# ASTROPHYSICS OF INTERACTING BINARY STARS

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# Contact details



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  - You are encouraged to ask questions during the lectures.
  - You can send me your questions by e-mail or phone me.

# Aim of the course



- The course will provide the necessary understanding of the physics of binary stars with white dwarfs, neutron stars, and black holes, mass-transfer, and the importance of binary stars and populations of binaries to modern astrophysics.

- Theoretical and practical considerations will be supplemented with the home exercises which constitute the important part of the course.

# Text Books



- *Interacting Binary Stars* (1985) – Edited by J.E. Pringle and R.A. Wade: Cambridge University Press / ISBN 0 521 26608 4.
- *Cataclysmic Variable Stars* (2003) – Brian Warner: Cambridge University Press / ISBN 0 521 54209 X.
- *Accretion Power in Astrophysics* (3rd edition, 2003) – J. Frank, A. King and D. Raine: Cambridge University Press / ISBN 0 521 62957 8.
- *Cataclysmic Variable Stars – How and Why They Vary* (2001) – Coel Hellier / Springer Science & Business Media. ISBN 1852332115.

- I will also give references to original papers where useful.

# Home exercises



- Compulsory homework sets will be assigned (return by the deadline). You are urged not to start these the night before they are due. For late exercises only **one half points** will be given.
- The most important thing you can learn from homework is how to solve problems yourself. This is what you need to do to succeed in the real world. Therefore, please try each problem for at least 1 hour before discussing it with anyone else.
- Please, write your homework solutions in an extremely clear manner. It will not be possible to give credits for work that is not clearly explained. Please, show your work since this will allow partial credit to be given if you cannot solve the whole problem.
- When it is relevant, use general formulae as long as possible and only plug in numbers at the end of a problem.

# Presentation



- Presentation (15 min) on one of the suggested topics.
- Practical (or possibly an observational) project. [?]

# Assessment



Your grade will be based on:

- 50% Exam on lecture course
- 30% Homeworks (problems)
- 20% Practical work / presentation

# Course Plan



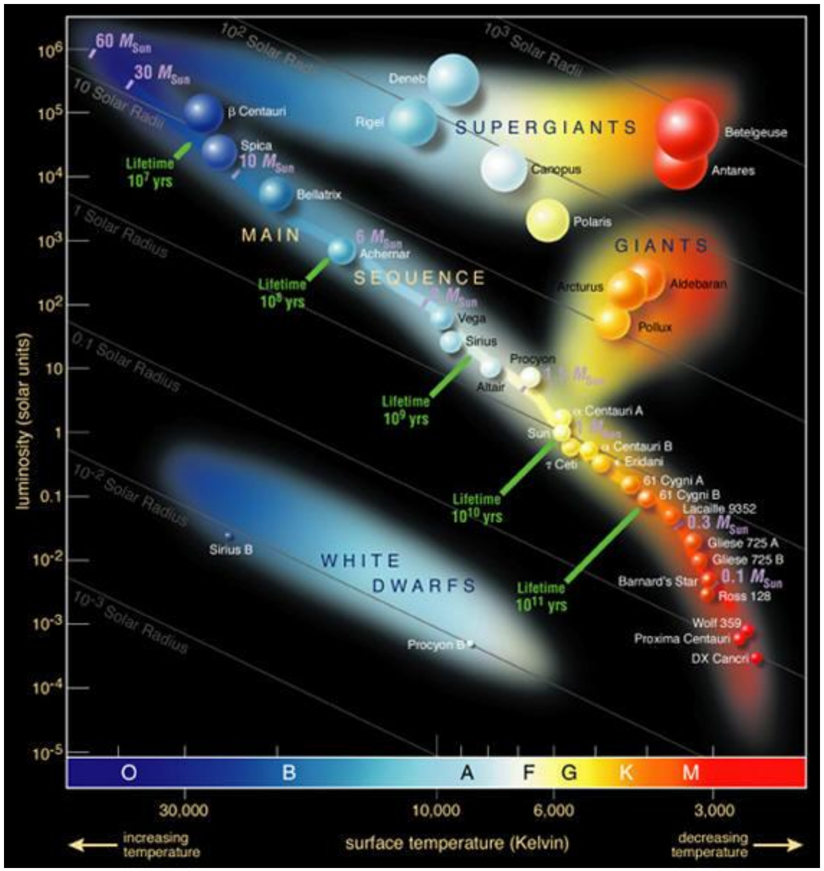
- Introduction
  - Binary Stars and Fundamental Stellar Parameters
- Interaction of stars
  - The shapes of stars in close binaries
  - Transfer of mass
  - Accretion disks
- Nomenclature – the stellar zoo
  - Cataclysmic Variables
  - AM CVn binaries
  - X-ray binaries
  - Contact binaries
  - etc
- Close binary evolution

# Introduction

Binary Stars and
Fundamental Stellar Parameters

# How to find the masses of stars ?






- Mass:
  most fundamental of stellar parameters
- Impossible to measure for isolated stars
- Well, then we have to weigh them, i.e to measure gravitational interaction with something else.

# Binary Stars

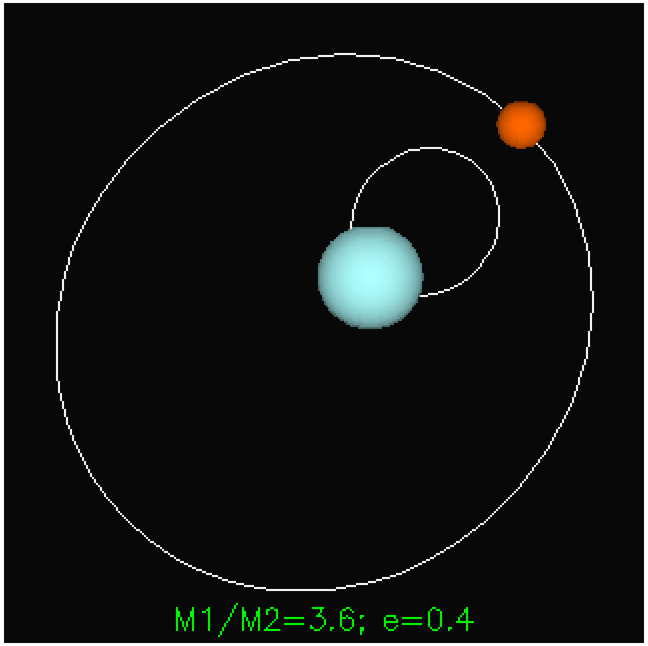


- Most stars are not isolated in space.
- About one half of all stars which we see are in a double or multiple star system.
- In a multiple star system, the stars all orbit about the common centre-of-mass of the system.
- This is not accidental! The process of star formation tends to cause many stars to be formed close to each other.

