Structure and Evolution of Stars

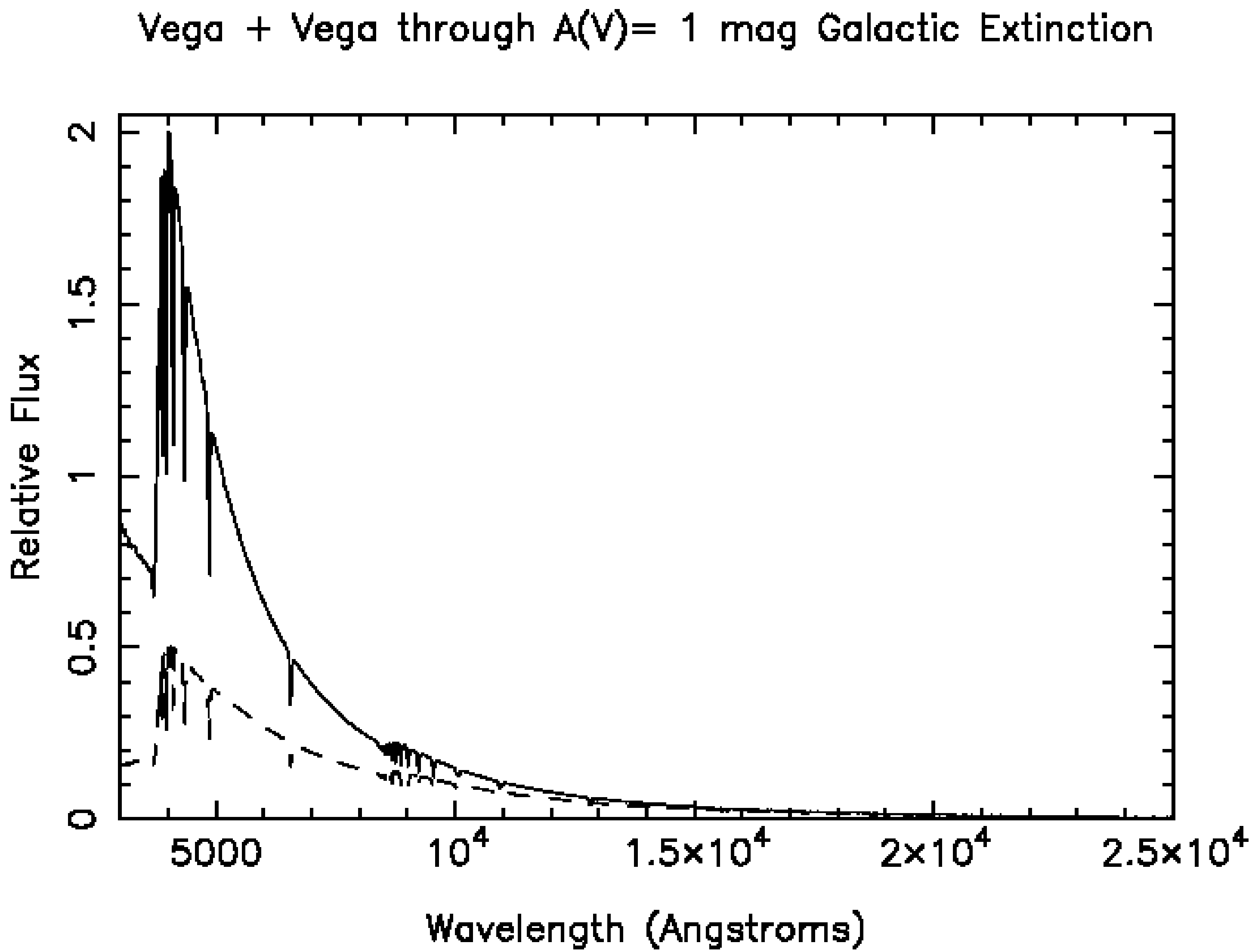
Lecture 4: Interstellar Extinction, Binary Stars, Stellar Masses and Radii

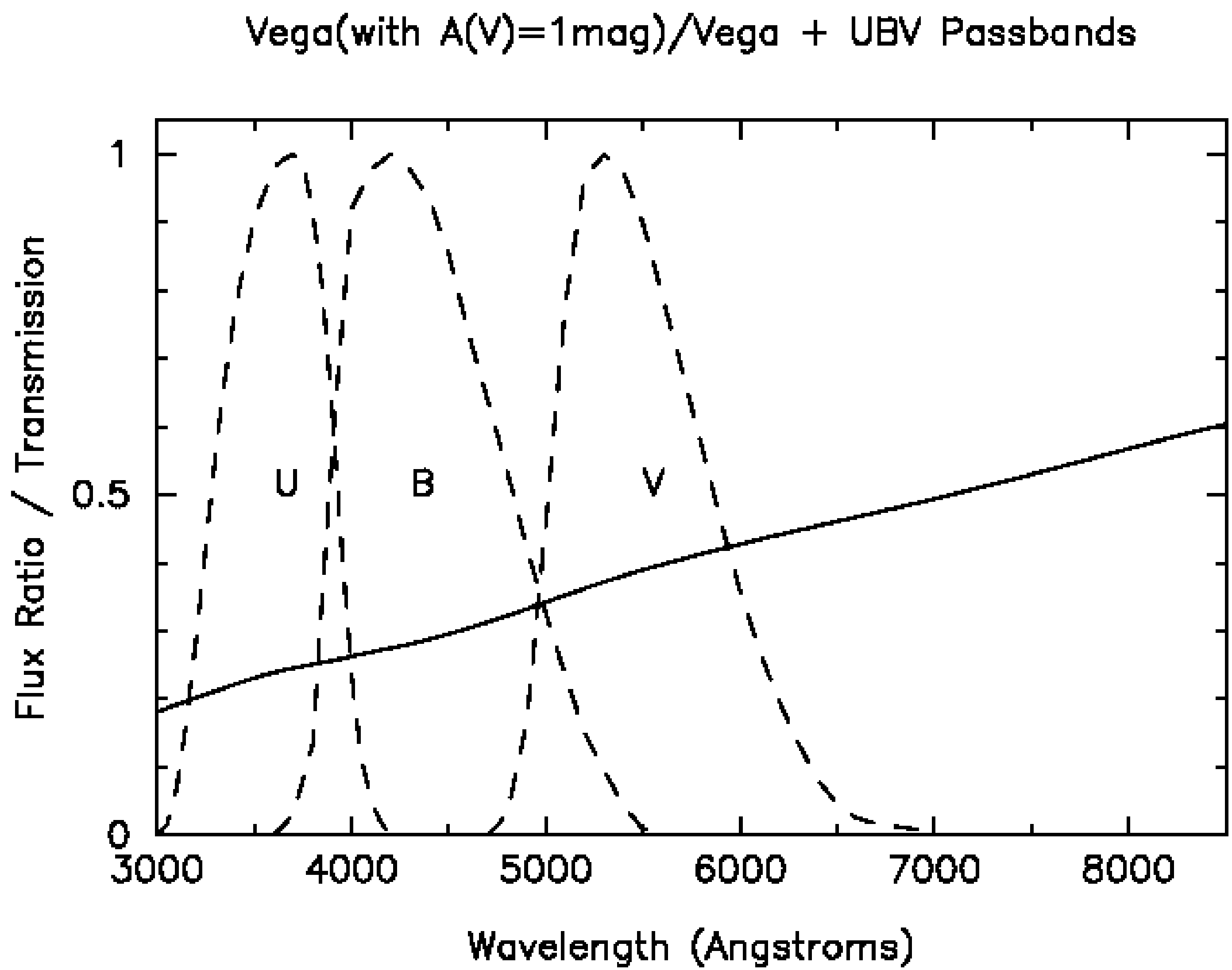
- Interstellar reddening and the effect of dust on the colours of stars

- Masses and radii of stars from binary systems
  - Visual binaries
  - Spectroscopic binaries
  - Eclipsing binaries

Interstellar Extinction and Reddening

- Presence of dust in the interstellar medium affects the observed flux distribution, and hence brightness and colours, of stars
- Dust both scatters and absorbs light. Empirically, the extinction [reduction in a stars brightness], measured in magnitudes, has a dependence on wavelength in the ultraviolet through near-infrared of $A(\lambda)$ proportional to $1/\lambda$ – i.e. the population of dust grains is more effective at scattering/absorbing light at shorter wavelengths for 0.1-3.0μ [or 1000-30000 Angstroms]
- If properties of the dust do not vary (on average mostly true) then the effect on the ratio of the fluxes at 2 or more wavelengths, and hence the colours between passbands (e.g. U-B and B-V) is the same
- Consider the observed flux distribution for Vega seen with no intervening dust and along a line-of-sight in the Galaxy with an extinction of 1.0 mag in the V-band, $A(V)$=1.0 mag


