Photometric variability of binaries

Research workshop on evolved stars

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Introduction

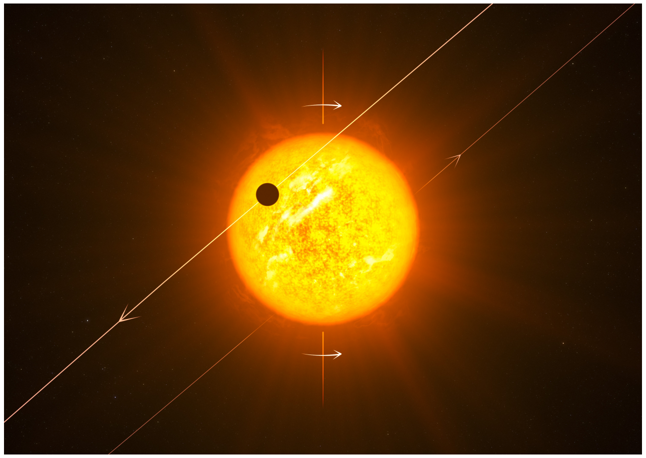
What are variable stars?

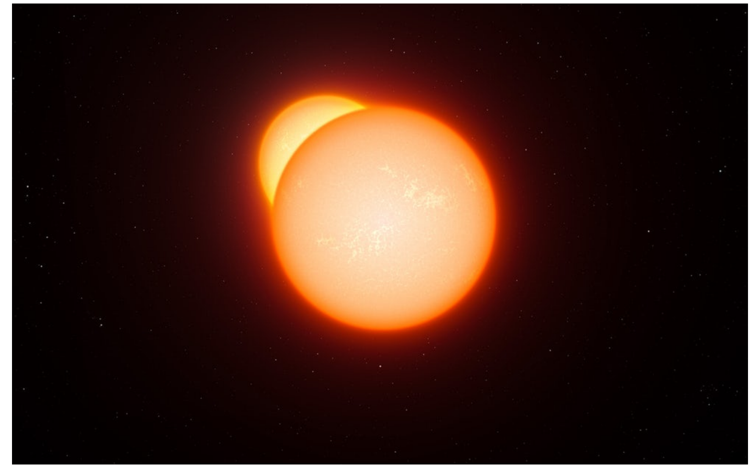
Stars, whose brightness vary periodically, semi-periodically or irregularly as seen from earth

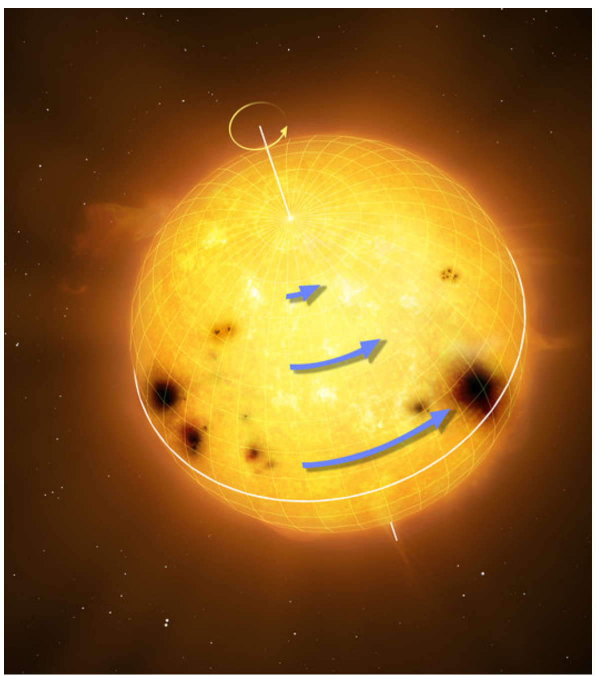
- extrinsic variables: variability is due to the eclipse of one star by another or the effect of stellar rotation
- intrinsic variables: variation is due to physical changes in the star or stellar system