# Types of Binary Stars



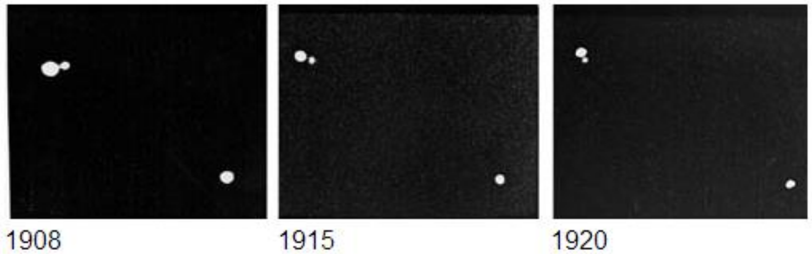
- A double star system where you can see both stars and they appear to move around each other is a **visual binary** (Herschel 1802)
  - >0.2 arcsec
  - both stars seen, orbital motion



# Visual Binaries

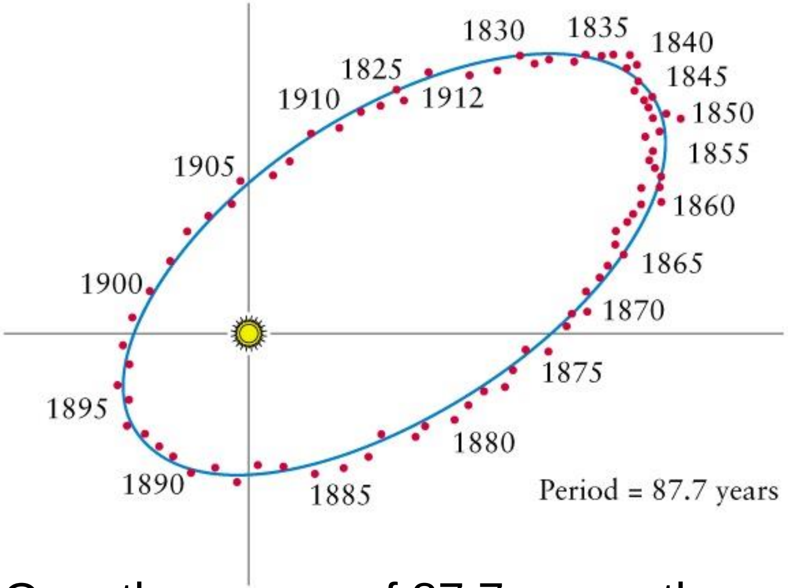


## Kruegar 60




From 1908 to 1920 the visual binary completed about 1/4 of a revolution.

## 70 Ophiuchi

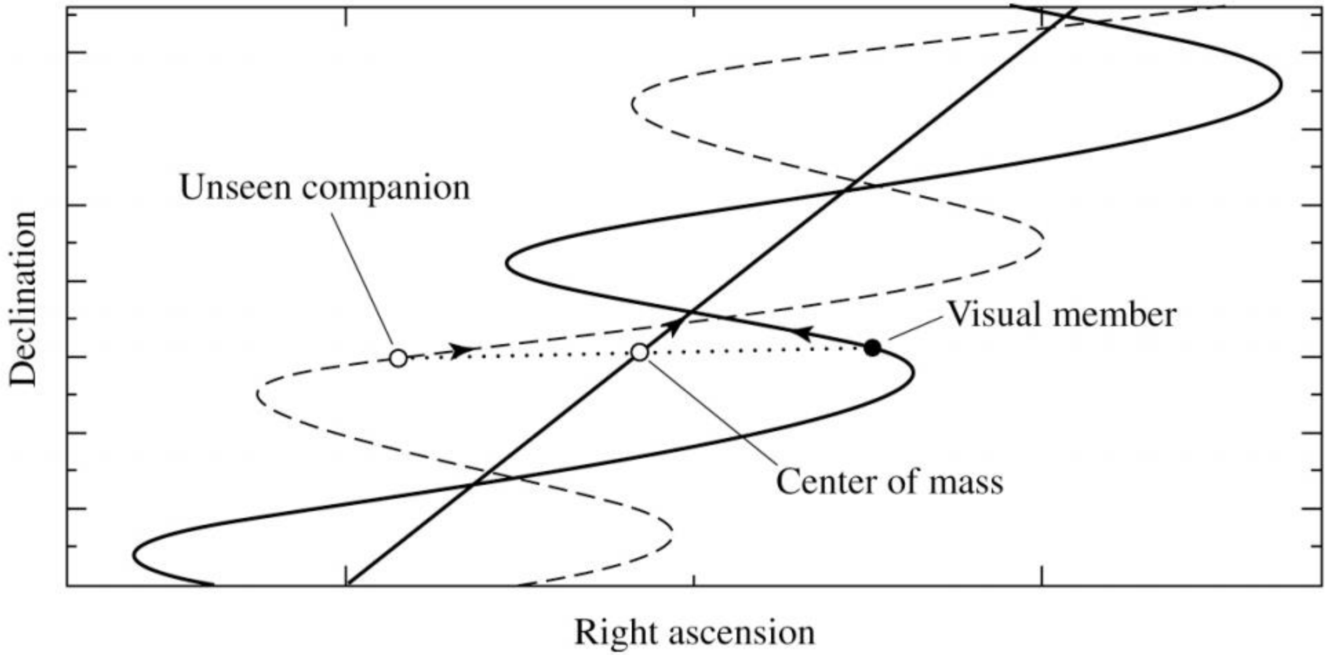



Over the course of 87.7 years, the star makes one full orbit.

