Astrophysics and Nuclear Astrophysics

(LPHY2263)

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Basic info for this course

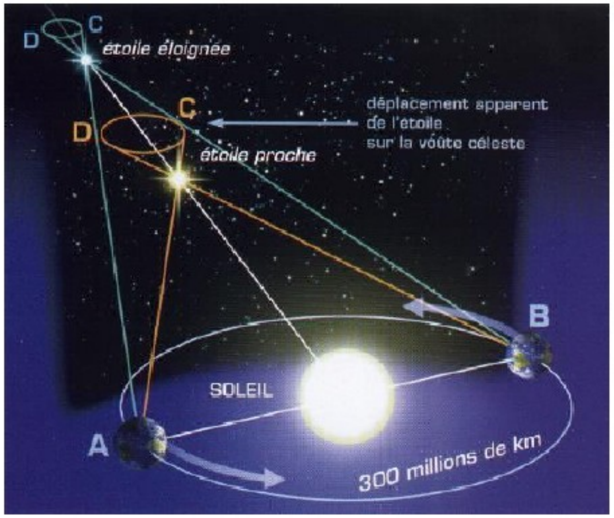
- Spoken language: as this is an International Master, you can choose between French and English
  - Anyway, all my slides will be in English, and I will recommend some articles and books in English
- You will be evaluated by an oral exam and a project
- Webpage: http://cern.ch/andrea.giammanco/astro
  - You will find all slides, plus some more material
  - It also contains the agenda of this course
- Please give me your e-mail addresses
- I am available for private meetings on Wednesdays, 9-12 am, or immediately after each lesson

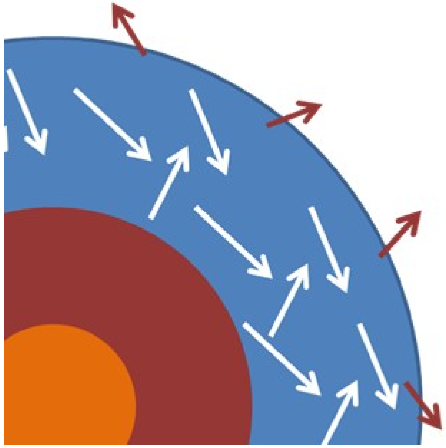
Getting to know each other

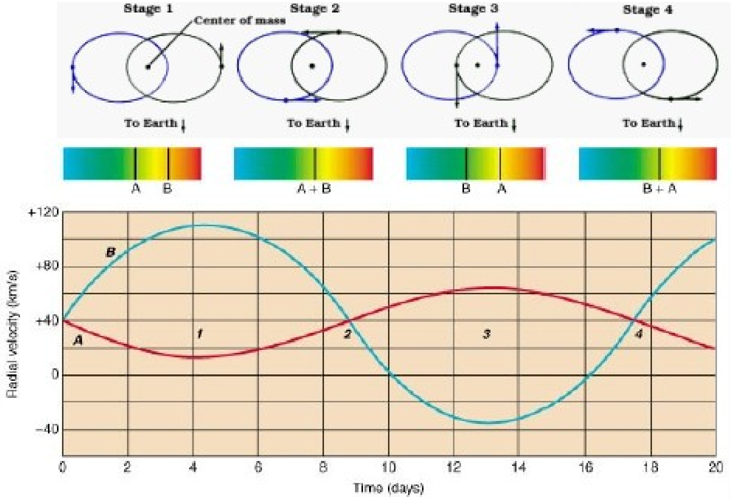
- **Who am I?**
  - FNRS researcher since 2007, at UCL since 2005
  - My research:
    - Master studies focused on Nuclear Physics
    - Since then, always in Particle Physics
    - ALEPH (1999-2003) and CMS (2003-...) experiments at CERN
  - This is the second time I teach this course
  - I also organize the seminars of particle physics and cosmology, every Wednesday between 1 and 2 pm
    - Some seminars might be of your interest
- **Who are you?**
  - What is your specialization?
  - How well do you think you know Quantum Mechanics? Hydrodynamics? Thermodynamics?

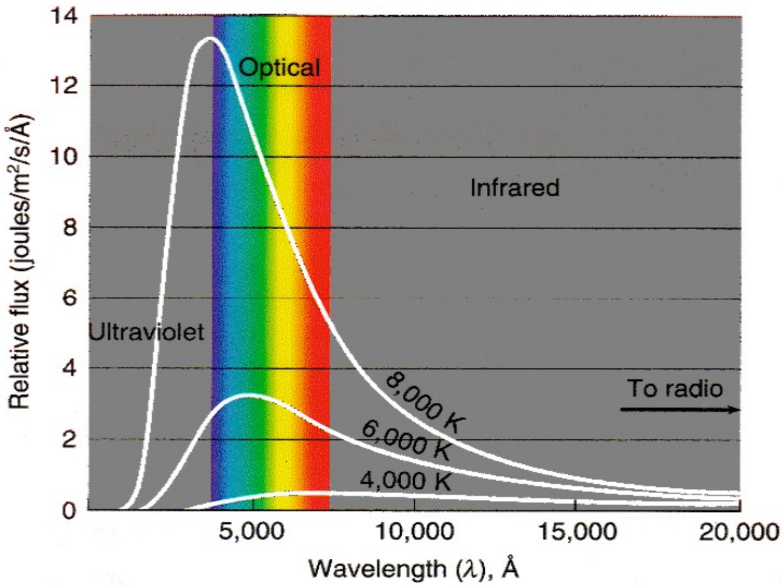
Chapter #1

- How to measure:
  - Distances
  - Luminosity
  - Temperature
  - Mass
  - Radius