Extrinsic variables

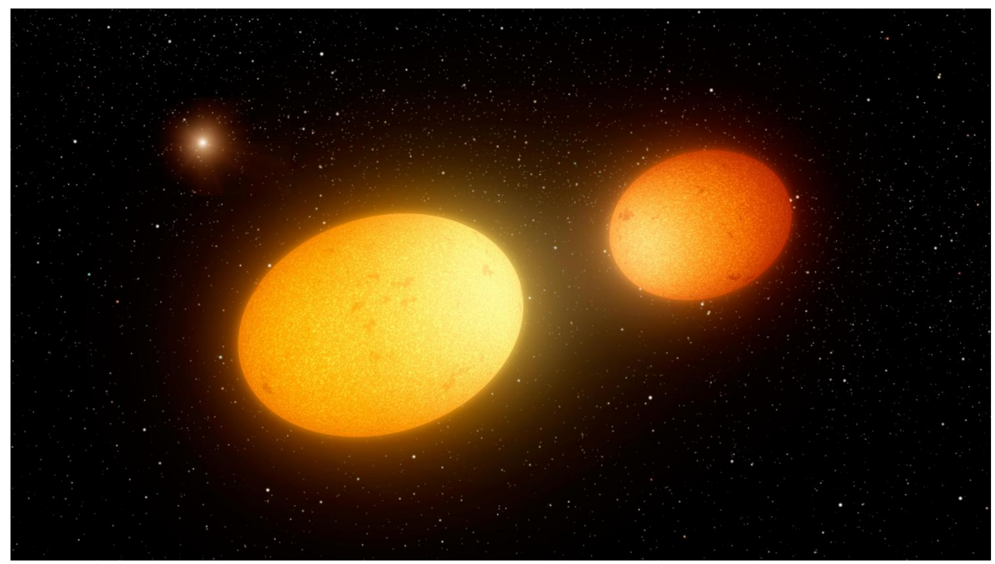
Transiting planets/Eclipsing binaries





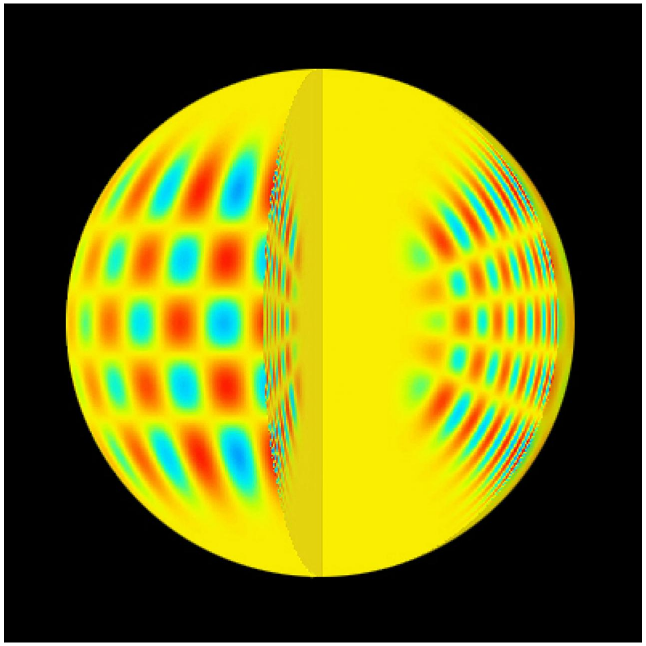


Rotating variables

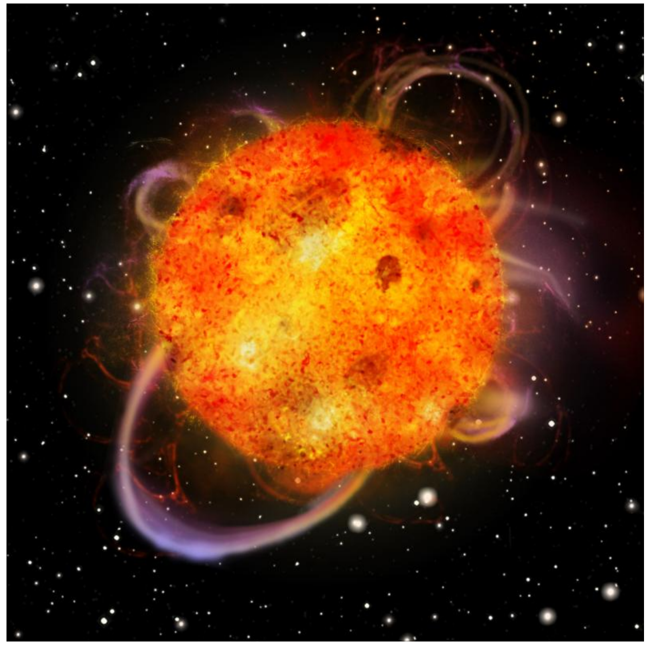


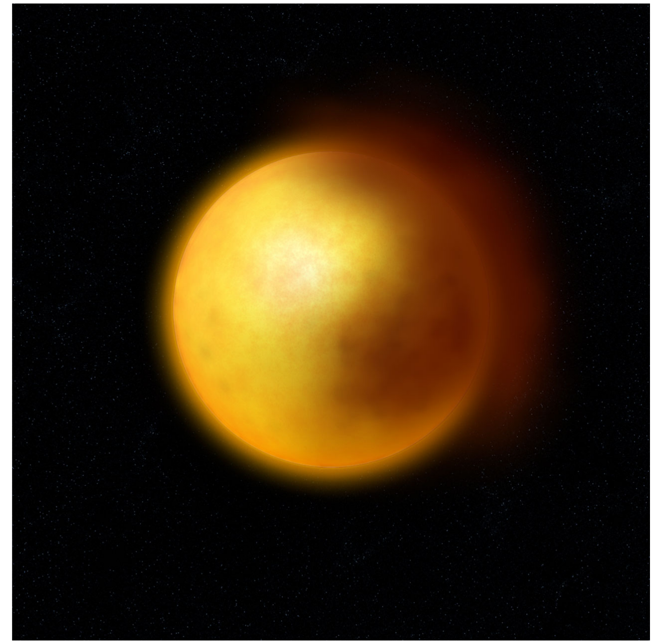
