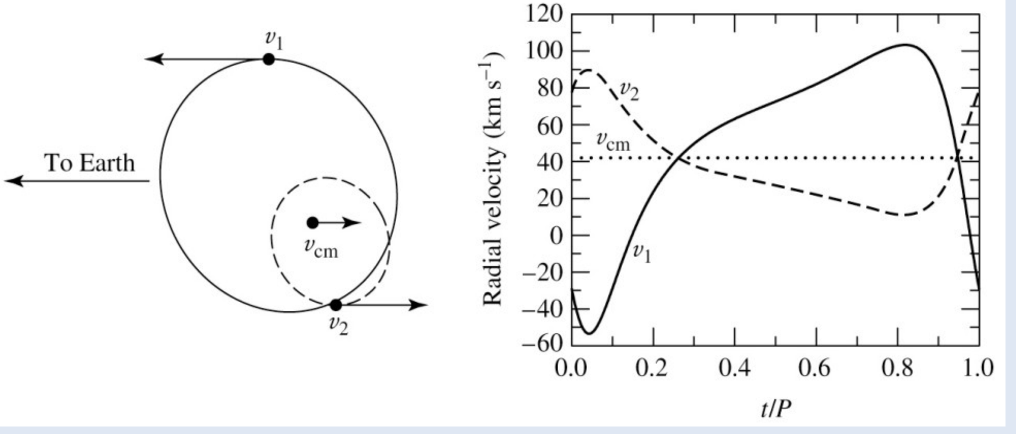




Spectroscopic binaries

- Orbit eccentricity affects radial velocity curve
- Semi-major axes: relative to the center of mass
- Semi-amplitude of radial velocity depends on P, a, e, sin(i)





Dynamical mass determination

- From Kepler's third law

$$\frac{(a_1+a_2)^3}{P^2}=\frac{G}{4\pi^2}(m_1+m_2)$$

- And from radial velocities

$$G(m_1+m_2)=\frac{P}{2\pi}\left(\frac{v_1+v_2}{\sin i}\right)^3$$

Mass function

- Determined observationally if we have one radial velocity. Mass function (units of mass):

$$f(m) = v_1^3 \frac{P}{2\pi G}(1-e)^{3/2} = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$

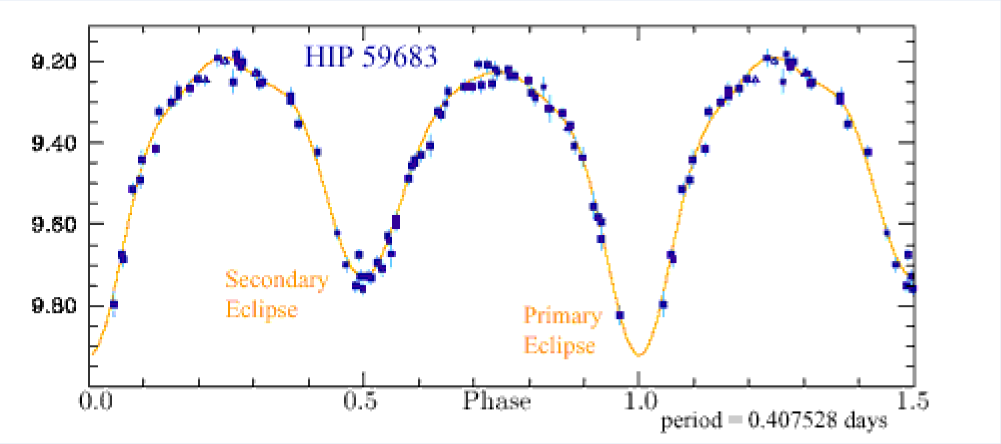
- We can estimate the mass ratio, knowing the orbital inclination
- We can have a lower limit for the m_2, mass of the unseen companion, if we know m_1

Eclipsing binaries

Many stars show a periodic change in their apparent magnitude.

It could be a single star that undergoes a change in its intrinsic luminosity. Such stars are called pulsating variables.