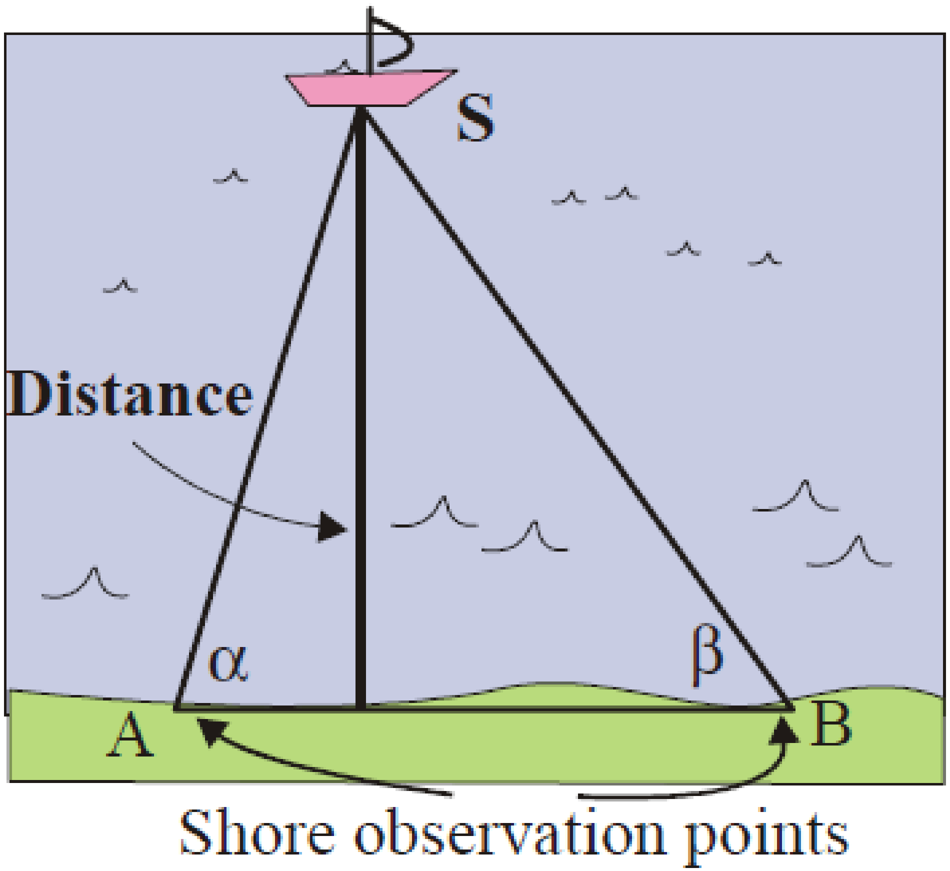






Distances

- Triangulation method (Thales, year ~600 B.C.)



Picture from
http://www.math.tamu.edu/~dallen/masters/Greek/thales.pdf

Exercise #1

- You are Posidonius in the III century B.C. and you want to measure the Earth radius, knowing that:
  - Constellation Draco passes through the zenith of Lysimachia in Thrace, constellation Cancer passes through the zenith of Syene in Egypt
  - The two constellations are δ=24º apart
  - Lysimachia and Syene are 20,000 stadia apart
  - (1 stadium = 0.185 km, source: click here)
  - *Note: all those numbers were later found to be wrong by large amounts, but anyway Posidonius just wanted to make the point that the Earth is not flat*

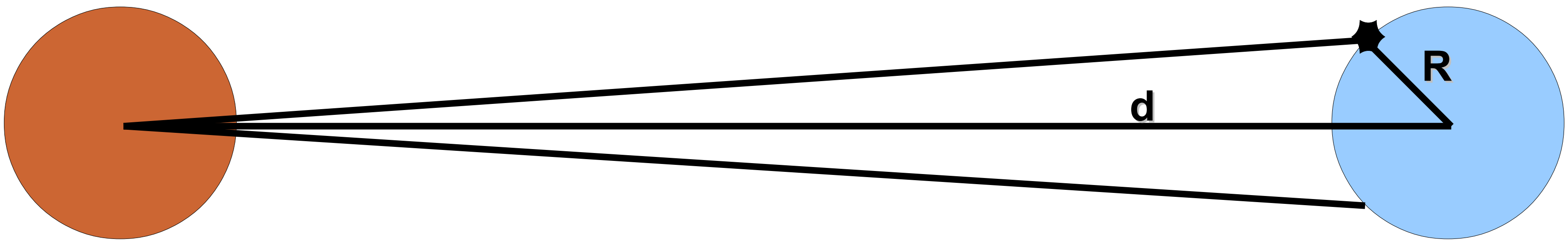
Parallax

- When you hold out a finger and view it only with your left eye, then with your right eye, your finger seems to shift relative to the distant background. This is the phenomenon of parallax.

Very nice examples here:
http://www.eaae-astronomy.org/WG3-SS/WorkShops/Triangulation.html

Earth-Mars distance

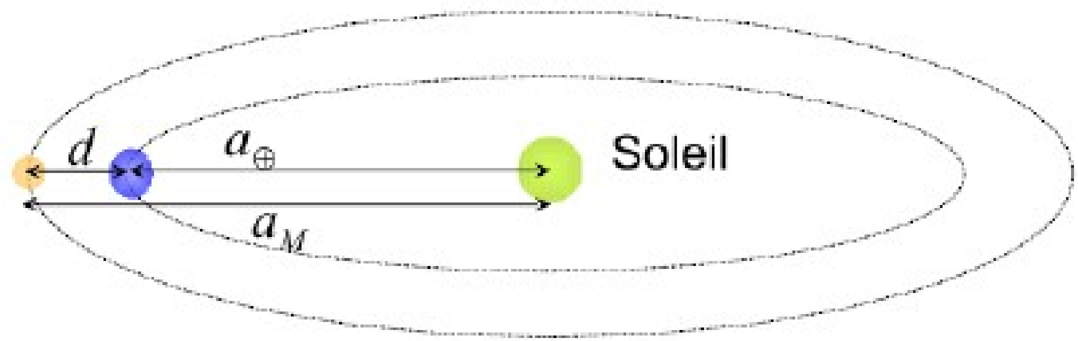
- Classical methods based on parallax:
  - Simultaneous measurement from two locations
  - Two measurements in different times from the same location (method of "diurnal parallax")
- *(Nowadays most precise method is by radar echo)*