Vega + Vega through A(V)= 1 mag Galactic Extinction
Relative Flux
0
0.5
1
1.5
2
5000
10^4
1.5×10^4
2×10^4
2.5×10^4
Wavelength (Angstroms)


Vega(with A(V)=1mag)/Vega + UBV Passbands
Flux Ratio / Transmission
0
0.5
1
U
B
V
3000
4000
5000
6000
7000
8000
Wavelength (Angstroms)

Extinction and Reddening Definitions

- For historic reasons everything is referenced to the *V*-passband, with the "reddening" or "differential extinction" associated with a given wavelength, or passband, written as $E(\lambda\text{-}V)$, e.g. $E(B\text{-}V)$, where $E(\lambda\text{-}V) = A(\lambda)\text{-}A(V)$
- $E(B\text{-}V) = (B\text{-}V) - (B\text{-}V)_0$ where $(B\text{-}V)$ is the observed colour and $(B\text{-}V)_0$ is the unreddened colour
- The ratio of the extinction to the reddening is written $R=A(V)/\,E(B\text{-}V)$ where, empirically for the interstellar medium in the Galaxy, R=3.1, so, $A(V)=3.1\times E(B\text{-}V)$
- Looking from the Sun out of the Milky Way, A(V)=0.1-0.2 mag, while in the plane of the Milky Way (e.g. towards the Galactic centre) A(V)≈1-2 mag per kpc – observations of the Galactic centre using optical passbands hard work [=impossible!]

Horshead nebula in Orion

Distance ~450 pc
Diameter ~2 pc

Extention of a molecular cloud with large A(*V*) ~10 mag

Observations in two colours, allow the true (no extinction) colours to be deduced in many cases. Empirically, in our own Galaxy, find $U\text{-}B = 0.72(B\text{-}V)$+const giving the slope of the "reddening line" in the 2-colour *UBV* diagram

Ambiguity for objects of intermediate spectral type.
Technique important historically.

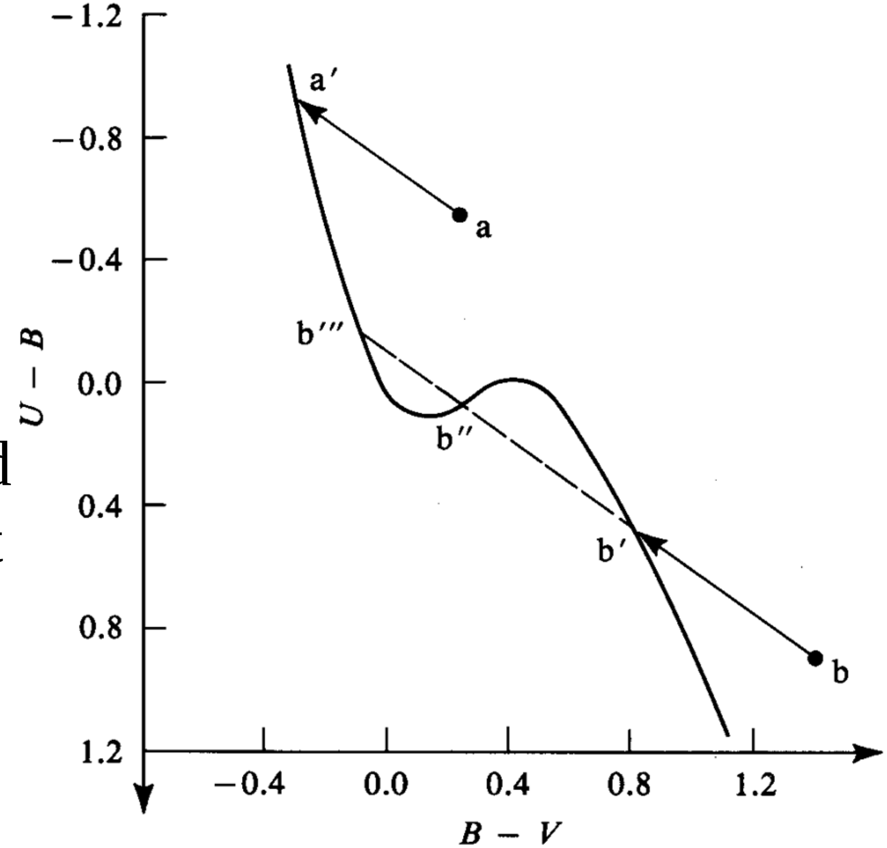
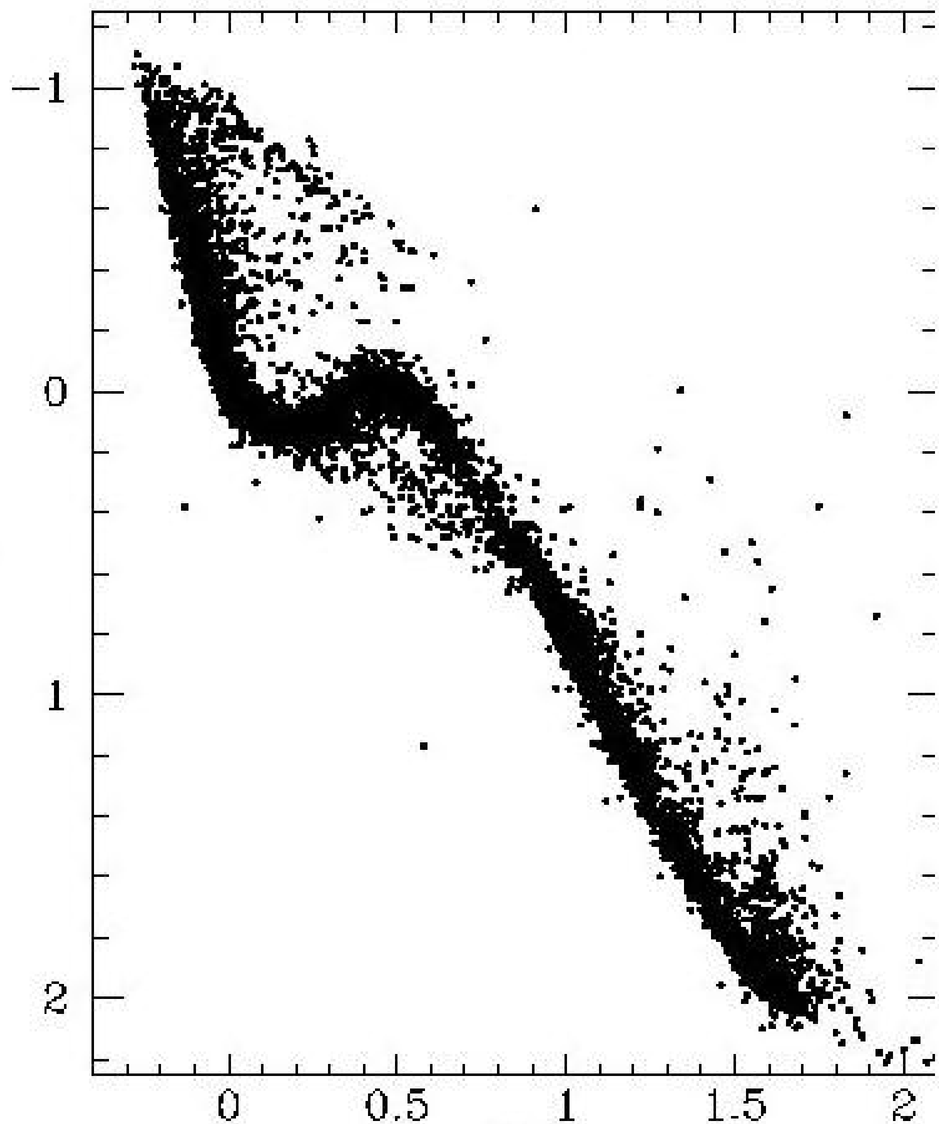


Figure 9.2. Correction for interstellar reddening. In the absence of interstellar reddening, the $B-V$ and $U-B$ colors of stars are found to lie along the wavy curve. (Notice that $U-B$ is conventionally plotted to increase downward.) Suppose star *a* is found to lie off this curve. We assume it has suffered interstellar reddening, and move it upward and leftward along a diagonal line of known slope until it falls on the unreddened curve at *a*′. The displacement in $B-V$ from *a* to *a*′ (0.4 magnitudes here) is called the color excess E_{B-V}. If star *b* were also measured to lie off the curve, we would also move it backward along the "reddening curve" of known slope; but now there are three possible choices for the unreddened position: *b*′, *b*″, and *b*‴. But if star *a* and star *b* lie in the same cluster, then the light from them has passed through the same line of sight, and star *b* should therefore have the same color excess E_{B-V} as star *a*. We would therefore deduce that point *b*′ gives the true colors of star *b*.