Intrinsic variables

Pulsating variables

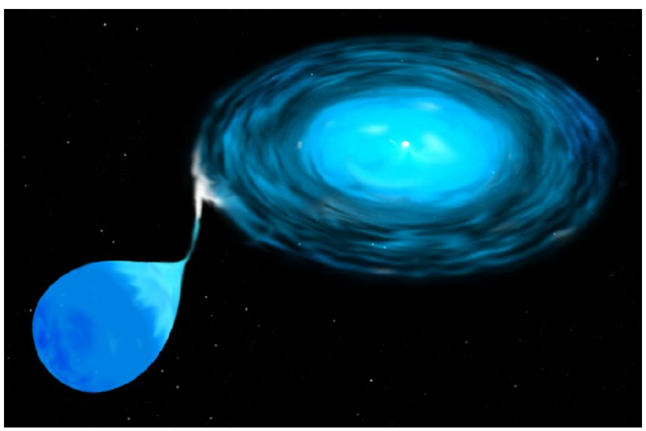


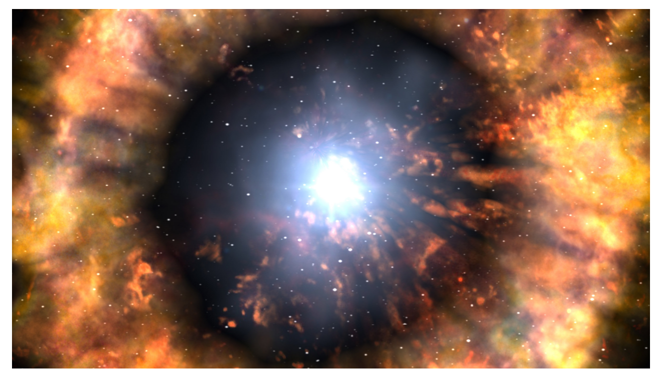
Eruptive variables





Cataclysmic variables

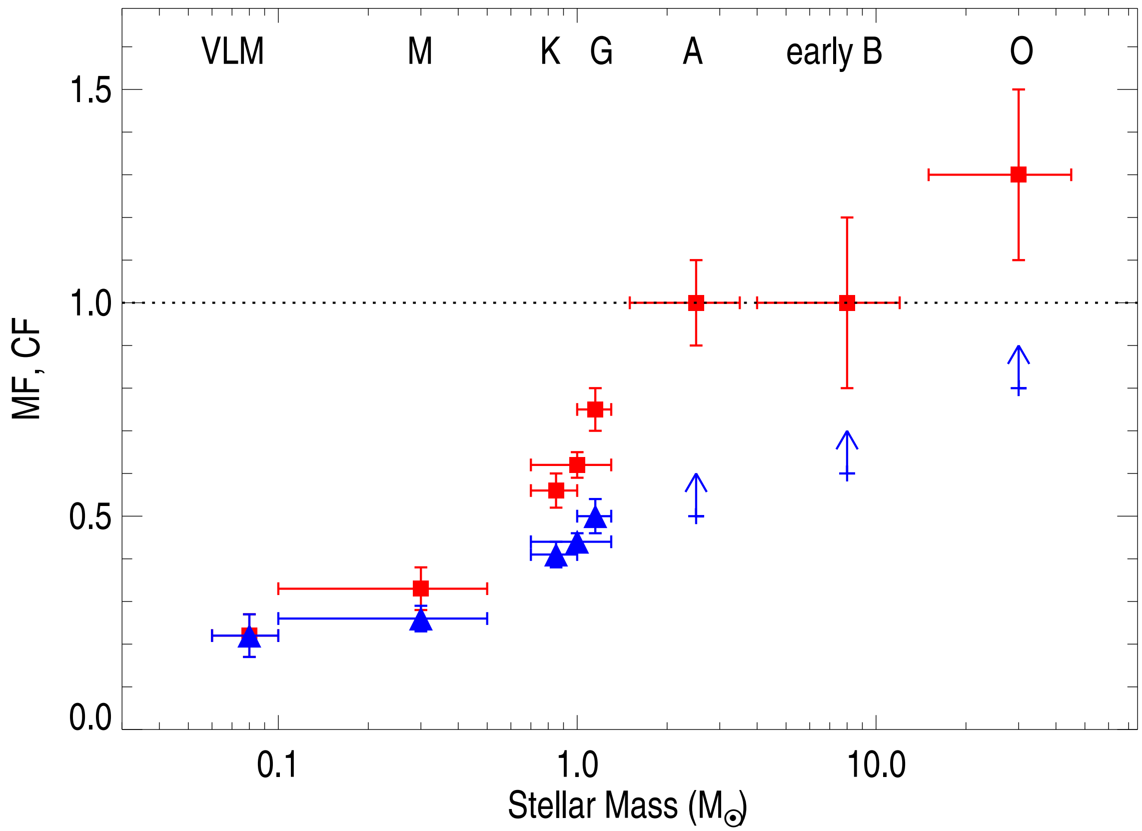




Binary Stars: Overview

Binaries

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



Duchene & Kraus 2013

$\rightarrow$ stellar evolution cannot be understood without understanding binary evolution

Types of Binaries

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).