Recommended reading:
http://www.mccarthyobservatory.org/pdfs/pm020102.pdf
http://sites.apam.columbia.edu/courses/ap1601y/PhysToday-2011-Kepler.pdf

Earth-Sun distance

- Kepler's third law: T^2/R^3 is a constant of the system
- Take Earth-Mars distance from previous method



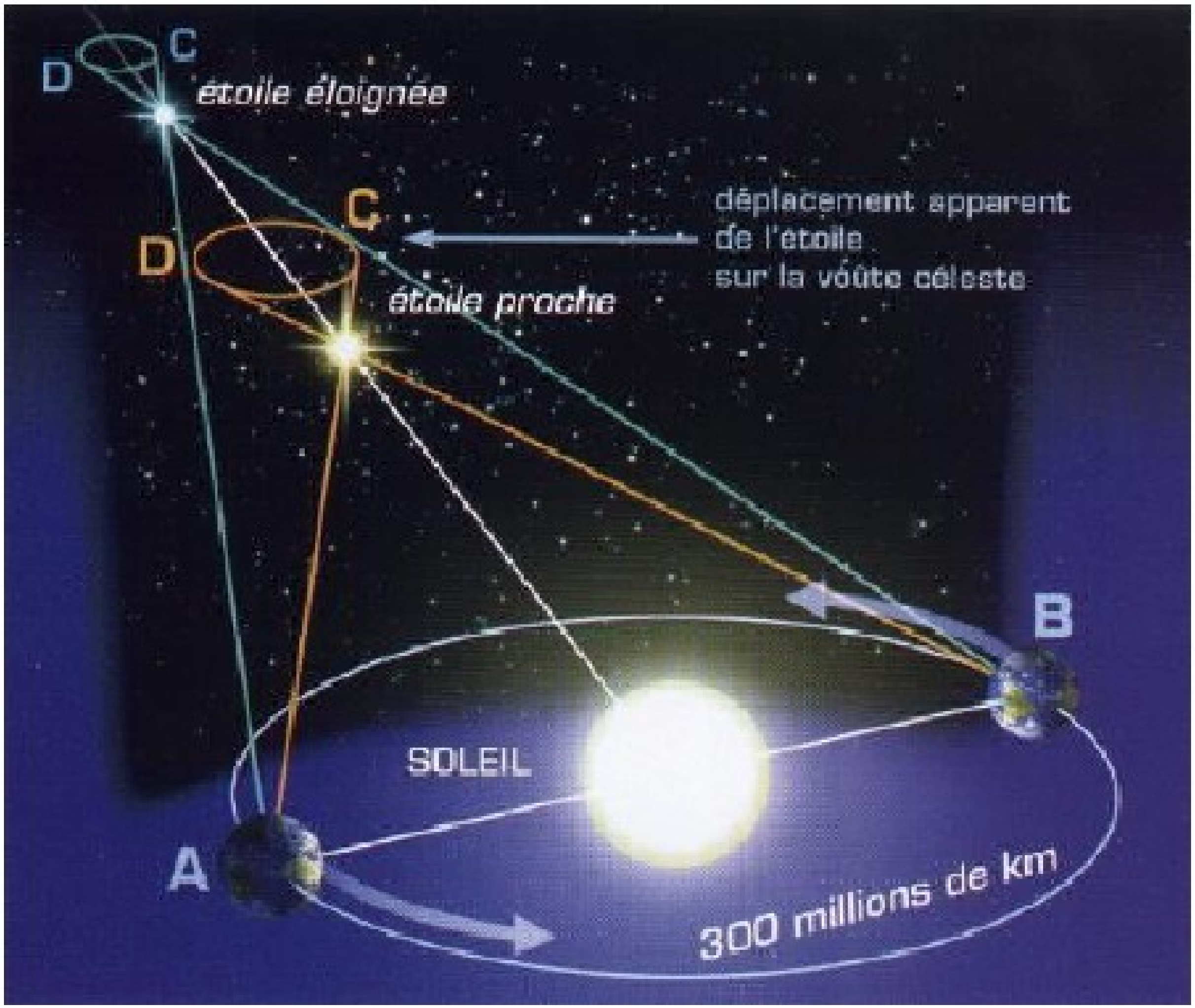
$$\Rightarrow \quad (T_M/T_T)^2 = \{(d + a_\oplus)/ a_\oplus\}^3$$

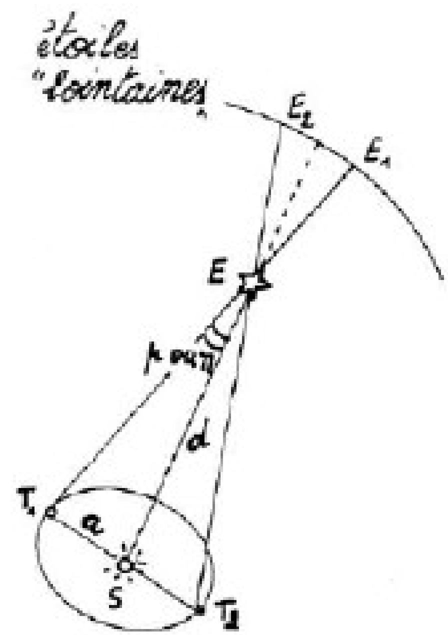
T_T = 1 year (by definition)
T_M = 1.88 years
d = 53 x 10^6 km

$\Rightarrow a_\oplus = 1$ UA = 150 10^6 km

Astronomic Unit is defined as the average Earth-Sun distance

Annual parallax





a = 1UA ; E_1 = position observée de l'étoile E quand la Terre est en T_1 ; E_2 = la même chose, six mois plus tard.