B-*V* versus *U*-*B* for stars in the sky with m_V<6.6 (just fainter than best naked eye detection)

Observations of stars corrected for the effects of interstellar reddening allowed stars to be placed on the x-axis of the HR-diagram.

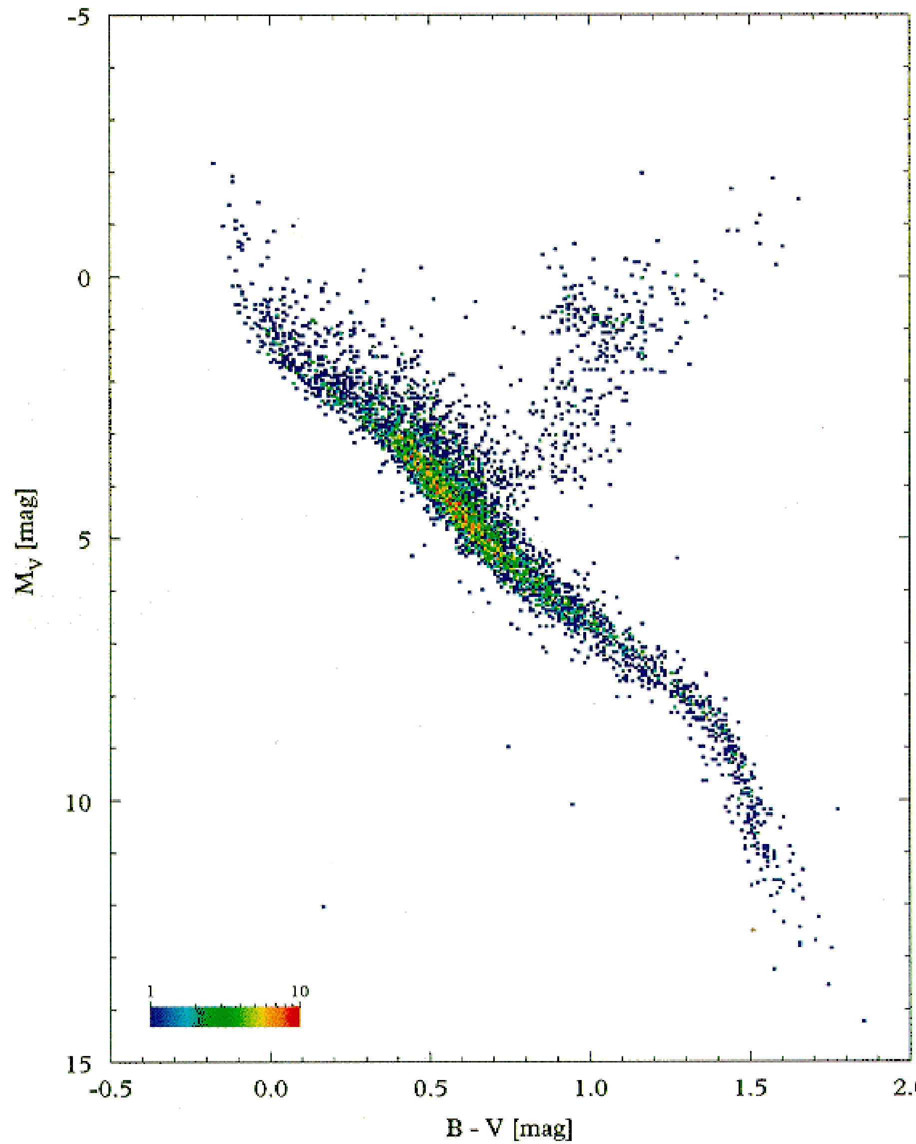
For observations of clusters of stars (where physical size << distance) can construct an HR-diagram [as illustrated in Lecture 3]



Hertzsprung-Russell diagram from HIPPARCOS satellite – bright, nearby stars detected down to a given magnitude.

Where on main sequence are the effects of interstellar dust most obvious?

Why?



Hertzsprung-Russell diagram in both observational form (Colour vs M_V or Spectral Type vs M_V) and theoretical form (T vs L)

Sun has spectral classification = G2V

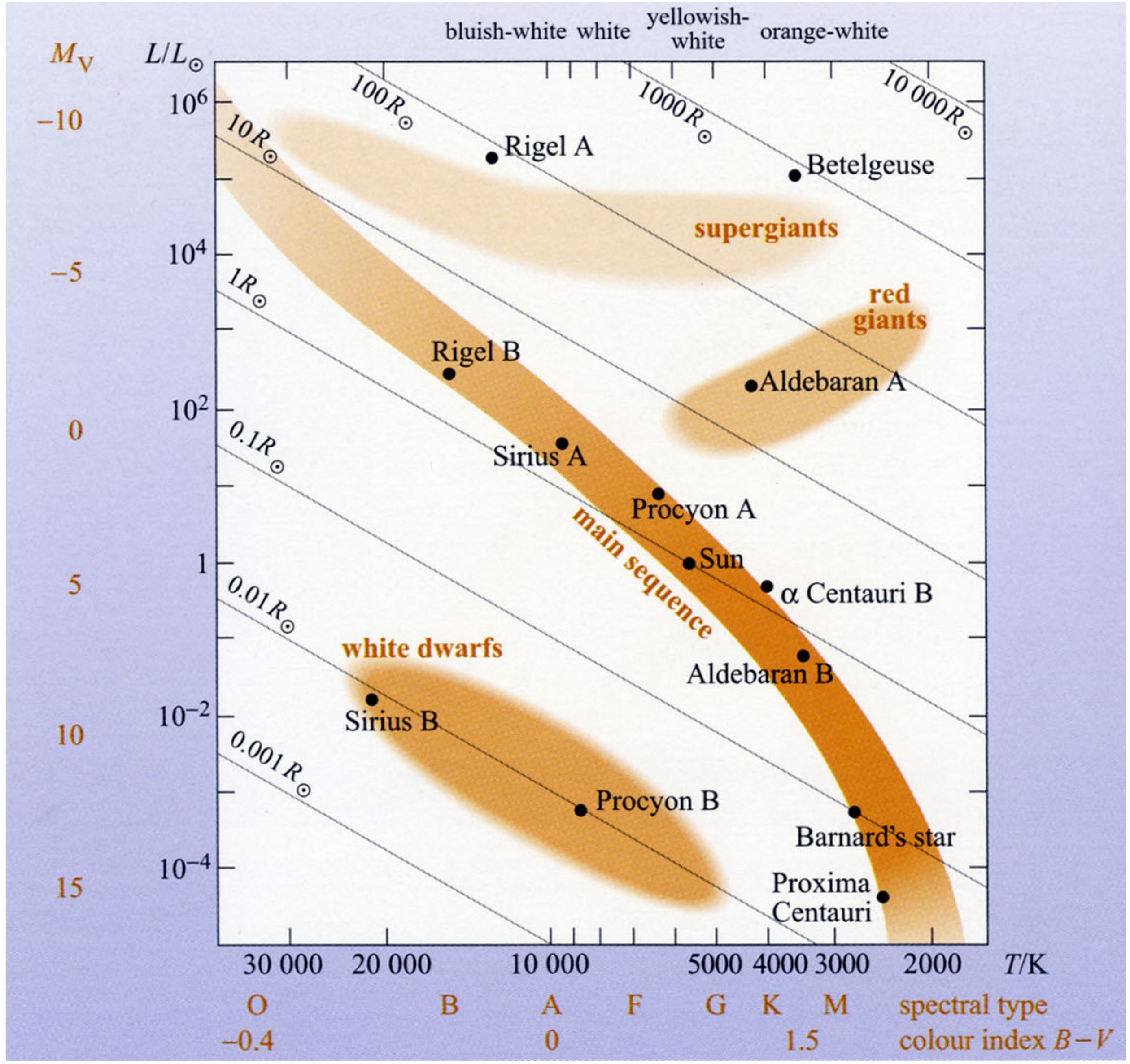


Figure 4.5 The H–R diagram in Figure 4.3, with the addition of stellar radii, and other information. (Adapted from Seeds, 1984)