The second possibility is that it is in fact a binary system in which the orbital plane lies edge-on to us so that the component stars periodically eclipse one another. These systems are called eclipsing binaries.



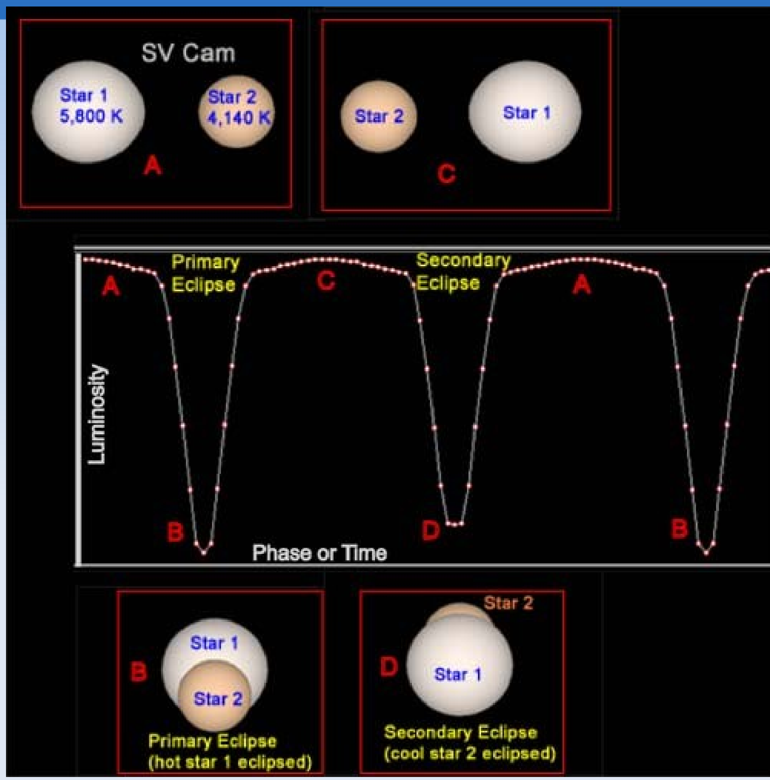
Folded light curve from the Hipparcos database.