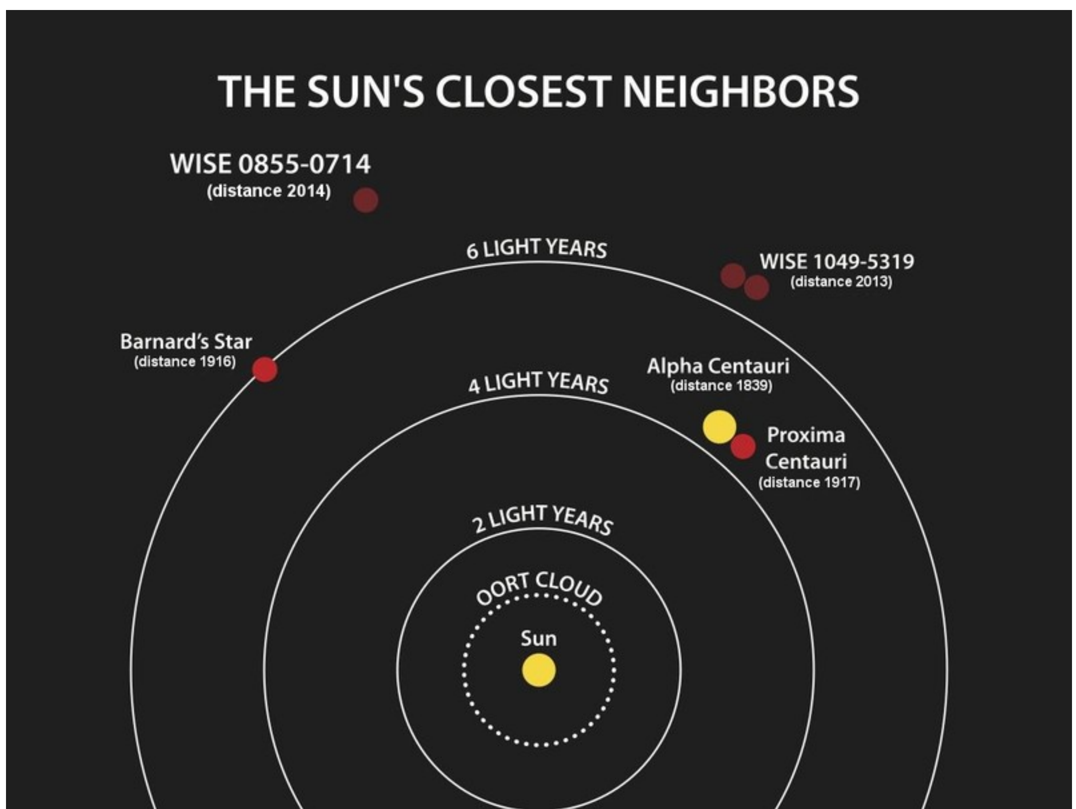
Annual parallax is defined as the ratio between Astronomic Unit and star-Sun distance

More useful units

- A parsec (parallax per second, pc) is defined as the distance of a star whose annual parallax is 1"
  - Hence, d=1/p with d in parsec and p in arcseconds
- A light year is defined as the distance traveled by a photon in one year (1 y = 31,536,000 s)
- Speed of light in vacuum: c=299,792,458 m/s
- 1 UA = 150 x 10^6 km
- Arcseconds = radians x (360 x 60 x 60)/2π
- 1 parsec ~ 206265 UA ~ 3 x 10^{13} km ~ 3 light years

Nearest stars

- How far is Proxima Centauri?
  - Parallax = 768.7±0.3 mas (milliarcseconds)
  - Give number in km, UA, pc, LY



Exercise #2

- You use the state-of-the-art parallax measurements from satellites (Hypparcos mission, Gaia mission):
  - Angular resolution: O(0.001")
  - What is the maximum distance that we can measure with the parallax method?
- You are Bessel in year 1838:
  - Angular resolution: O(0.1")
- You are Tycho Brahe in year 1600:
  - Angular resolution: O(1')
- Question: in which cases are you justified in believing that the stars (apart from Sun) are all at the same distance from the Earth?

How bright is an object?

- Two ways to intend the question:
- Intrinsic luminosity
  - Total energy emitted
  - Independent of distance
  - Measured in power units: energy emitted by the source per unit time (e.g., Watts)
- Apparent brightness
  - How bright it looks from a distance
  - Measured in flux units: energy received by the observer per unit time and unit area

Inverse square law

- Apparent brightness, as any kind of flux, is inversely proportional to square of distance
- Think about a point-like source that, at a given time, emits a certain amount of energy
- Draw a spherical surface around it. This surface receives all of its energy, equally spread
- An instant later, that light has reached a larger radius, but the energy is the same
- And the surface of a sphere is $4\pi R^2$

$$\text{Flux} = \frac{\text{Luminosity}}{4\pi d^2}$$

Magnitude (apparent, or relative)

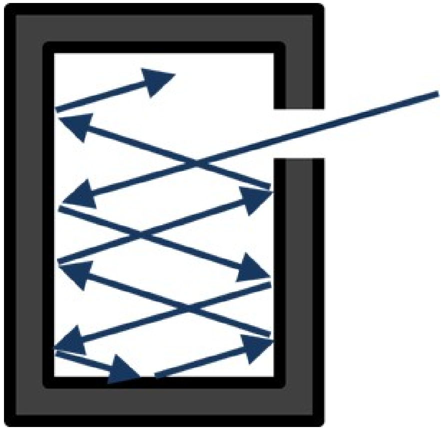
- Ancient system based on subjective classification:
  - 1st magnitude: the brightest stars
  - 6th magnitude: at the limit of being observable by naked eye
- Now it is based on objective flux measurements
  - Flux is measured by light-sensitive detectors
  - Detectors calibrated by "standard candles", i.e., stars of known intrinsic luminosity (I will say more on that later)
  - It was observed that 1st and 6th magnitude stars differed by a factor ~100 in flux, so this became part of the convention:
    - Every 5 steps in magnitude, factor 100 in flux
    - e.g., 10th magnitude is 100 times fainter than 5th
    - Between two steps of magnitude, factor of $\sqrt[5]{100} \sim 2.512$