# Types of Binary Stars



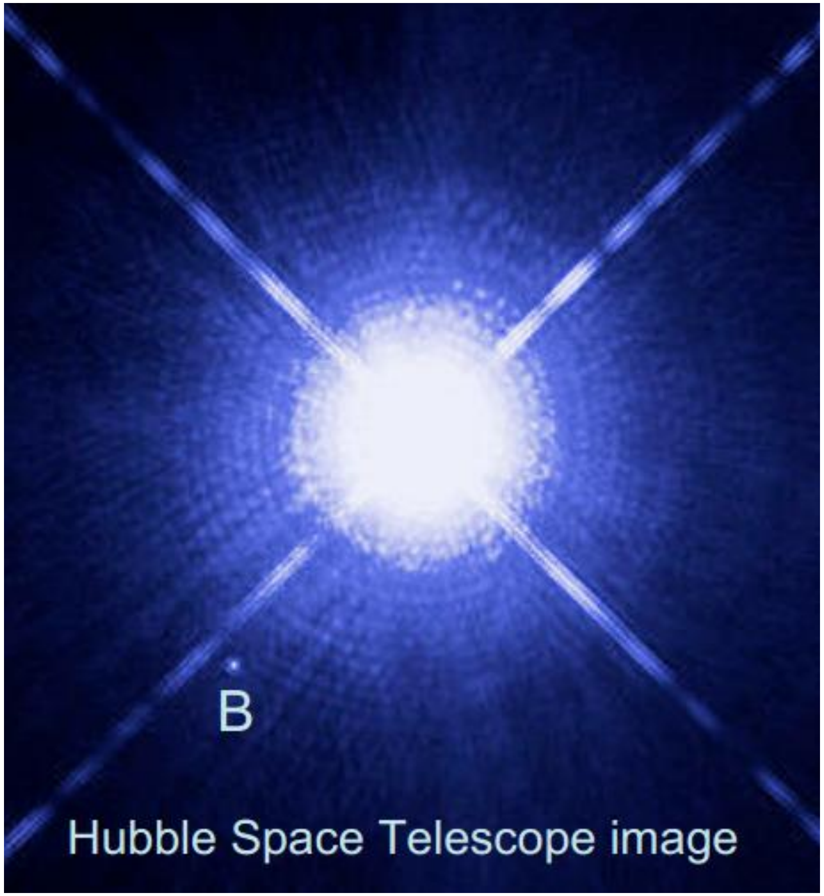
- If only one star is visible, but we can detect that it wobbles about an unseen centre-of-mass, then we have an **astrometric binary.**



# Astrometric Binaries

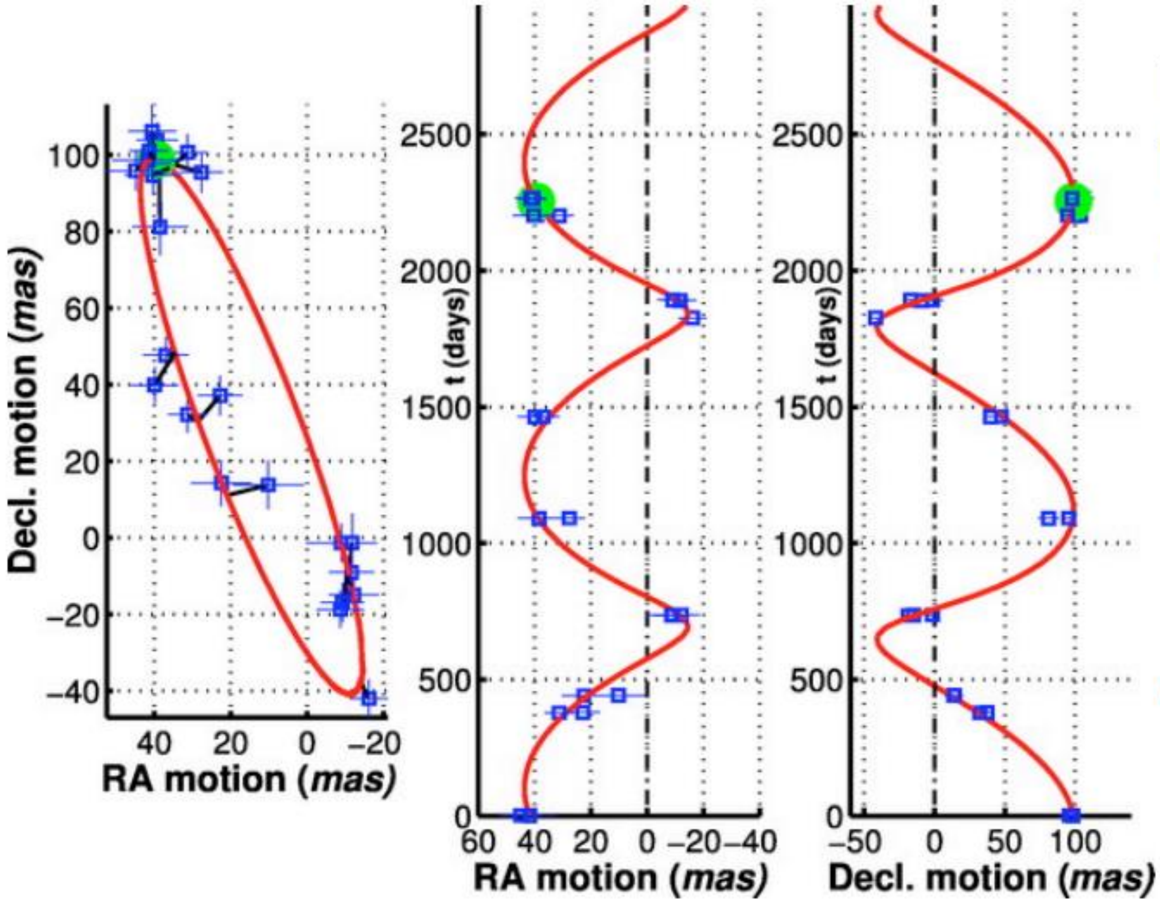


- The star Sirius is actually a binary system, but Sirius A is so much brighter than Sirius B that we only see Sirius A.
- Sirius B was first detected by observing the motion of the brighter Sirius A.
- Now also a visual binary.