Mass determination in binaries

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

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

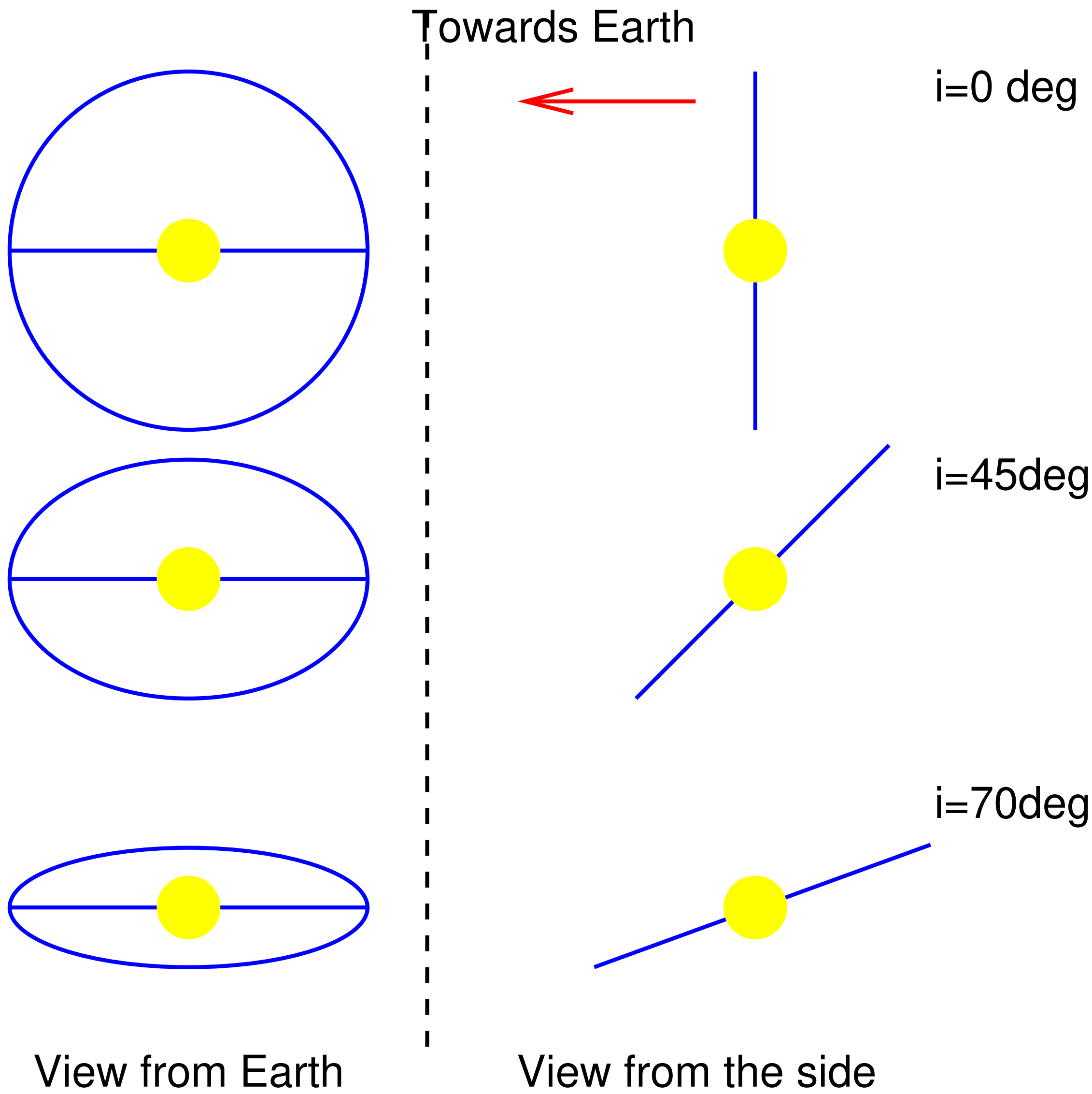
where

- $M_{1,2}$: 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

Mass determination in binaries

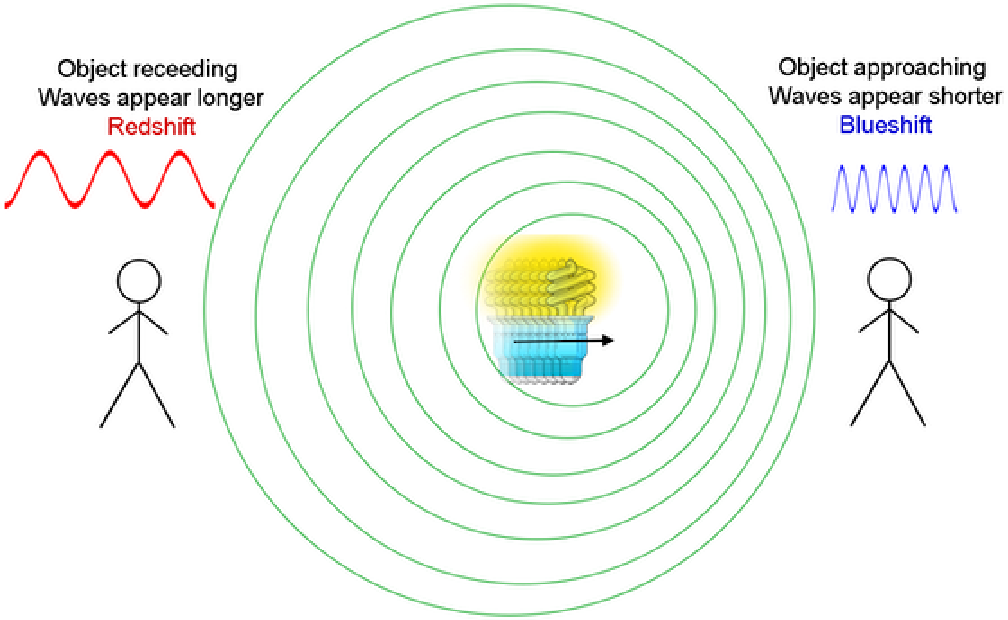


Problem when analysing orbits: orientation of orbit in space: “inclination”

In simplest case: real semi-major axis:

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

Spectroscopic Binaries



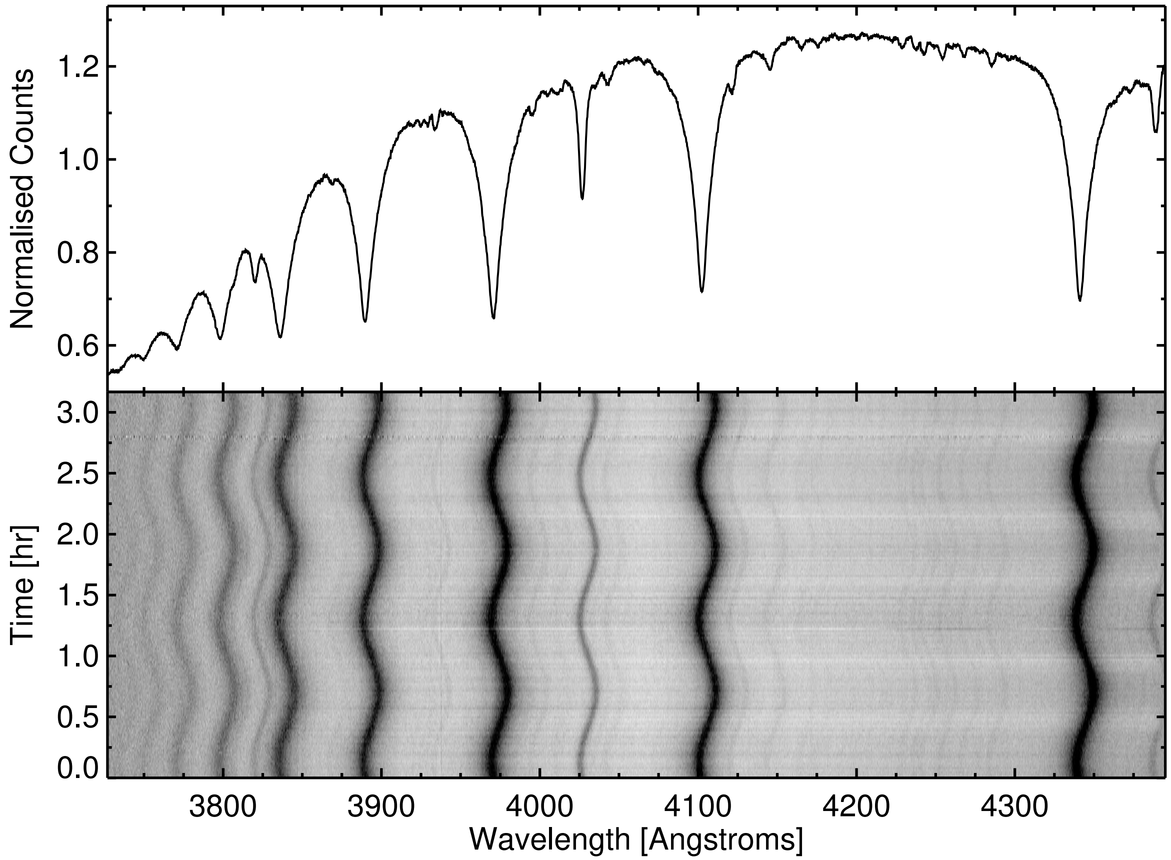
Spectroscopic binaries: Components close together: orbital motion via periodic Doppler shift of spectral lines.

SB2 = both spectra are visible

SB1 = only one spectrum visible

in **eclipsing** SB2 systems the inclination (close to i=90°) and masses for both components can be determined.

Spectroscopic Binaries



CD−30°11223 (Geier, ..., Schaffenroth et al. 2013, A&A 554, 10)

Motion of star visible through Doppler shift in stellar spectrum:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c} = \frac{v \sin i}{c} \sin \frac{2\pi}{P} t$$

Spectroscopic binaries

Double-lined spectra, case SB2

Assume circular orbit ($e = 0$)

K_1, K_2	velocity half amplitudes of components 1 & 2
P	orbital period
$2\pi a_{1/2}$	orbital radii of components 1 & 2

$$K_{1/2} = \frac{2\pi a_{1/2}}{P} \sin i$$

$$\Longrightarrow a_{1/2} \sin i = \frac{P}{2\pi} K_{1/2}$$

again sin *i* remains indetermined

Spectroscopic binaries

centre of mass law:

$$\frac{M_1}{M_2} = \frac{a_2}{a_1} = \frac{K_2}{K_1}$$

Kepler's third law:

$$M_1 + M_2 = \frac{4\pi^2}{G P^2} a^3,$$

$$a = a_1 + a_2 = \frac{P}{2\pi}(K_1 + \frac{P}{2\pi}K_2) / \sin i$$

$$\Longrightarrow M_1 + M_2 = \frac{4\pi^2}{G P^2} \frac{P^3}{(2\pi)^3} \frac{(K_1+K_2)^3}{(\sin i)^3} (\star)$$

$$\Longrightarrow M_1 + M_2 = \frac{P}{2\pi G} \frac{(K_1+K_2)^3}{(\sin i)^3}$$

$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}(K_1 + K_2)^3$$

$\Longrightarrow$ two equations for three unknowns ($M_1 + M_2$, $\sin i$),
$\sin i$ can only be determined for eclipsing binaries

Spectroscopic binaries

Single-lined spectra, case SB1

(only one spectrum visible):

K_2 unknown: $K_2 = K_1 \frac{M_1}{M_2}$

Insert in equation $(\star)$:

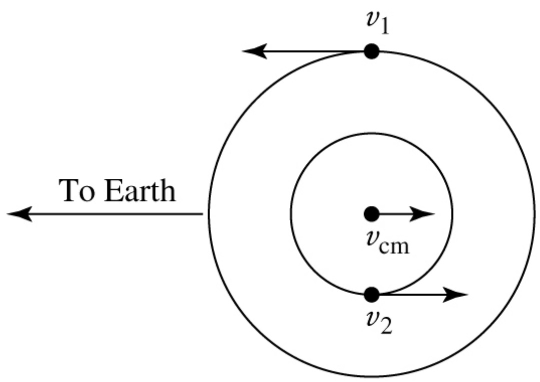
$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}(K_1 + K_1 \frac{M_1}{M_2})^3$$

$$\frac{M_2(1 + \frac{M_1}{M_2})(\sin i)^3}{(1 + \frac{M_1}{M_2})^3} = \frac{P K_1^3}{2\pi G}$$

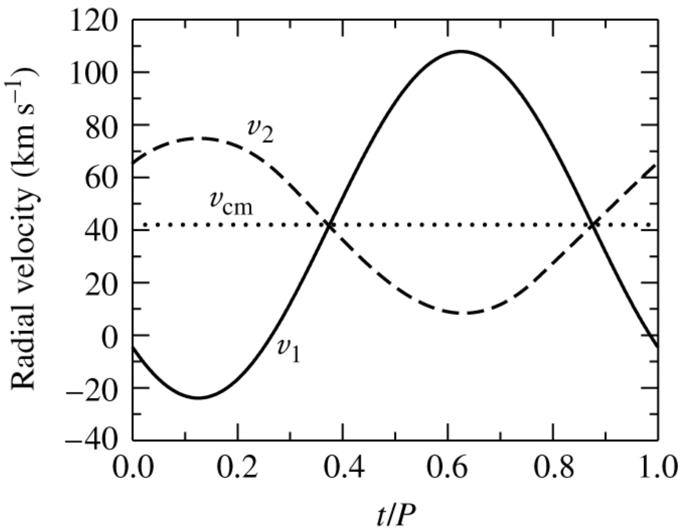
Mass function $f(M)$:

$$f(M) = \frac{M_2 (\sin i)^3}{(1+\frac{M_1}{M_2})^2} = \frac{P K_1^3}{2\pi G}$$

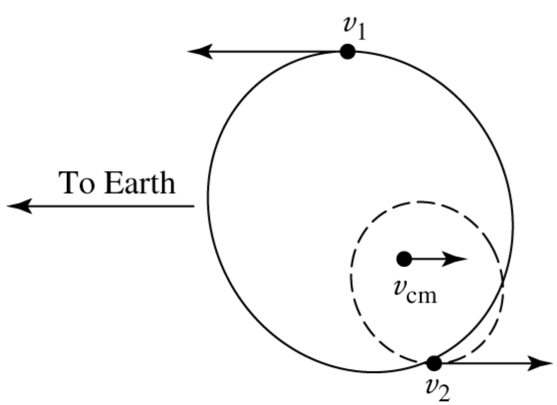
Spectroscopic binaries: Radial velocity curve



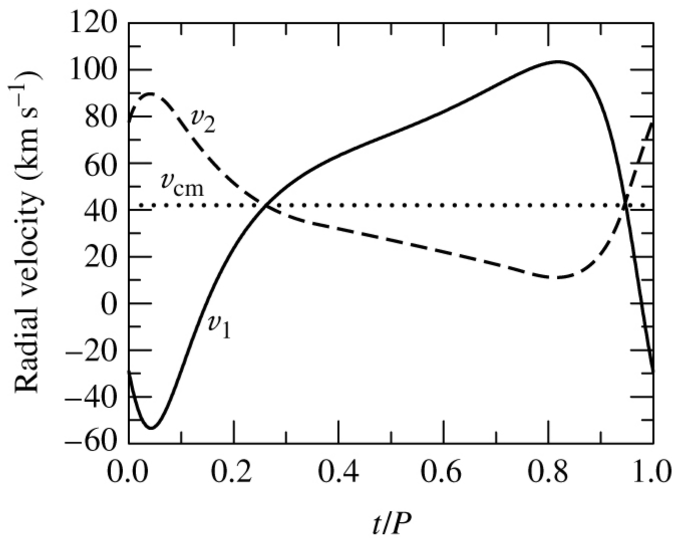
(a)



(b)



(a)