Visual Binaries

- Nearby examples include Sirius A + B
- Stars in orbit about common centre of mass

Newton implies

$$\frac{m_1}{m_2} = \frac{r_2}{r_1}$$

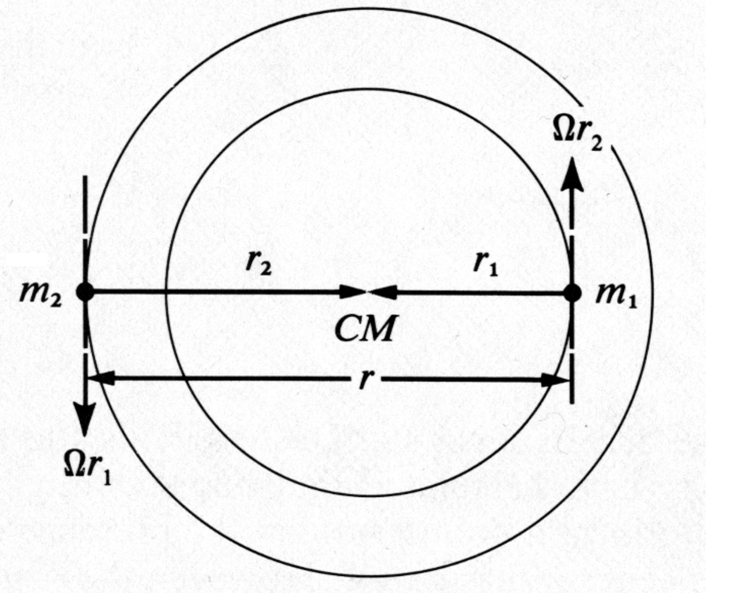


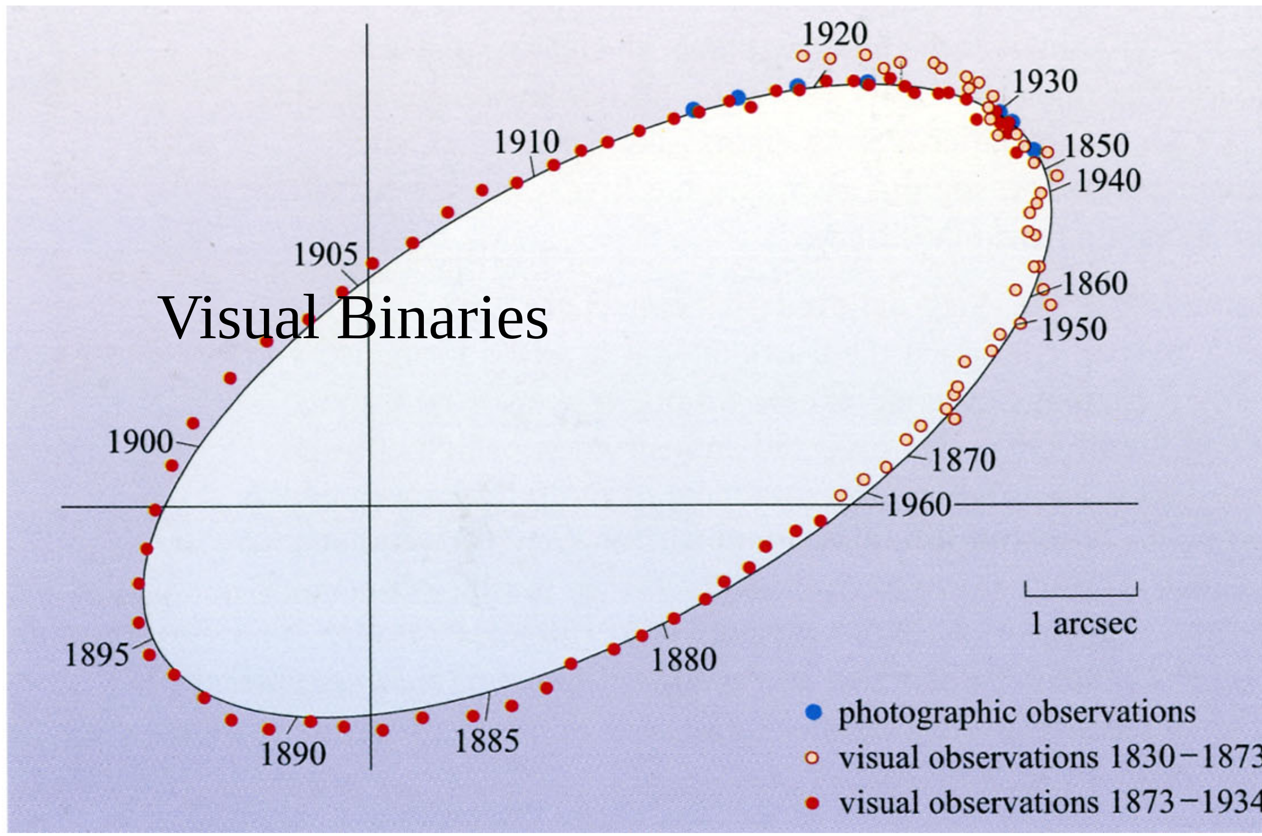
Figure P10.1b

and know mass ratio even without distance as θ=r/D, where D is the distance, which cancels in the ratio $\theta_1/\theta_2=r_1/r_2$

- Combine with Keplers 3rd Law:

$$P^2 = \frac{4\pi^2 (r_1 + r_2)^3}{G(m_1 + m_2)}$$

Visual Binaries



Visual Binaries

Figure 3.12 The orbit in the sky of one star relative to another in the visual binary system 70 Oph. The orbital period is 88 years. (Strand, 1973)

Visual Binaries

- For systems with known distance, D, can obtain orbital radii, r_1 and r_2, and hence individual masses, m_1 and m_2 once period, *P*, measured
- Represents ideal case but few systems known with reliable distances
- In general, orbit is not "face-on" and the plane of the orbit is inclined at an angle *i* to the line-of-sight. Measure apparent angular size of orbits $\theta' = \theta \cos i$
- Mass ratio $m_1/m_2 = \theta'_2 / \theta'_1$ is still known
- Now, Keplers 3rd Law becomes

$$m_1 + m_2 = \frac{4\pi^2}{G}\left(\frac{D}{\cos i}\right)^3 \frac{\theta'^3}{P^2} \quad \text{where} \qquad \theta' = \theta'_1 + \theta'_2$$