# Astrometric Binary: GJ 802AB






unseen brown dwarf companion

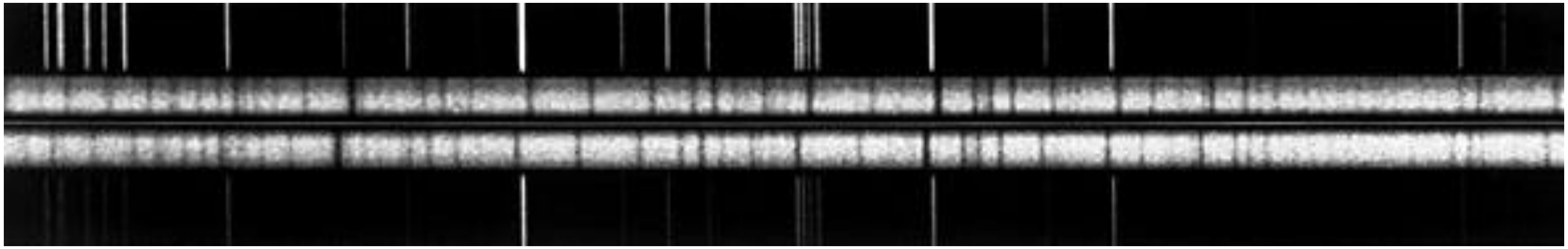
$a > 0.5\text{–}2\text{AU}$

*(Pravdo et al. 2005)*

# Types of Binary Stars



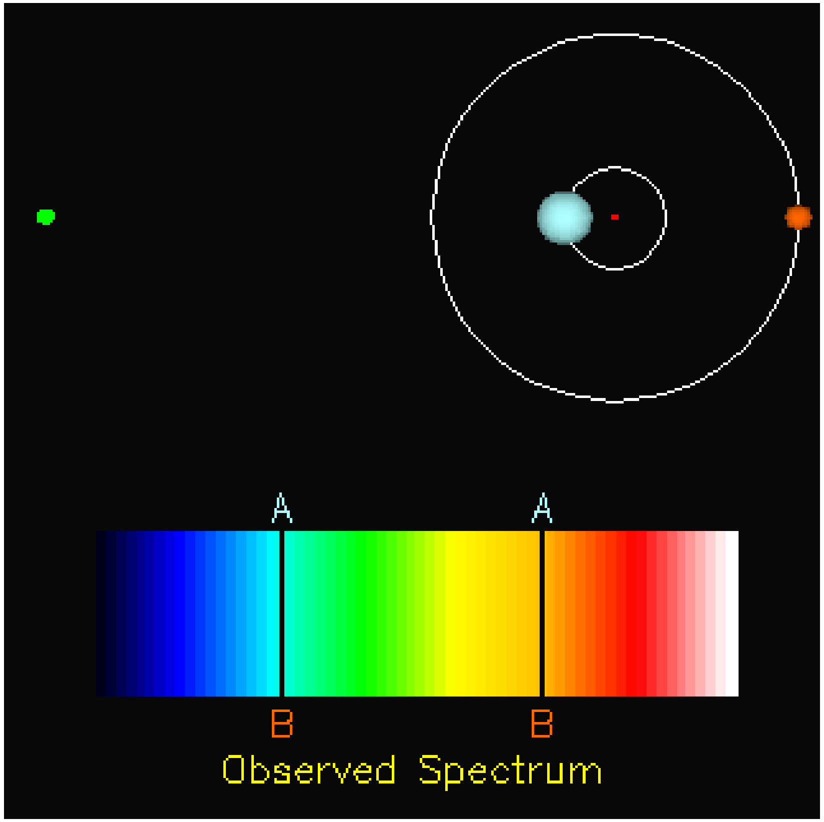
- Sometimes, the only evidence of a binary star comes from the Doppler effect on its emitted light. The spectrum of the star shows Doppler shifts which change from redshift to blueshift periodically.
- **Spectroscopic Binaries**
  - composite spectra, doppler-shifted lines
  - SB1, SB2 = spectra from 1 or both stars



# Spectroscopic Binaries



- The spectral lines in the light emitted from each star shifts first toward the blue, then toward the red, as each moves first toward us, and then away from us, during its motion about their common center of mass, with the period of their common orbit.

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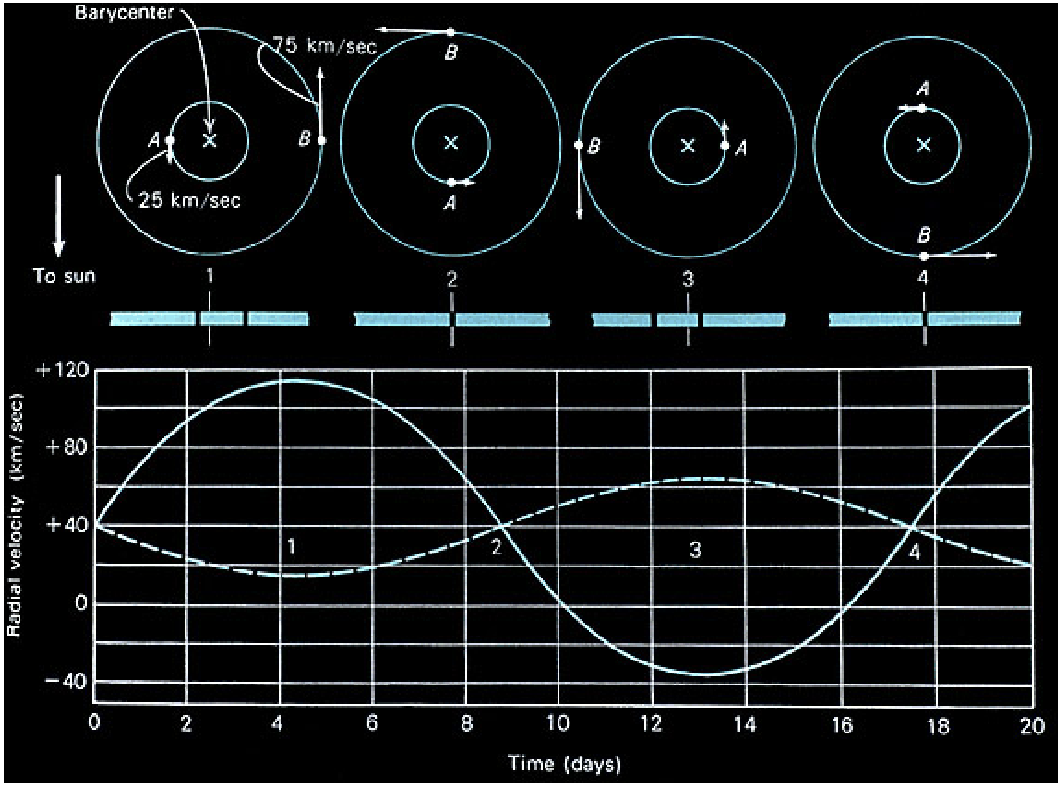
# Spectroscopic Binaries



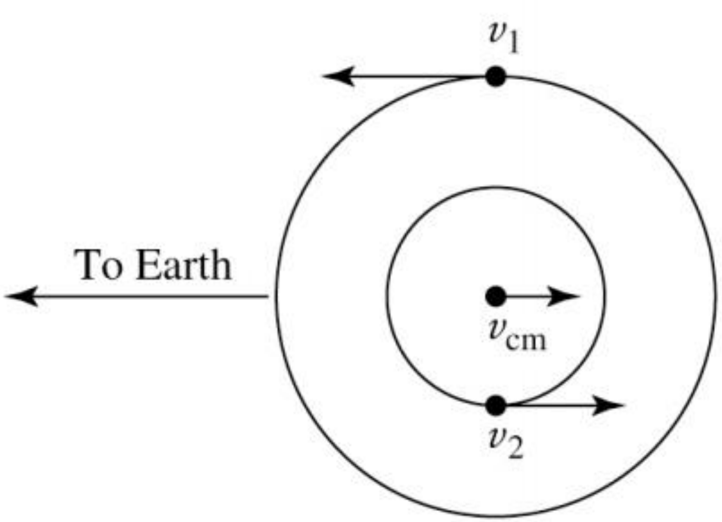
- From the Doppler shift data, we can reconstruct the component of the stars' velocities in our line of sight.
- In *double-lined spectroscopic binaries* it is possible to measure the radial velocity curves of both components, whereas in *single-lined spectroscopic binaries* only one of the radial velocity curves is measurable.
- The true velocities are only known if the binary's inclination angle with our line of sight is known.