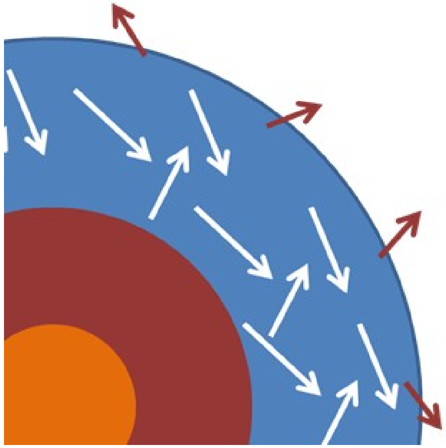
Magnitude (absolute)

- Defined as the relative magnitude at 10 parsec
- Relationship with relative magnitude m:
  - $M = m + 5 (1 - \log_{10} d)$, with d in parsec
  - $M = m + 5 (1 + \log_{10} p)$, where p is the parallax
- It is an approximation, valid for near stars:
  - It assumes Euclidean geometry; curvature of the Universe affects measurement for distant stars
  - It neglects the red-shift phenomenon (we will discuss it in one of the last lessons); all instruments are only sensitive to a range of wavelengths, so red-shift affects the measurement of m

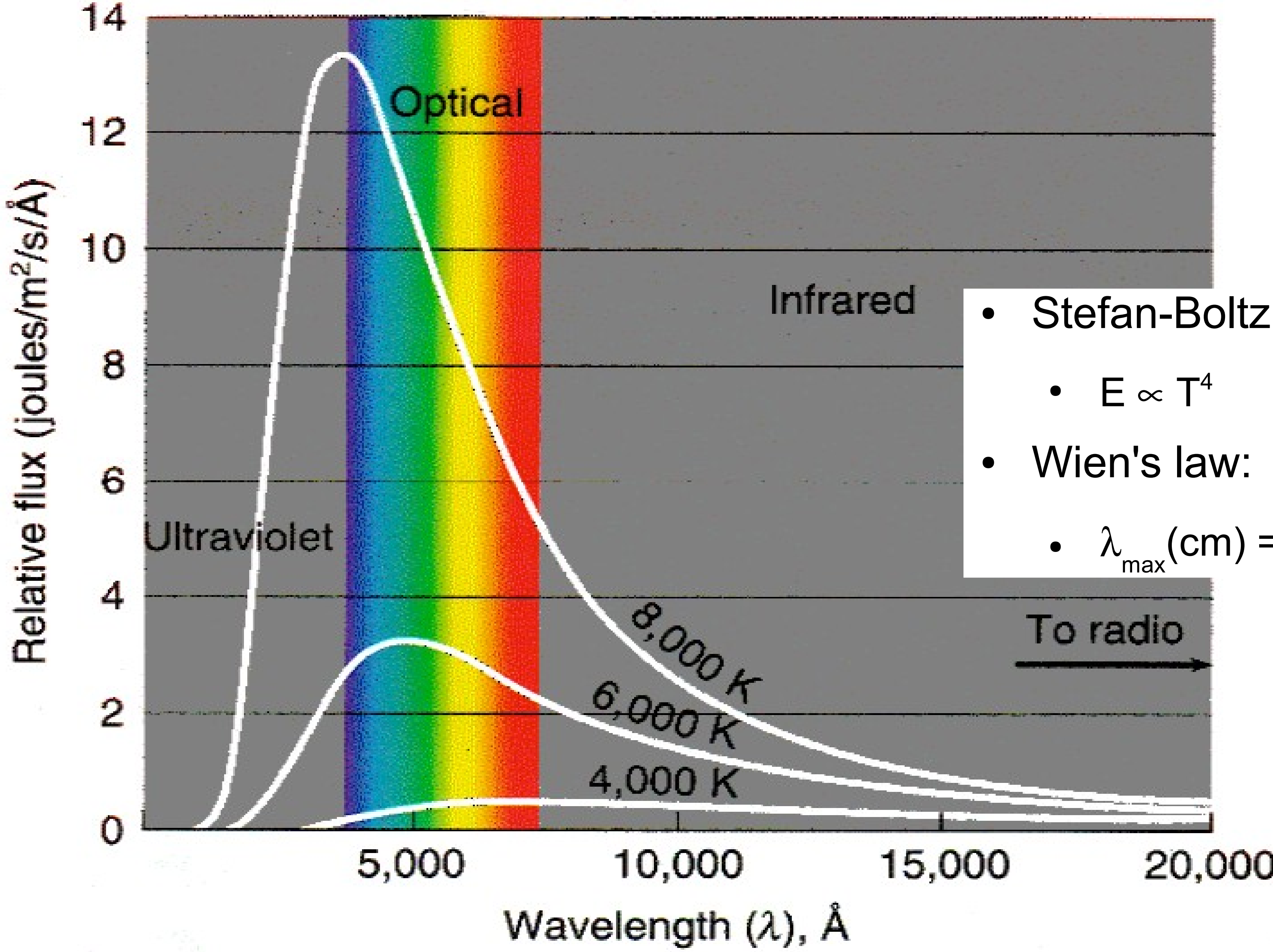
Stars as "Black Bodies"