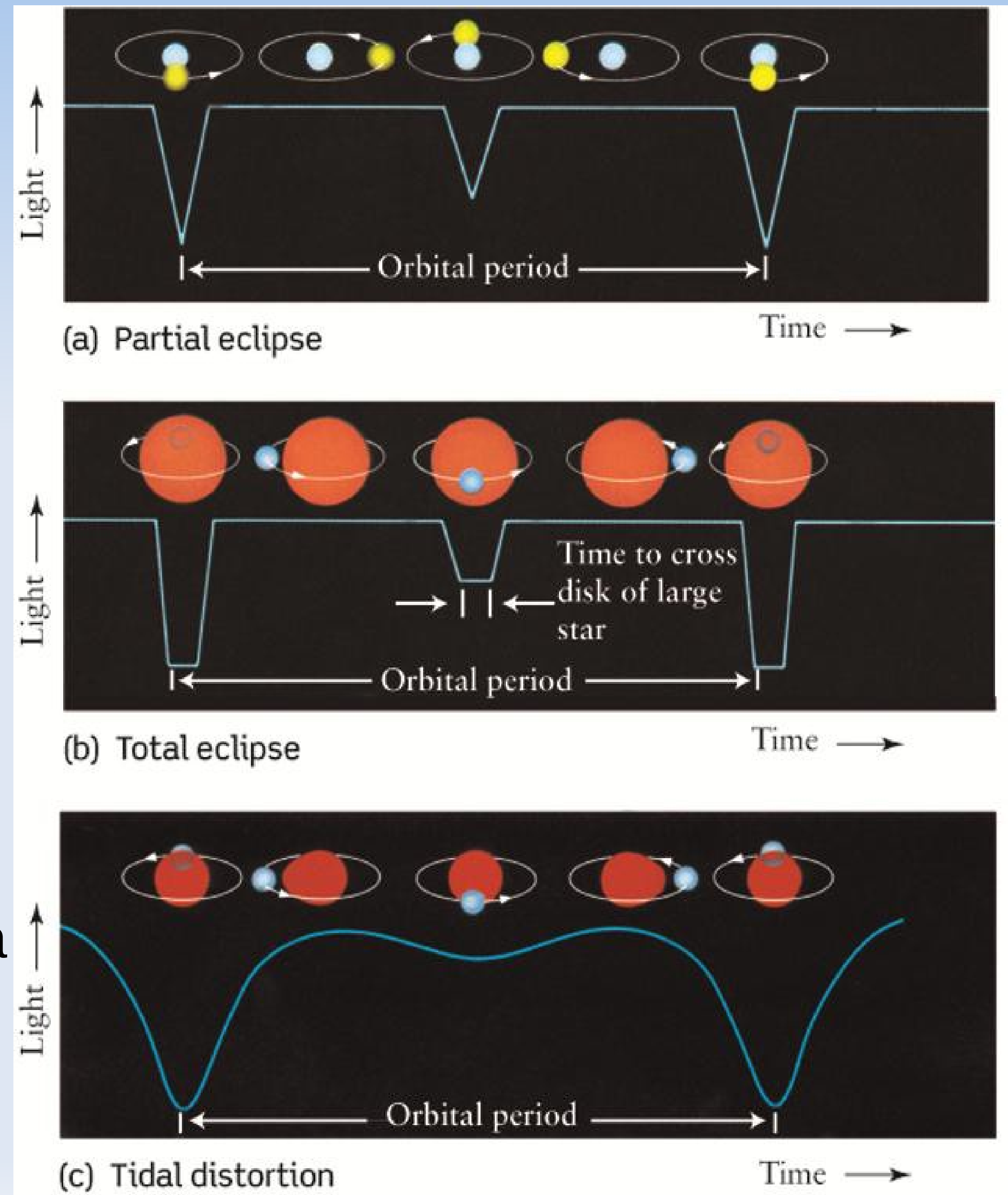
Phase is shown on x-axis, instead of period

The periods of most eclipsing binaries are a few hours or days.

There are a few thousand such systems known, most of which are also spectroscopic binaries. A few are also visual binaries. The first eclipsing binary detected was Algol, β Perseus, also known as the Demon star

Eclipses seen in the lightcurves





Secondary effects:

- Orbit eccentricity - unequal times of primary and secondary minima
- Distortions from spherical shape
- Reflection of radiation

Effective temperatures of stars

- In eclipse of deeper minimum, the brighter star is eclipsed
- We assume that brighter star is larger: primary eclipse is a transit type and secondary is an occultation type
- Ratio of primary and secondary minima gives the ratio of effective temperatures

$$\frac{F_{max}-F_p}{F_{max}-F_s}=\frac{\pi R_2^2 \frac{J_1}{d^2}}{\pi R_2^2 \frac{J_2^2}{d^2}}=\left(\frac{T_{eff,1}}{T_{eff,2}}\right)^4$$

Determination of radii

- Radii of the stars can be determined from eclipses (from times of the secondary star ingress and egress)

$$2R_1 + 2R_2 = 2\frac{\pi}{P} a \Delta T \qquad 2R_1 - 2R_2 = 2\frac{\pi}{P} a \delta t$$