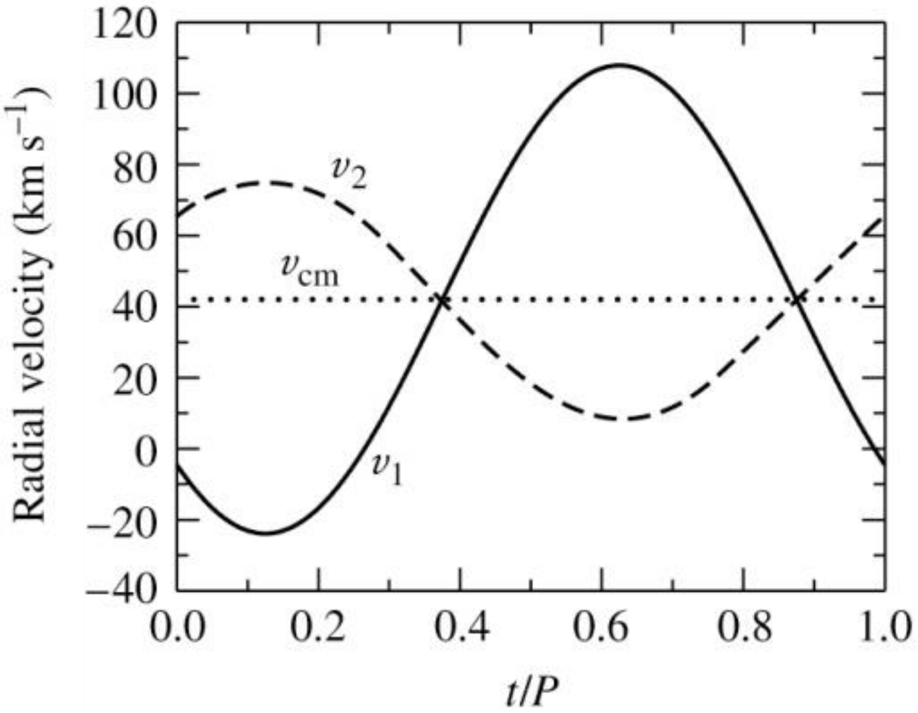


# Spectroscopic Binaries



- Radial Velocity curve for Double-lined SB in **a Circular Orbit:**

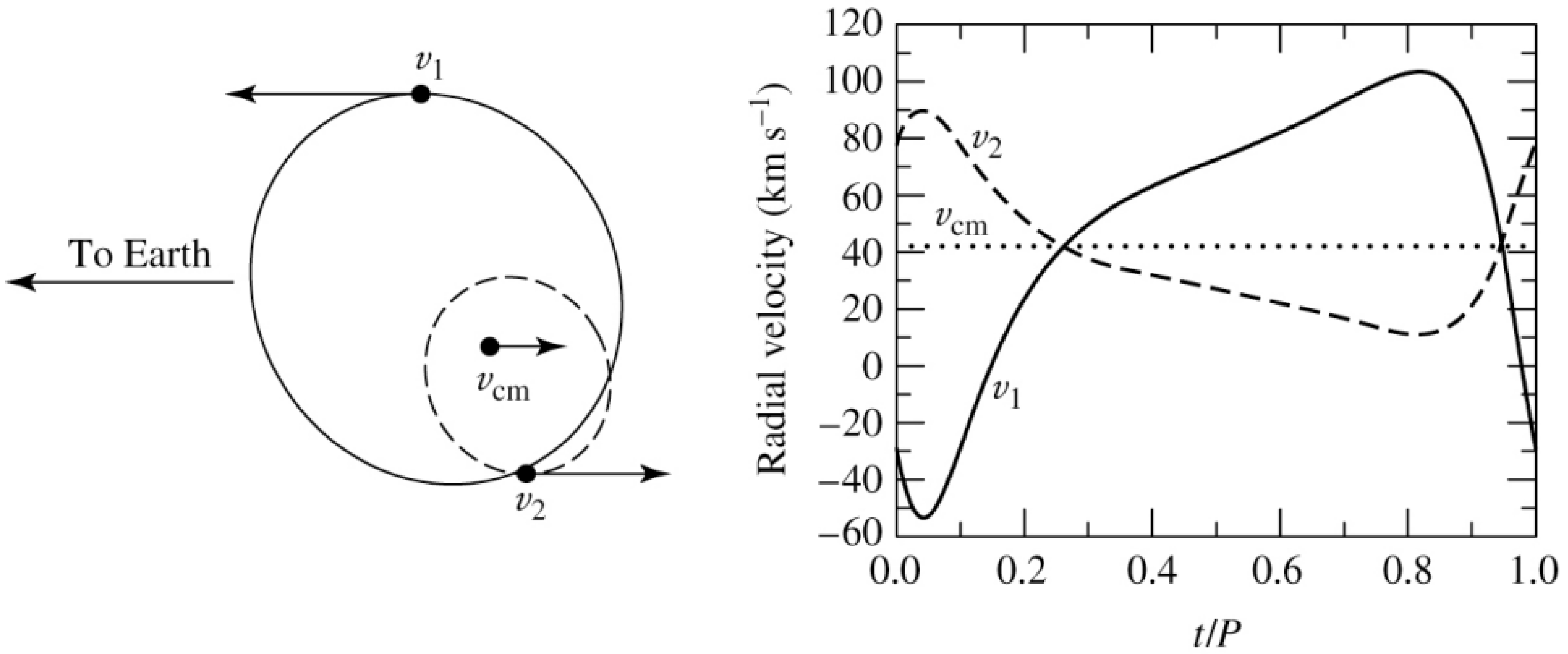


# Spectroscopic Binaries



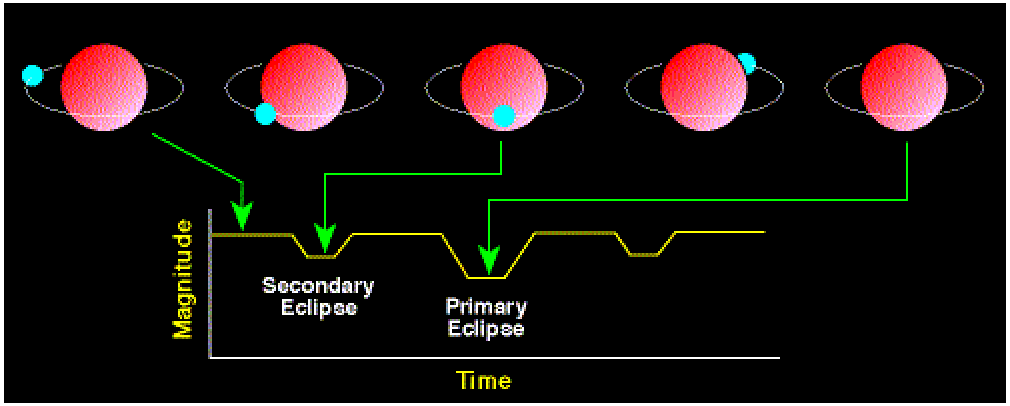
- Radial Velocity curve for Double-lined SB in **an Elliptical Orbit (e=0.4):**