- A Black Body is an idealized physical system, capable of absorbing 100% of incident light
- Like any other body, it also emits energy
- Useful property: emission spectrum does not depend on its material properties, only on temperature
- We make the approximation that stars are Black Bodies, because this allows to define an effective temperature
- It is a good approximation anyway:





Temperature of a "Black Body"



- Stefan-Boltzmann's law:
  - $E \propto T^4$
- Wien's law:
  - $\lambda_{max}(\text{cm}) = 0.29 / T(\text{K})$

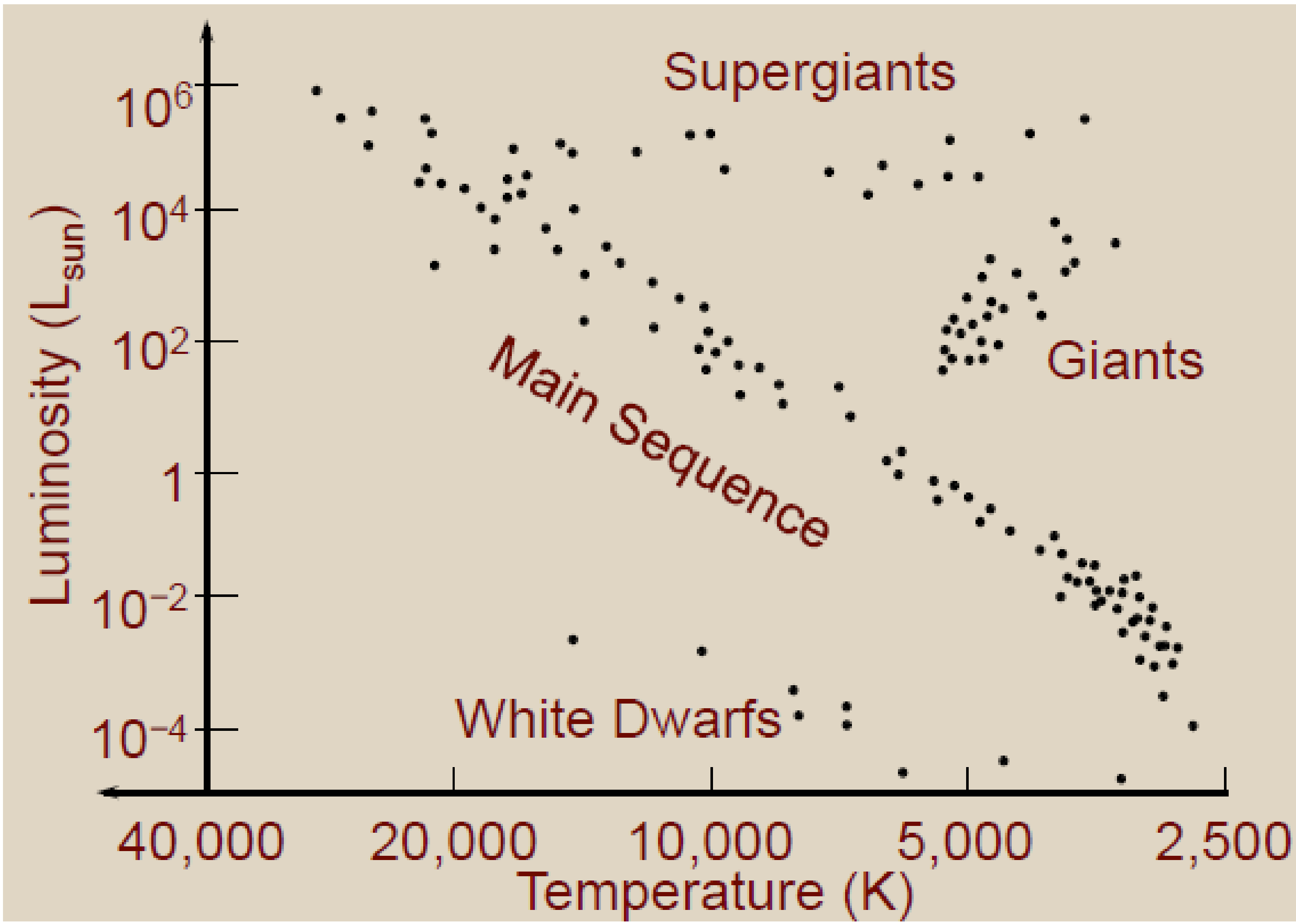
Effective temperature of a star

- It is defined as the temperature of a black body with the same luminosity and the same radius

$$\mathbf{L = 4\pi R^2 \sigma T^4_{eff}}$$

- E.g., L(Sun)~4×10^{26} W, R(Sun)~7×10^{8} m, means that T_{eff}(Sun)~6000 K
- You get the same result from Wien's law (previous slide), from $\lambda_{peak} \sim 5 \times 10^{-5}$ cm
- <u>Discussion</u>: what temperature is this in practice? Average / at the center / at the surface?

Hertzsprung-Russell diagram



You will see this graph many times during my course

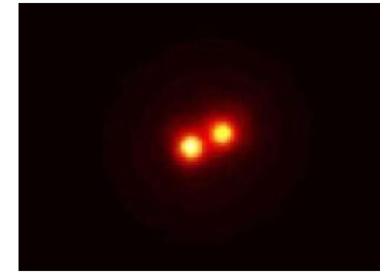
How to measure mass?