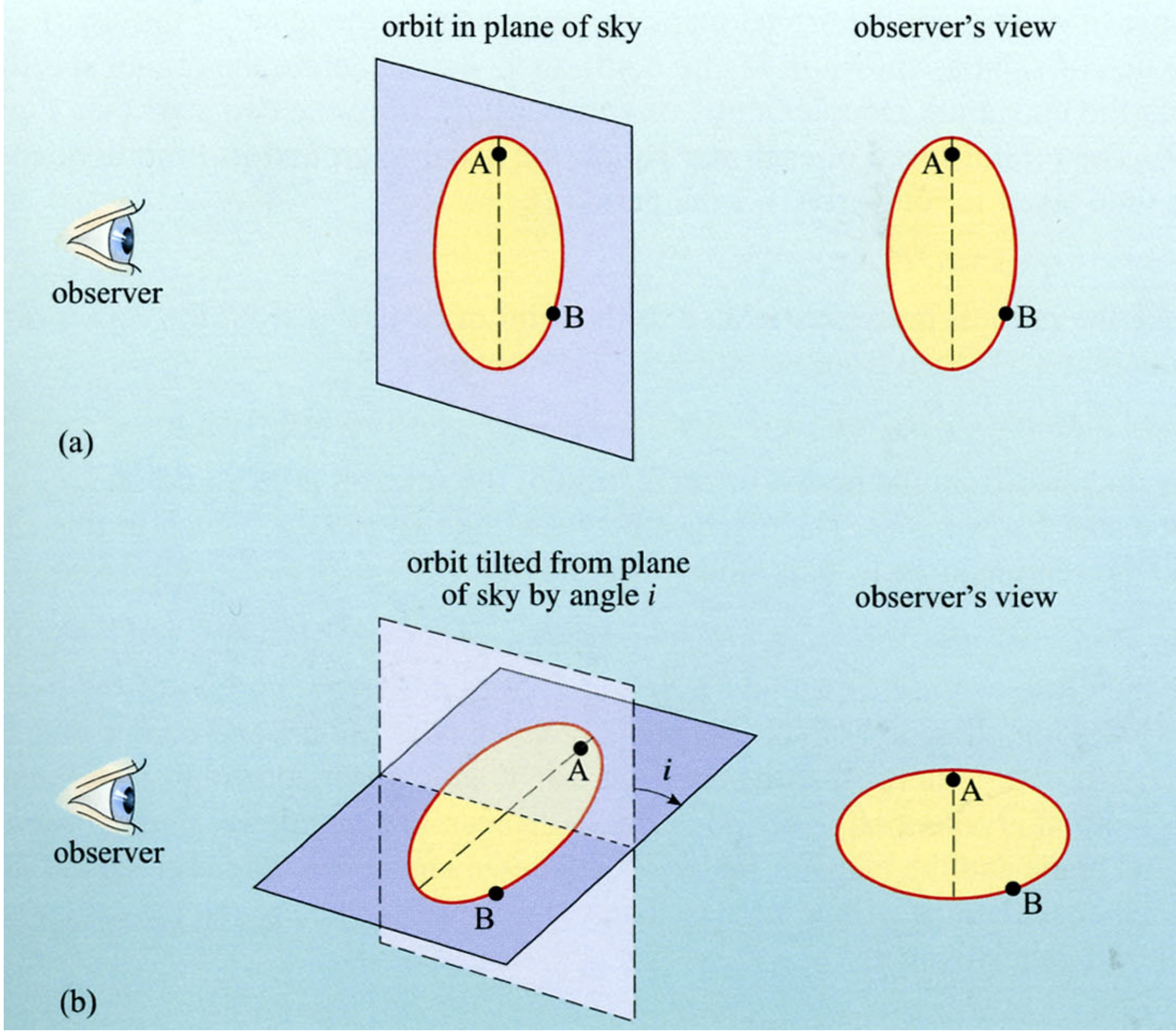


Figure 3.38 The change in appearance of an orbit due to its projection onto the plane of the sky. The dashed line shows the major axis of the orbit. In case (b) the true major axis is not the longest axis when projected onto the plane of the sky.

Visual Binaries

- Angular size of orbits and period from patient measurement
- Distance D from parallax
- Can determine inclination, *i*, from detailed model fit to positions of stars over their orbit
- Result is that for small number of systems, stellar masses know to high accuracy
- Binary systems with parallax distances and visual orbits do not contain broad range of stellar masses or stars in different parts of the HR-diagram – information is limited

Spectroscopic Binaries

- Far more common are spectroscopic binaries, systems where the individual stars can not be resolved (no angular information on properties of the orbits) but the change in the orbital velocities of the stars can be measured via the Doppler shift
- Spectroscopic binaries may be "double-lined", where the spectroscopic signal of both components are seen, or "single-lined", where the spectroscopic signature of only one component is seen, i.e. there exists an unseen companion to the single star whose change in orbital velocity with time can be measured. An unseen companion may be a normal star that is very faint relative to the more luminous component, or, the companion may be an exotic object, e.g. neutron star or black hole

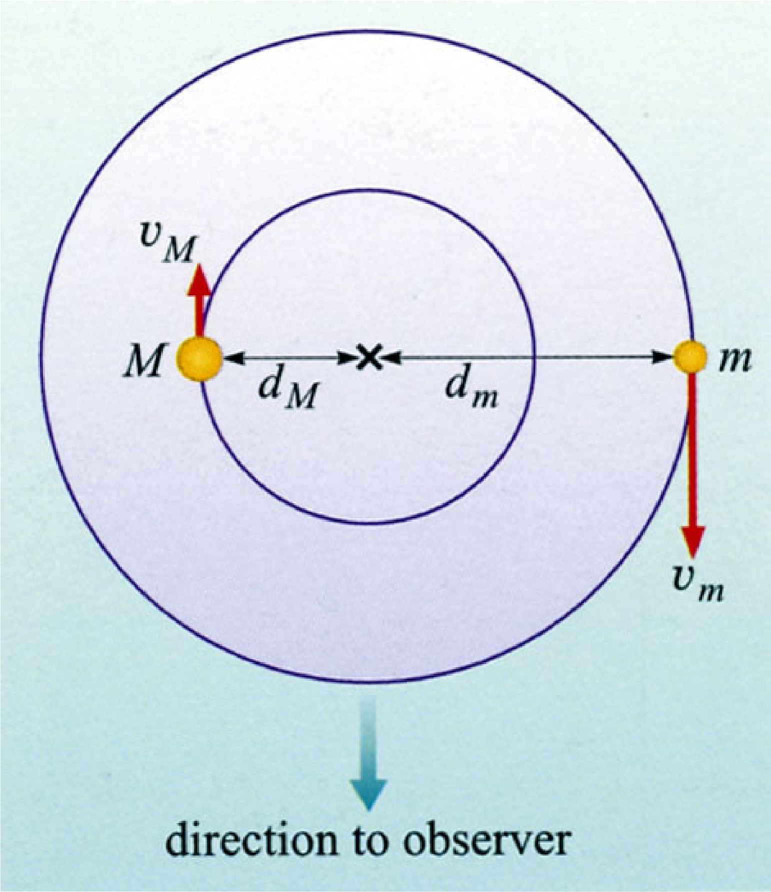


Figure 3.40 Circular orbits in a spectroscopic binary system relative to the centre of mass (×) of the system. The stars are at a position where the maximum separation of their spectral lines will be observed due to the Doppler shift.