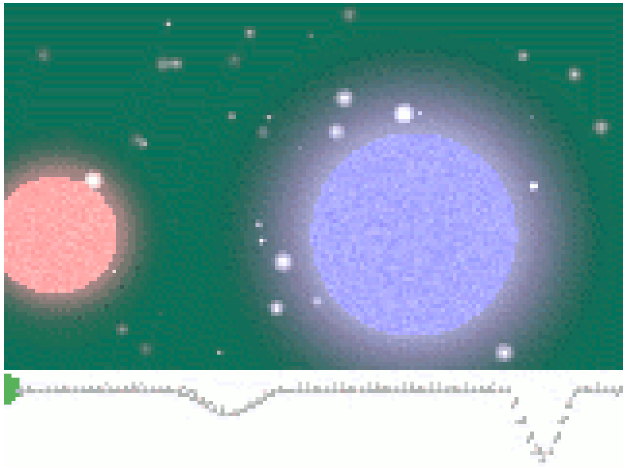


# Types of Binary Stars



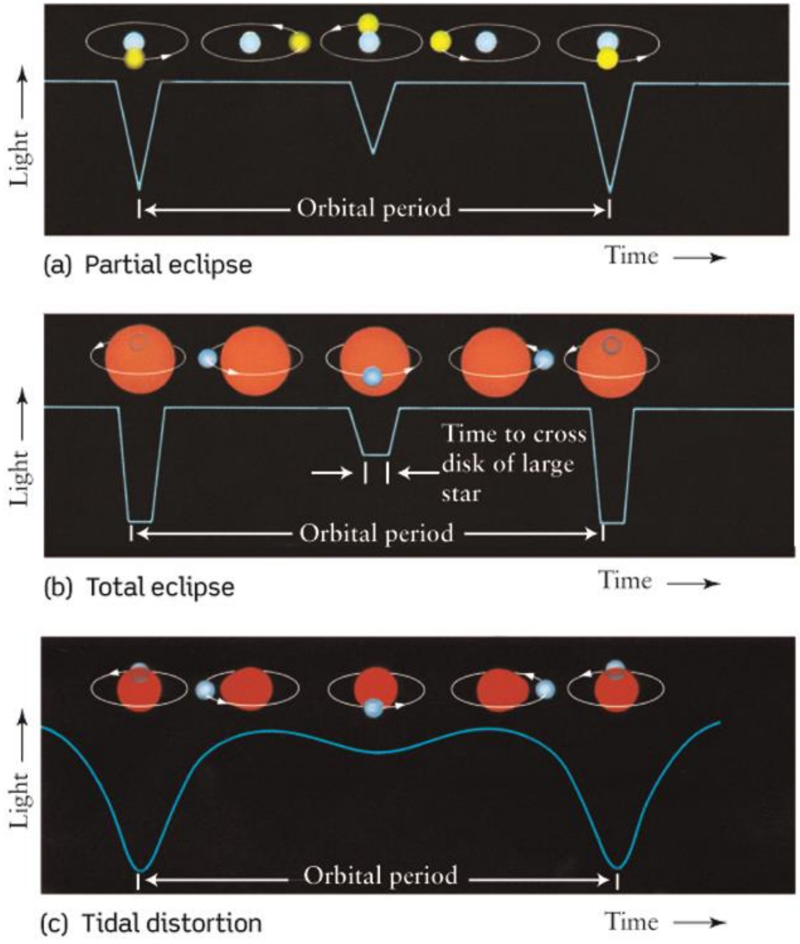
- **An eclipsing binary** is a binary which shows regular light variations due to one of the stars passing directly in front of its companion, as viewed from the Earth.