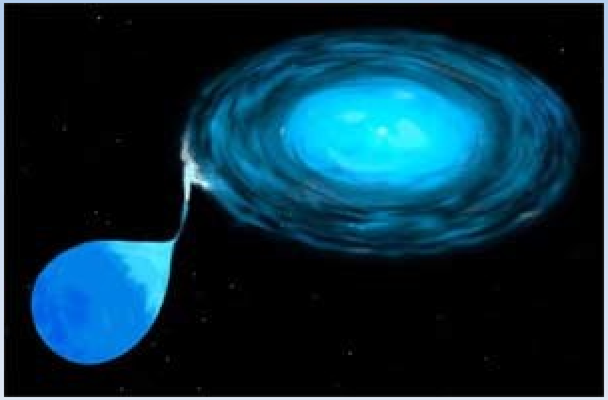
- With radial velocity curves, we can determine the masses

$$\frac{m_1}{m_2} = \frac{a_2}{a_1} = \frac{v_{2r}}{v_{1r}}$$

Summary: what we have fom binary stars observations

- Visual binaries: semi-major axis *a*, eccentricity *e*, inclination *i*
- Eclipsing binaries: radii R_1, R_2, luminosity ratio L_1/L_2 , *i*, *e*
- Spectroscopic binaries:
- single-lined give $a_1 \sin(i)$, *e*, *f(m)*;
- double-lined give $m_1 \sin^3(i)$, $m_2 \sin^3(i)$, $a_1 \sin(i)$, $a_2 \sin(i)$, *e*
- If both eclipsing and spectroscopic, then we have masses and radii

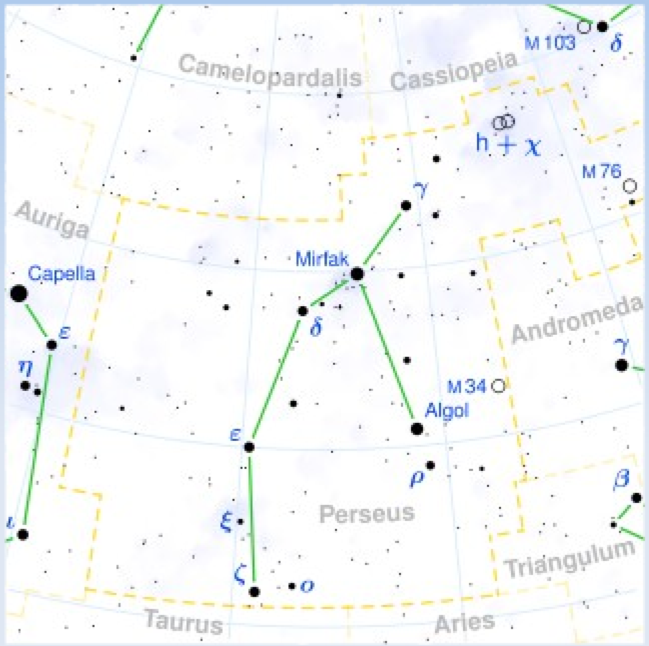
Compact binaries



- Massive stars must radiate more energy, so they burn hydrogen quickly and evolve away from the main sequence
- Algol paradox: in these binaries, the more evolved star is less massive (i.e. a subgiant, m_1~ 0.8 M_{sun}). The companion is still a main sequence star (m_2~3.7 M_{sun})
- Some compact binaries have very short periods, P~2 hrs. Orbital separation must be very small

Algol system

- First known eclipsing binary, ”Deamon’s head”
- Beta-Persei. Variable star discovered in 17th century.
- Spectroscopic binary, P=2d 20 hrs
- Although components of a binary star formed at the same time, the more massive component Algol A is still in MS, but the less massive Algol B is a subgiant, a later evolutionary stage



Interacting binaries

- The paradox may be solved by the mass transfer between the binary components
- Interactions between the stars might also be due to tidal effects or due to irradiation
- Some binaries might have gone thorugh the phase of common envelope (contact binaries)

Next week

- More about stellar evolution and compact object formation
- Interacting binaries
- Contact binaries, mass transfer

Suggested literature and textbooks

S. Shapiro. S. Teukolsky, ”Black Holes, White Dwarfs, and Neutron Stars”, Wiley

J. Frank, A. King, D. Raine, ”Accretion Power in Astrophysics”, Cambridge

M. Demiański, ”Astrofizyka Relatywistyczna”, PWN