Spectroscopic Binaries

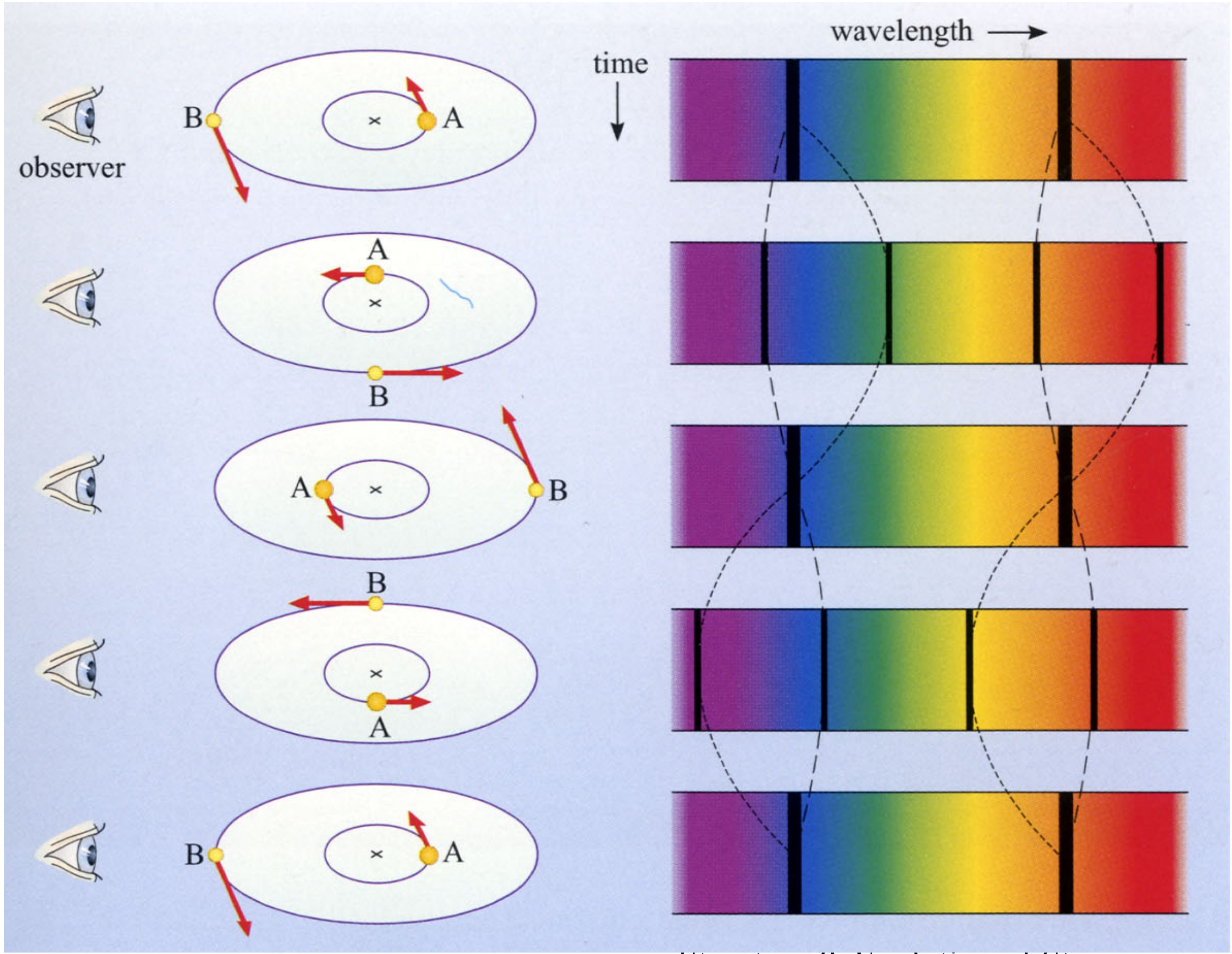


Figure 3.13 Identification of a spectroscopic binary star from Doppler shifts of spectral lines as the stars orbit their common centre of mass (marked with a cross). The diagrams on the left show the geometry of the stars in their orbits. On the right is a schematic representation of part of the spectrum of the stars (the spectra cannot be separated as the stars are too close together to be resolved).

Spectroscopic Binaries

For binary in a circular orbit the velocity around the orbit is constant and $v=2\pi r/P$

Measured radial velocity $v_r = v \sin i$, where again, the inclination is unknown

Stars take same time to complete orbit and

$$\frac{v_1 \sin i}{v_2 \sin i} = \frac{v_{1r}}{v_{2r}} = \frac{r_1}{r_2} = \frac{m_2}{m_1}$$

and, as for visual binaries, for double-lined objects without known distance, can determine the mass ratio for the stars

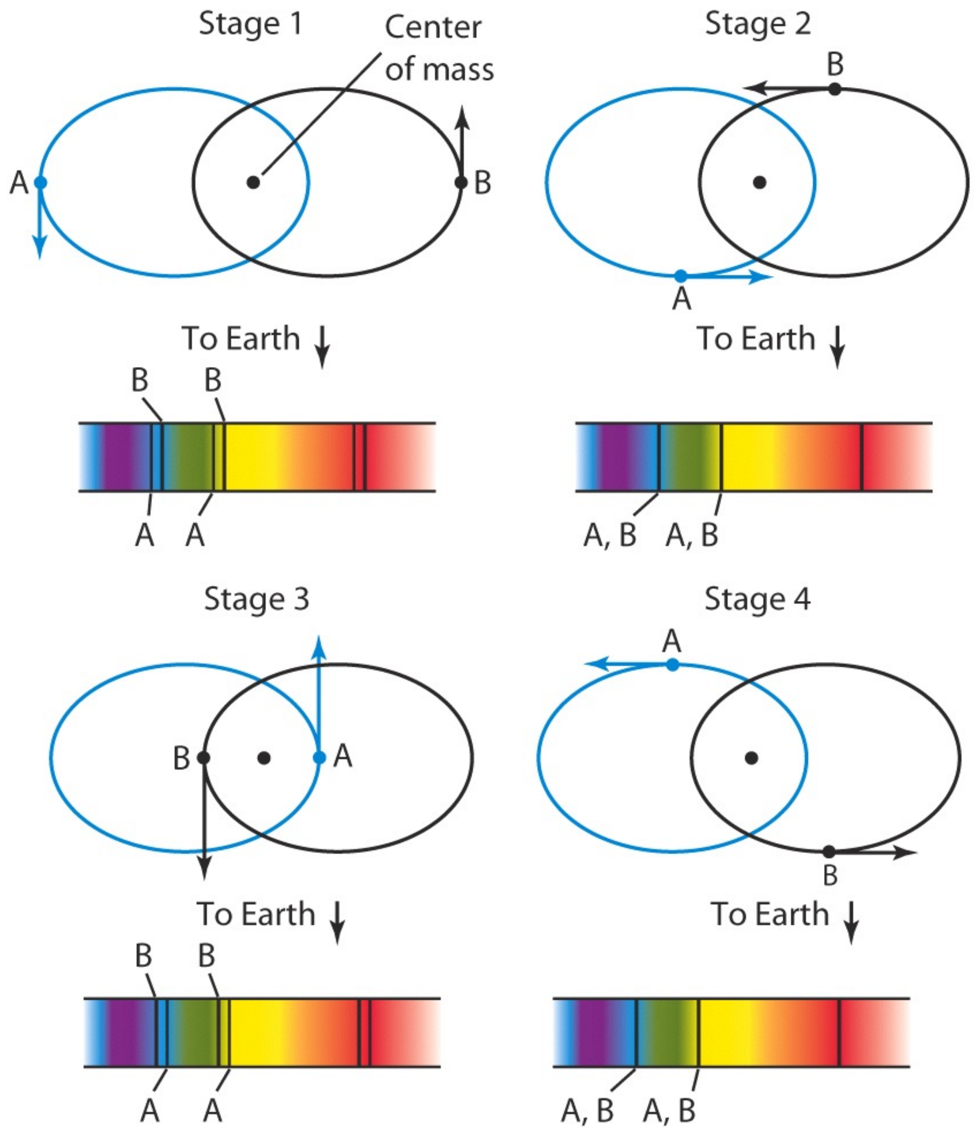
Spectroscopic Binaries

$vP=2\pi r$ for both components in orbit and $vP \sin i = 2\pi r \sin i$
Substitute for r in Keplers 3rd Law and multiply by $\sin^3 i$

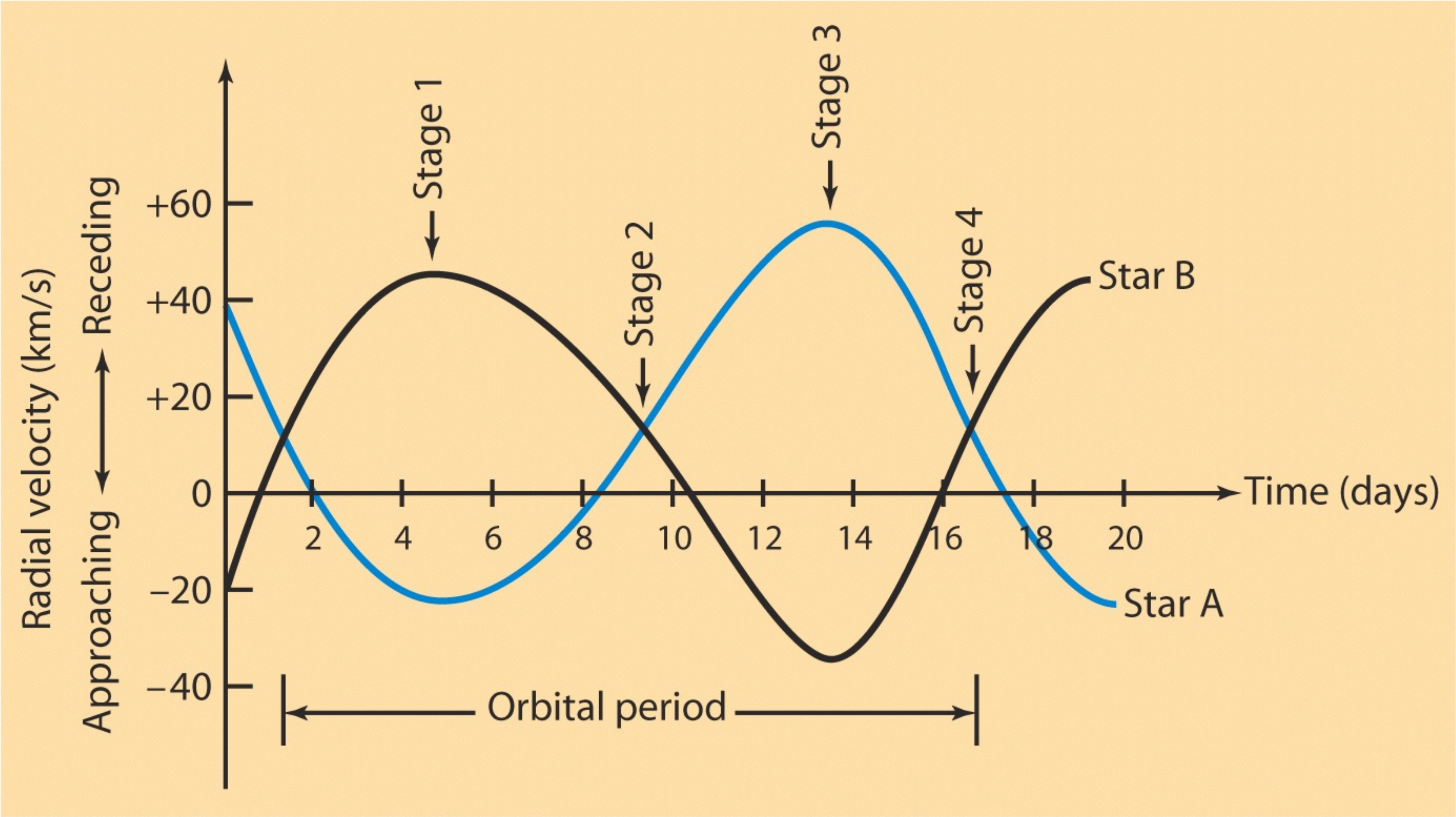
$$(m_1 + m_2)\sin^3 i = \frac{4\pi^2 (r_1 + r_2)^3 \sin^3 i}{GP^2} = \frac{P}{2\pi G}(v_{1r} + v_{2r})^3$$