# Eclipsing (Photometric) Binaries

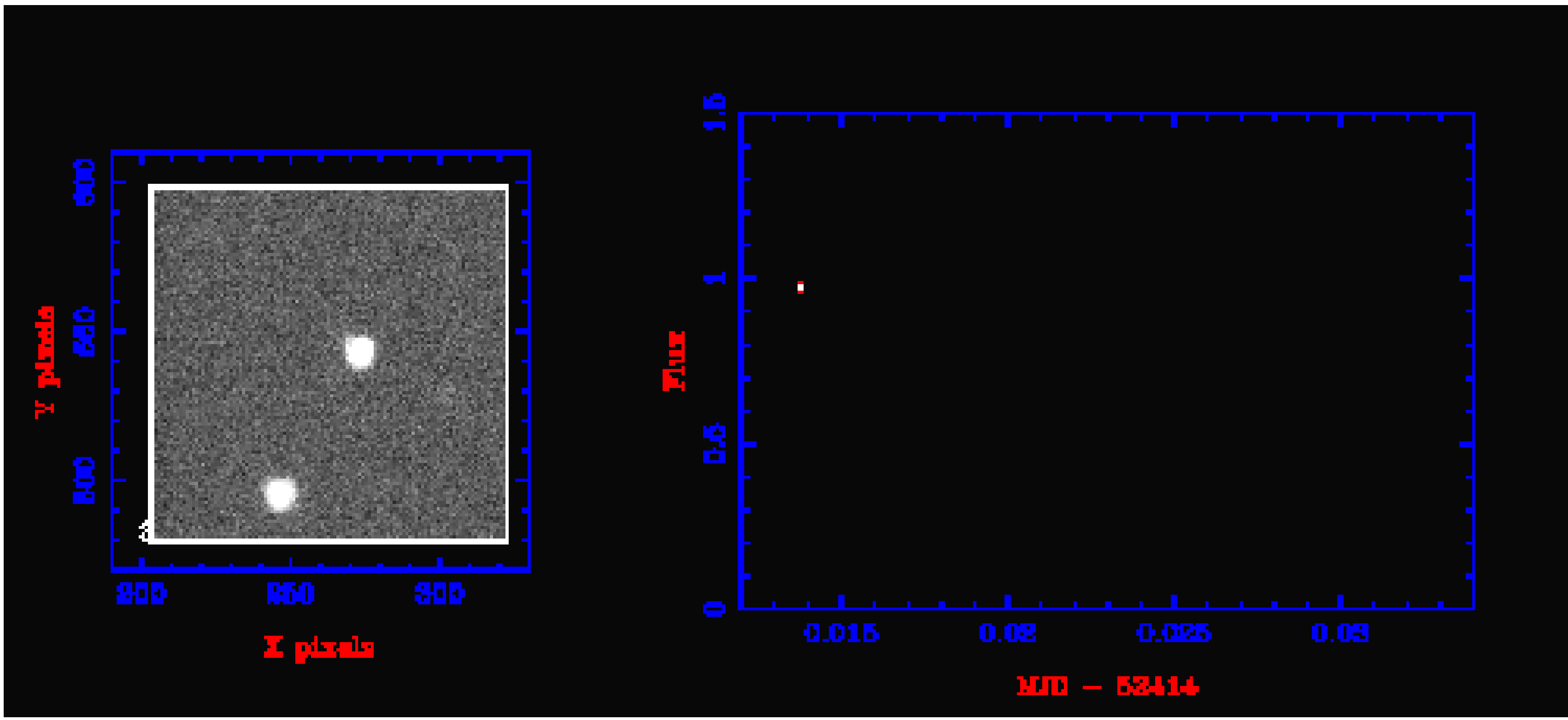





- By studying the shape of the eclipses, in conjunction with a knowledge of their radial velocity curves, it is possible to determine the masses and radii of the stars in the binary.
- Eclipsing binaries are hence extremely useful systems.

# Totally Eclipsing Binaries



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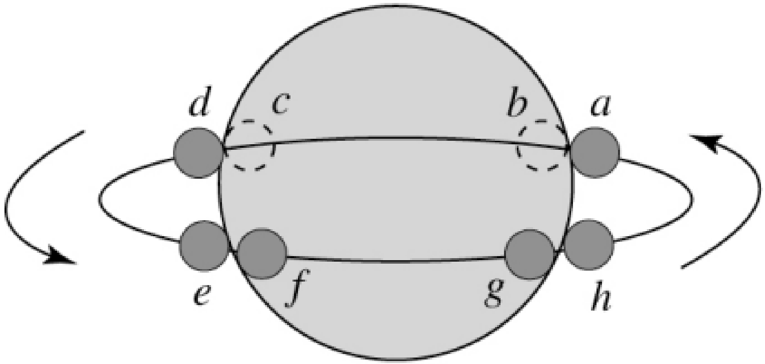
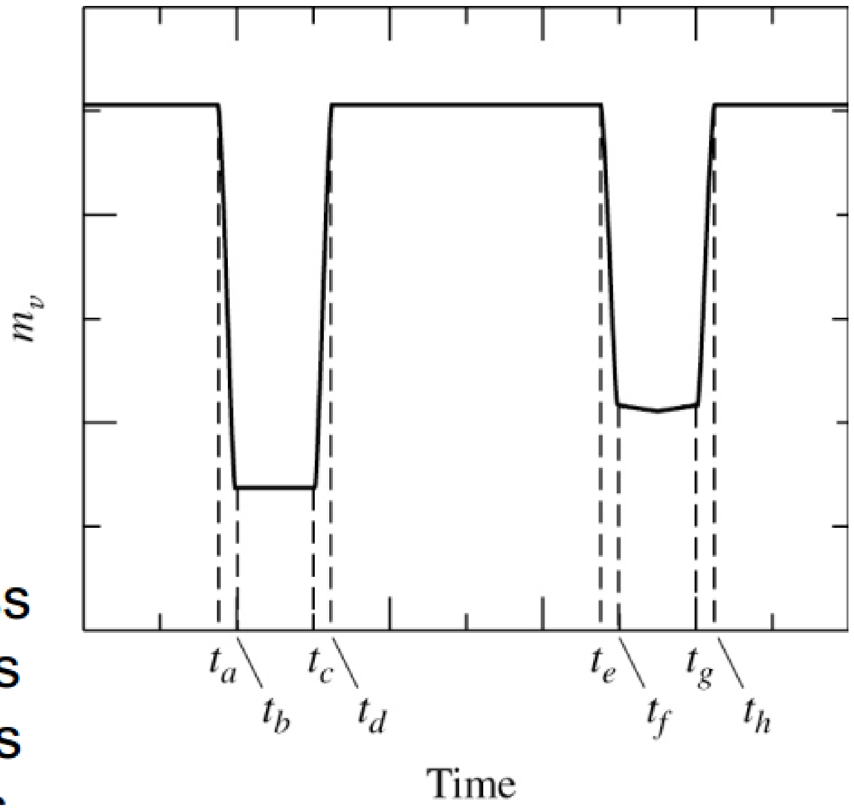
# Totally Eclipsing Binaries