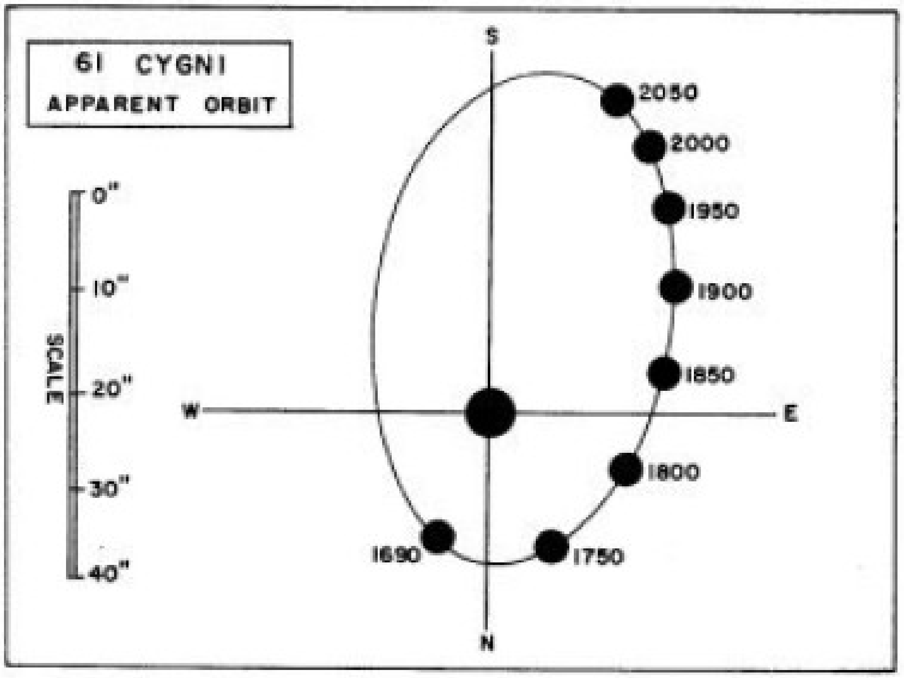
- Direct measurements, with the methods that I will explain in the next slides, are possible only for a sub-sample of all stars: binary stars
- These are stars that orbit around a common center of mass
- It may be surprising to know that they are not rare: between 20 and 80% of all stars belong to multiple systems
- However, we manage to measure the mass only of those that are relatively near (~200 stars)
- For all the others, we can extrapolate by using the relationships with other variables, that we can deduce from this sub-sample (some of these relationships will be explained in this course)

Binary stars

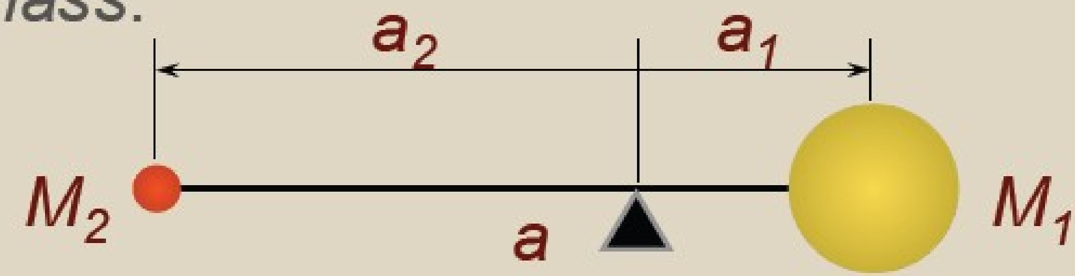
- For our purposes, let's classify them as:
  - Visual binaries
    - We can see both stars and follow their orbits over time
  - Spectroscopic binaries
    - We cannot see them as separated, but we can see their spectra change periodically because of Doppler effect
  - Eclipsing binaries
    - We cannot see them as separated, but we can see a drop in brightness as they eclipse each other

Visual binaries





- Two stars orbit about their *center of mass*:



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

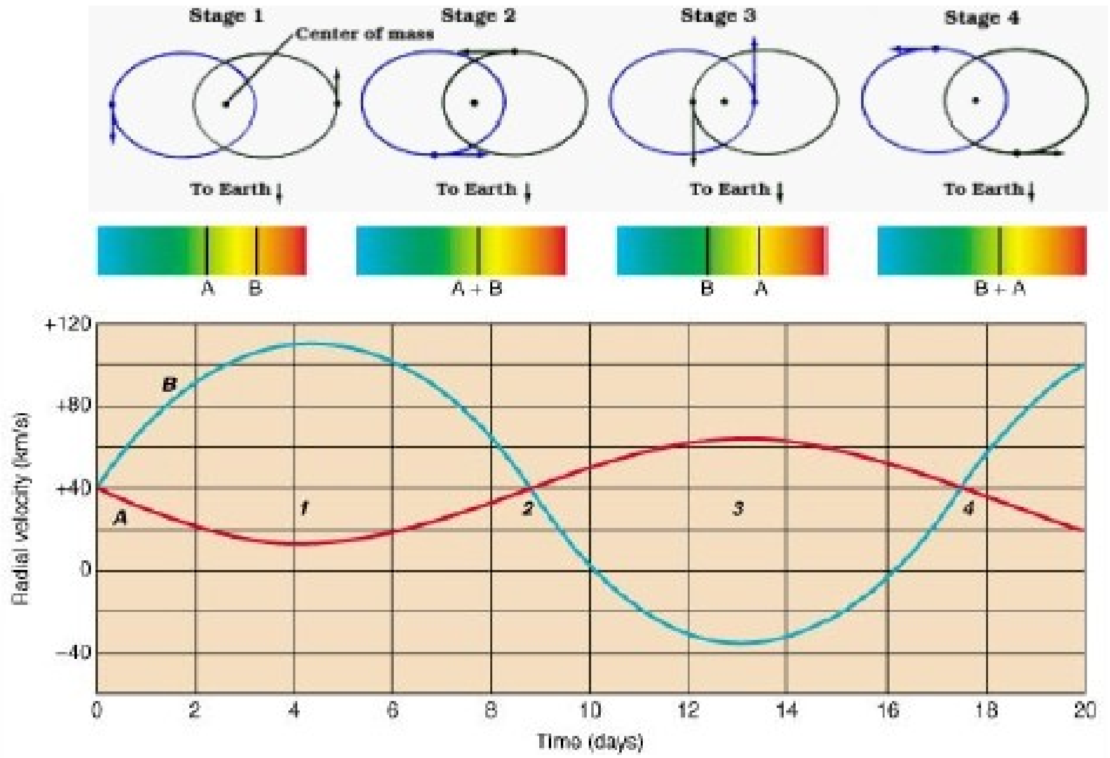
<u>Homework</u>: derive this formula from Kepler's Law.