$$\Rightarrow m_1 + m_2 \geq \frac{P}{2\pi G}(v_{1r} + v_{2r})^3$$

where quantities on rhs are observable but only a limit on the sum of the masses for double-lined systems


Stage 1
Center of mass
A
B
To Earth
B
B
A
A
Stage 2
B
A
To Earth
A, B
A, B
Stage 3
B
A
To Earth
B
B
A
A
Stage 4
A
B
To Earth
A, B
A, B

Radial-velocity curve for double-lined spectroscopic binary



Spectroscopic Binaries

Single-lined system, can determine only one velocity, v_{1r}, however, write v_{2r} in terms of mass and v_{1r}

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

Keplers 3rd Law then can be written

$$(m_1 + m_2)\sin^3 i = \frac{P}{2\pi G} v_{1r}^3 \left(1 + \frac{m_1}{m_2}\right)^3$$

rearrange

Gives the “mass function” on the lhs in terms of observables on the rhs

$$\frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2} = \frac{P}{2\pi G} v_{1r}^3$$

Spectroscopic Binaries

Can obtain a lower limit to mass of the unseen companion object, m_2, from noting that m_1>0 and sin $i \leq 1$ and then

$$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i = \frac{P}{2\pi G} v_{1r}^3 < m_2$$

Observations of single-lined spectroscopic binaries provide best constraints on mass of stellar mass black hole

When $m_2 << m_1$, i.e. planets, then $m_1+m_2 \approx m_1$ and knowledge of m_1 gives $m_2 \sin i$

$$m_2^3 \sin i^3 \approx \frac{P}{2\pi G} v_{1r}^3 m_1^2$$

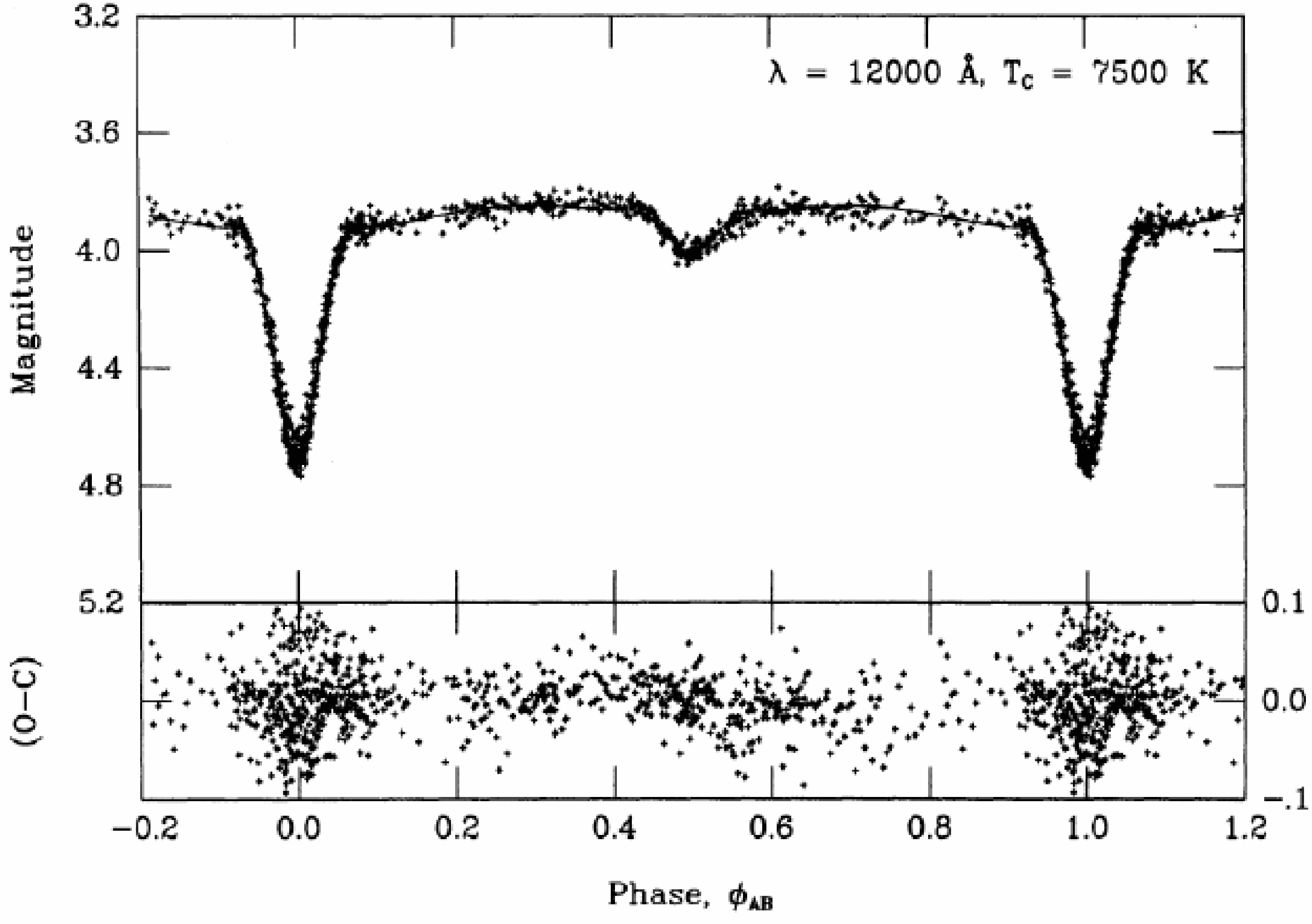
Again, unknown inclination is severe limitation, although statistics of samples are fairly robust

Eclipsing Binaries

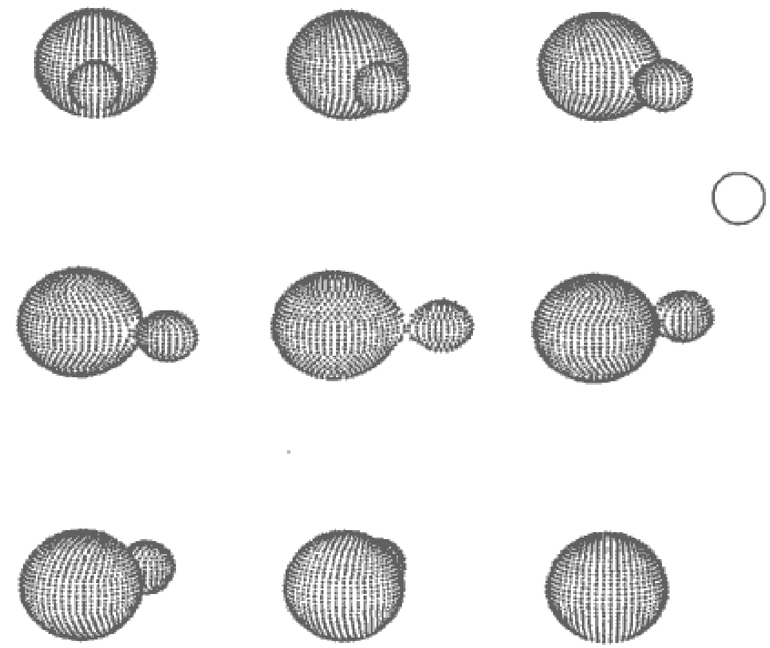
Constraints from double-lined and single-lined binaries of use in many cases but determination of accurate individual masses is precluded by unknown orientation of system – do not know inclination, i.