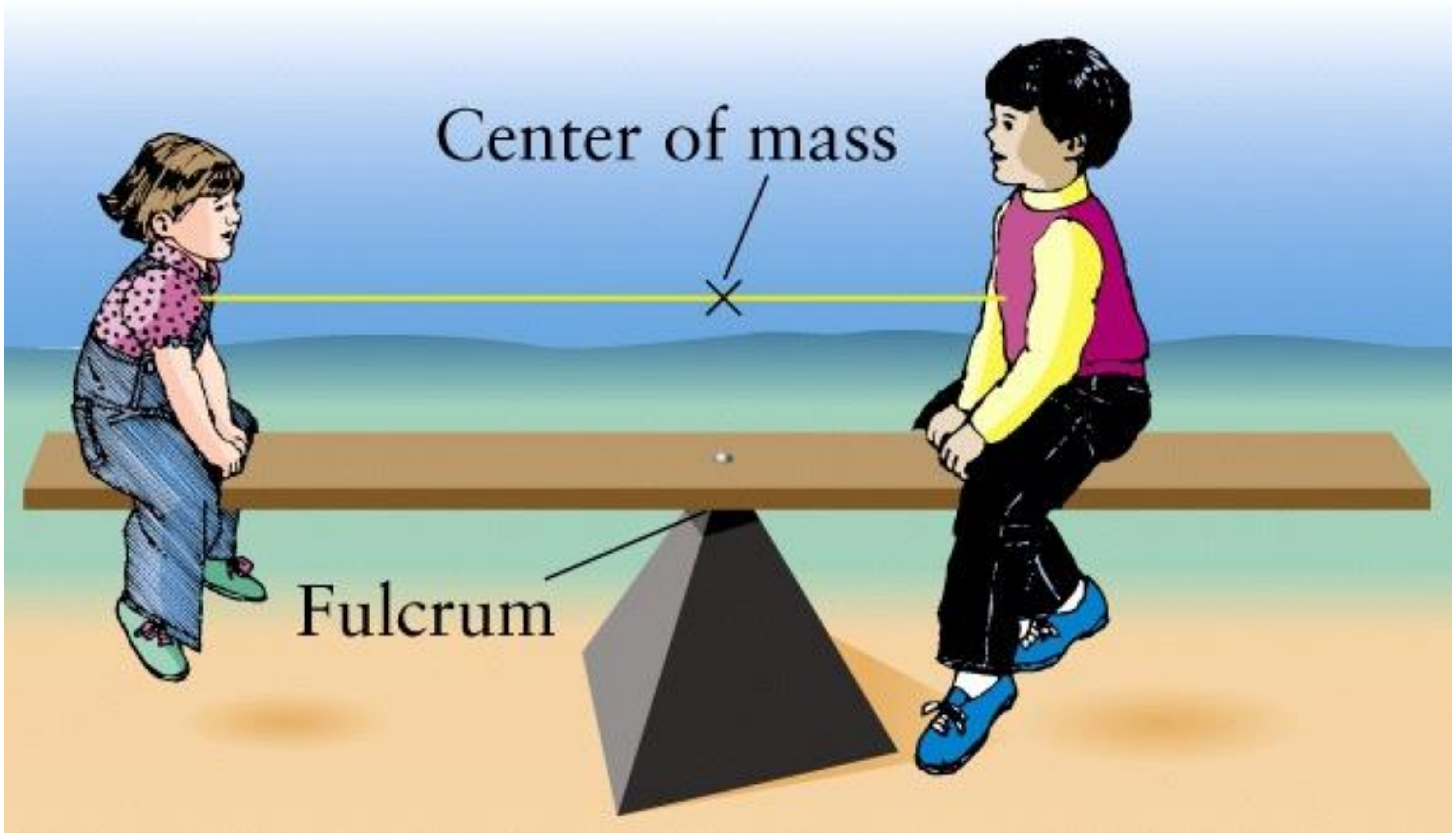



$t_a$ – start of secondary ingress
$t_b$ – end of secondary ingress
$t_c$ – start of secondary egress
$t_d$ – end of secondary egress

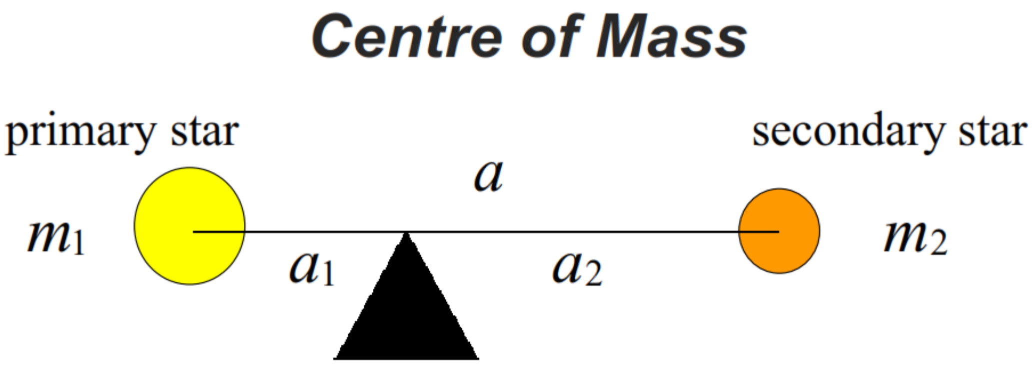
# Using Binaries to Weigh Stars





# Dynamical Mass Determination






The Centre-Of-Mass Formula is

$$a_1 m_1 = a_2 m_2$$

If orbital major axes (relative to centre of mass) or radial velocity amplitudes are known, then we know the ratio of masses:

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

# Dynamical Mass Determination



- If the period, $P$, and the sum of semi-major axis lengths, $a=a_1+a_2$, are known, Kepler's third law can give masses separately:

$$P = \left(\frac{4\pi^2}{G(m_1+m_2)}a^3\right)^{1/2}$$

- If only the two radial velocities are known (SB2), the sum of masses (from Kepler's third law) is:

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

# Dynamical Mass Determination



- If only one radial velocity is known (SB1), a useful quantity is the mass function:

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

**Why ?**

- If the orbital inclination, $i$, is known, this allows determination of $m_2/m_1$

# Determination of Radii and Teff's



- Duration of eclipses and shape of light curve can be used to determine radii of stars:

(radius of secondary) $$R_s = \frac{v_1 + v_2}{2}(t_2 - t_1)$$

(radius of primary) $$R_\ell = \frac{v_1 + v_2}{2}(t_3 - t_1)$$

$t_1$ – start of secondary ingress
$t_2$ – end of secondary ingress
$t_3$ – start of secondary egress

- Relative depth of primary (deepest) and secondary brightness minima of eclipses can be used to determine the ratio of effective temperatures of the stars:

$$\frac{F_0 - F_{\text{primary}}}{F_0 - F_{\text{secondary}}} = \left(\frac{T_{e,s}}{T_{e,\ell}}\right)^4$$

# Binary Stars



- Binary star systems are important because:
  - they allow us to find the masses and radii of stars
- Test:
  - stellar evolution
  - stellar atmospheres
  - general relativity - pulsars timing
- micro-arcsec tomography (eclipse / doppler / zeeman)
  - stellar surfaces
  - accretion disks

# Binary Stars



- Properties of some binary stars are inexplicable in terms of the ordinary evolution of isolated stars:
  - **Algol paradox:** the less massive star ($M_2=0.8M_{sun}$) is already a subgiant, and the star with much greater mass ($M_1=3.7M_{sun}$) is still on the main-sequence.
  - **Compact binaries**: many binaries containing white dwarfs or other compact stellar remnants have periods $P < 2$ hours, which implies separations $a < R_{sun}$. Must have been interactions between the progenitors when they were on the main sequence.

# Interacting Binary Stars



- Resolution of these paradoxical situations is often mass transfer between the components of a close binary.

- By definition, **close (or interacting) binaries** are binary systems in which some significant interaction other than simple inverse square law gravitational attraction between point masses takes place. The interaction may be radiative, as in the heating of the face of one component by a hot companion, or it may be tidal, distorting both components through the combination of gravitational and centrifugal effects.

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# How does mass transfer occur?

Roche lobe and Roche-Lobe overflow

# How does mass transfer occur?



- Two possible mechanisms for mass transfer between stars in a binary system:
  - Stellar wind accretion:
    - If one component ejects mass in a stellar wind and a part of that material is gravitationally captured by the nearby companion.
  - Roche-lobe overflow:
    - If the binary orbit is sufficiently close, matter from the outer layers of one star can flow directly to the companion.
- Stellar winds from low mass and/or late type stars are not usually strong and mass transfer occurs mainly through Roche-lobe overflow.