Period T is known by observing the orbit, same for semi-major axis a. We also know that $m_1/m_2 = a_2/a_1$

Problems with this method

- Measuring the orbit can take decades
- Strong dependence on measured distance of the star:
  - $a=\theta * d$, where θ is the measured angle between the two binary stars
  - Hence, measured mass goes like d^3
  - Which means that the relative uncertainty $\Delta m/m$ is three times the relative uncertainty $\Delta d/d$
    - <u>Exercise</u>: demonstrate that

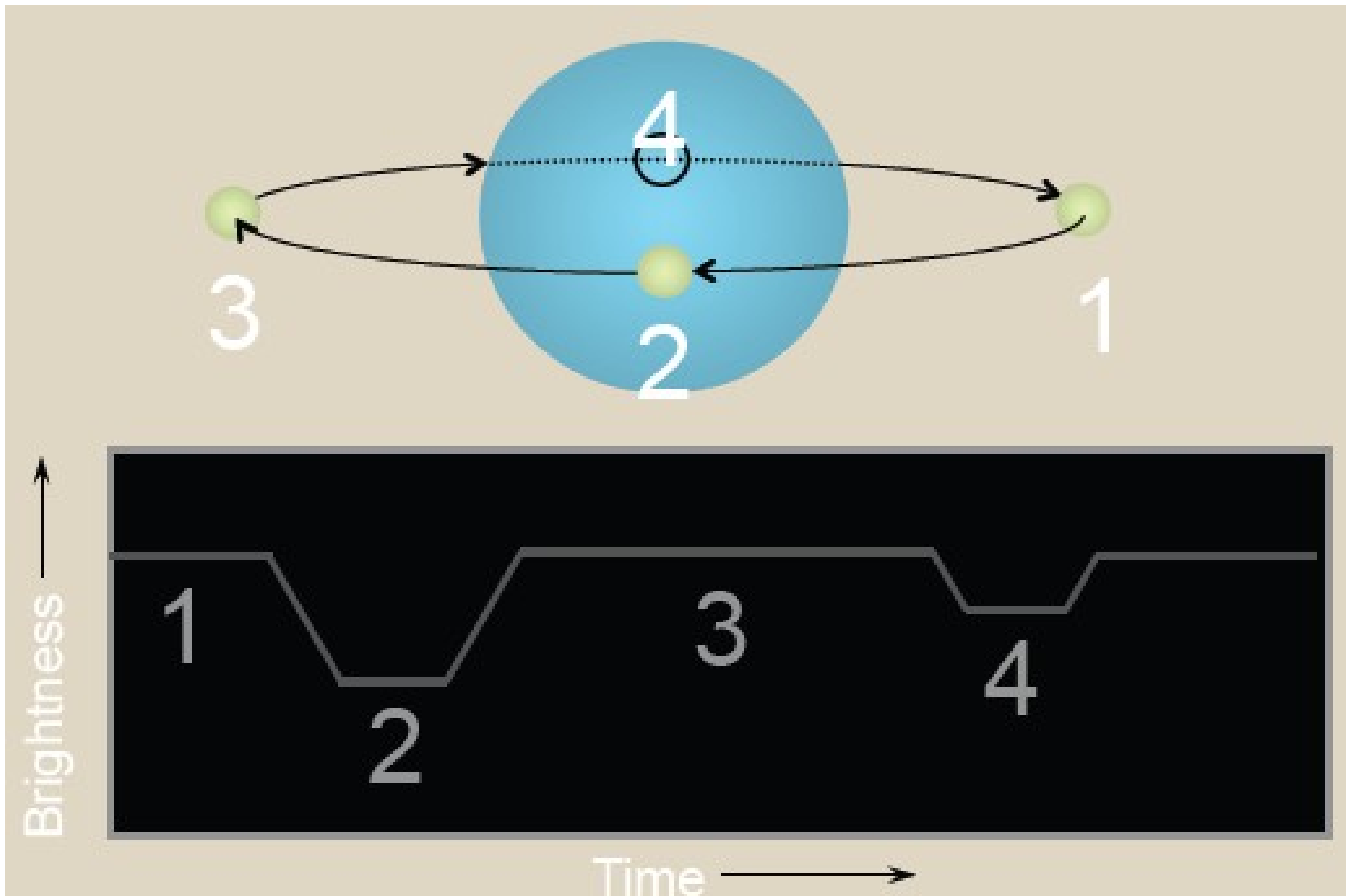
Spectroscopic binaries



$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

- We measure the velocity vs time of both stars
  - (Note: it is the velocity component along our line of sight)
- <u>Homework</u>: from these inputs, deduce the mass
  - Is there less dependence on distance?
  - Do we need to know the inclination of the orbit?

Eclipsing binaries



Combine with spectral measurements (Doppler shifts) to get the orbital speeds.

<u>Homework</u>: find the masses without knowing the distance

Problems with this method

- Eclipsing binaries are very rare
  - Orbital plane must line up just right
- Measurement of light curve is affected by:
  - Partial eclipses
  - Edges are softened by star's athmospheres
  - Close binaries can be tidally distorted

How to measure radius?

- Single stars:
  - Interferometry
  - Lunar occultation
- Binaries:
  - Eclipses, again (using distance)
- Very difficult measurements because of distance, possible only for ~500 stars
- When we cannot measure, we have to rely on the formula that we derived earlier:

$$\boxed{L = 4\pi R^2 \sigma T_e^4}$$

Questions?