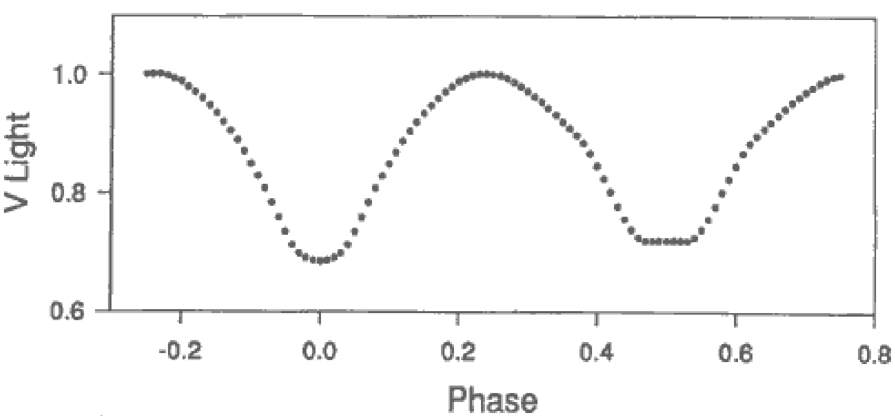
Eclipsing binaries provide the solution by constraining the inclination, i, such that $i \approx 90°$. Constraint strong for all but very close systems where stellar radii are a significant fraction of the orbital separation.

Lightcurve of eclipsing binary (Algol type)

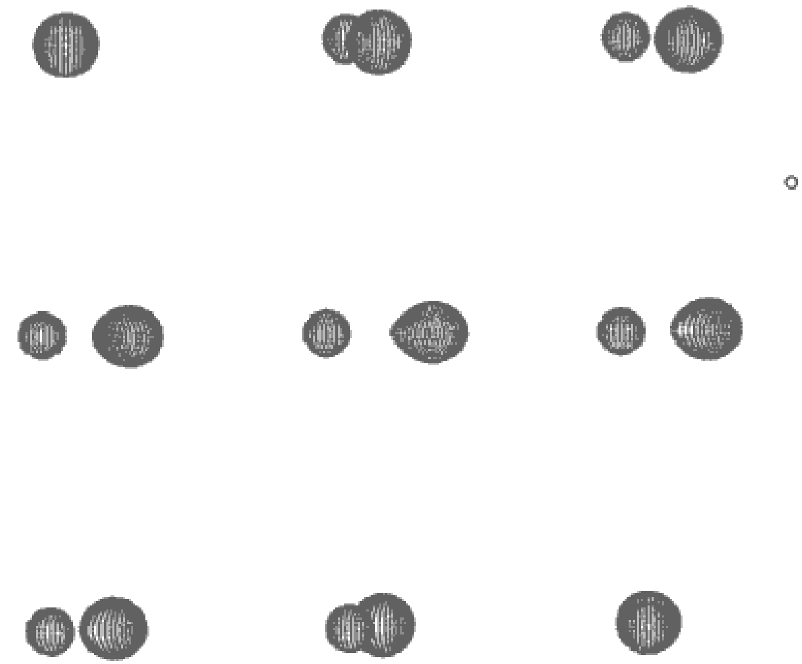


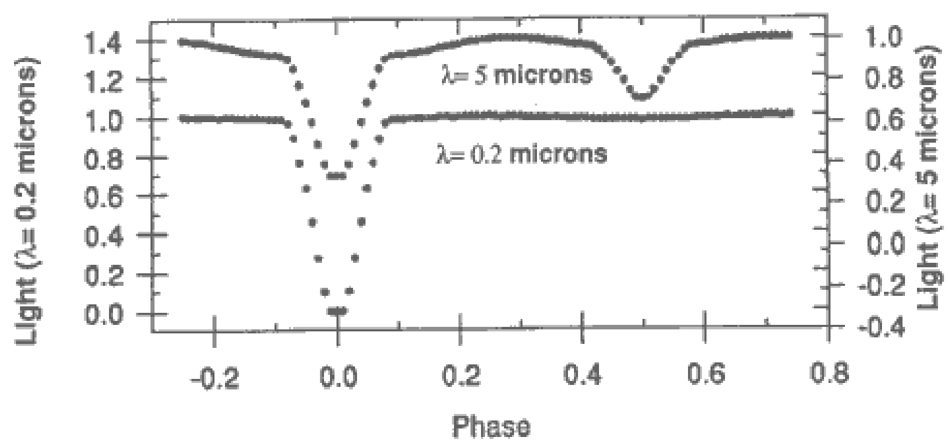
Close separation “contact binary. Note continuous variation in light curve with orbital phase. Inclination can in fact be quite far from 90°. (from R E Wilson – Florida)





Wider separation system, no contact but larger distortion. Light-curve observed at infrared wavelengths and at 2000A shown. Why so different? (from R E Wilson – Florida)





Stellar radii from eclipsing binaries

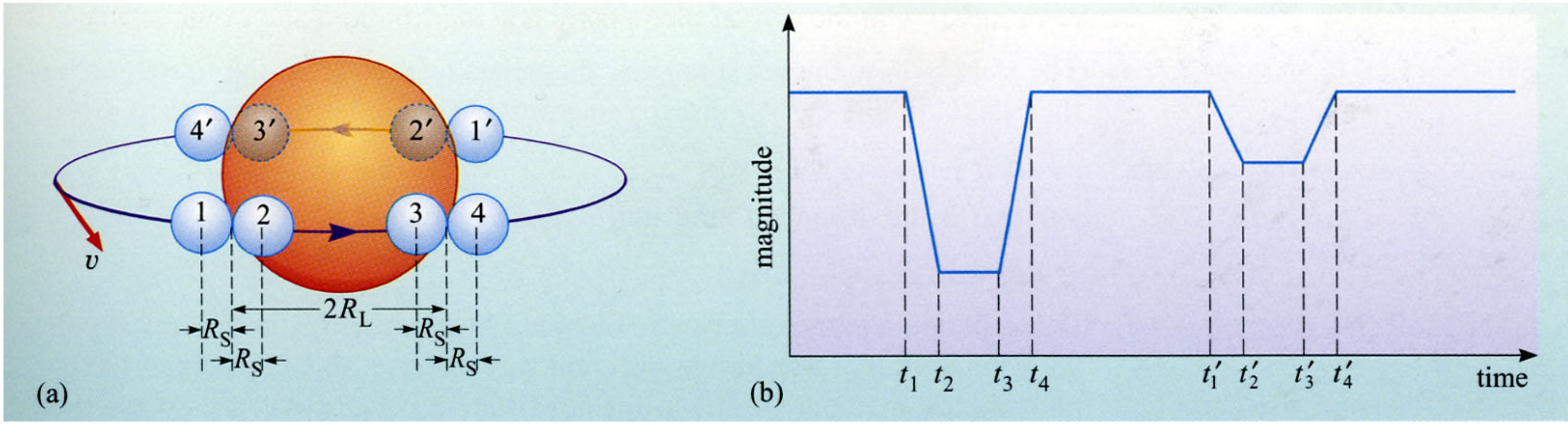


Figure 3.41 (a) Schematic of an eclipsing binary showing the different phases of eclipses.
(b) Light curve indicating times of each event during the eclipses. Primary minimum occurs when the hotter star is eclipsed since the light emitted per unit area is greater for the hotter star. The example shows the case when the larger star is the hotter one.

Radii from Eclipsing Binaries

- For orbit with $i \approx 90°$ the size of the orbit is known, $vP=2\pi r$, and size of stars can be calculated directly from timing of phases of the eclipse.
- Flat-bottomed eclipses indicate total disappearance of star
- For two stars with radii R_s and R_L in the figure have radius of smaller star from $2R_s = v \times (t_2 - t_1)$
- Straightforward to deduce that radius of the larger star is given by $2R_L = v \times (t_4 - t_2)$
- Direct geometric determination of radii but number of systems small

Lecture 4: Summary

- You should understand the effect of interstellar dust on the colours of stars.
- Masses of stars can be obtained from binary systems with special geometries.
- You should be able to calculate masses and radii of stars given parameters for binary systems

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