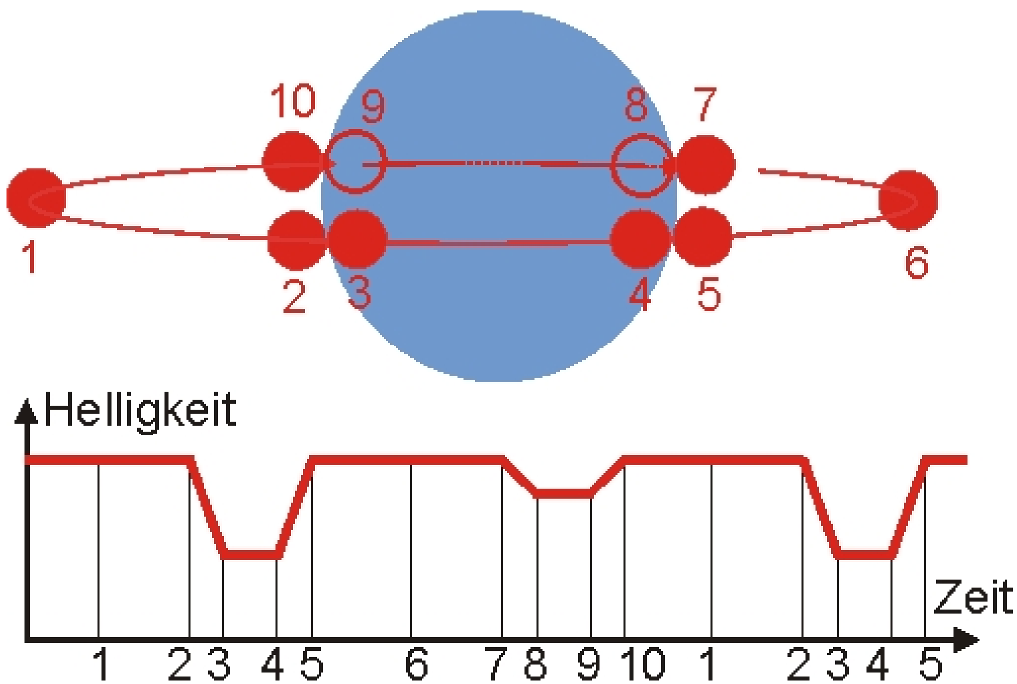
(b)

http://astro.unl.edu/naap/esp/animations/radialVelocitySimulator.html

Light Curves of Eclipsing Binary Stars

Stellar Diameters

Eclipsing Binaries



Determination of diameters d_A and d_B from eclipse timing:

Duration of eclipse:

$$d_A + d_B = v(t_5 - t_2) \tag{3.1}$$

Duration of eclipse egress:

$$d_A - d_B = v(t_4 - t_3) \tag{3.2}$$

therefore:

$$d_A = \frac{1}{2}v(t_5 - t_2 + t_4 - t_3) \tag{3.3}$$

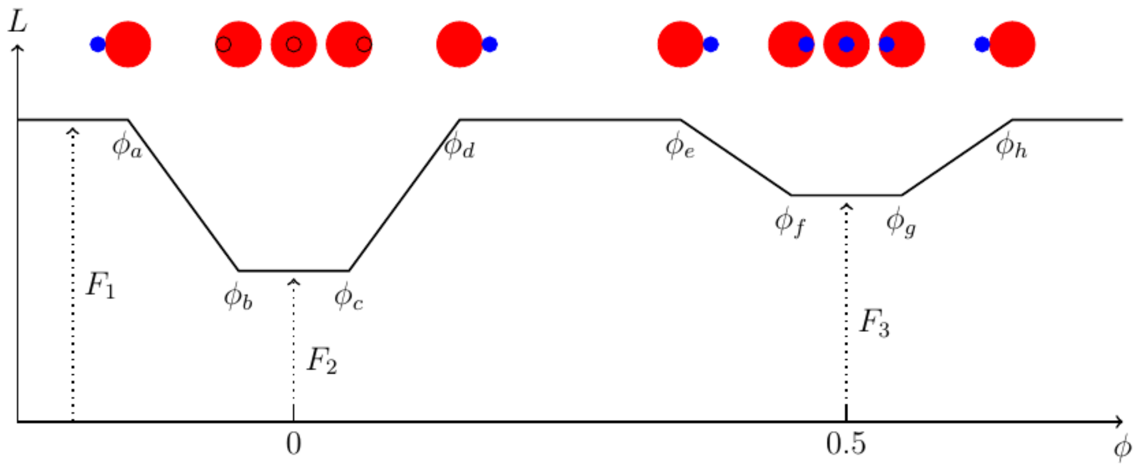
$$d_B = \frac{1}{2}v(t_5 - t_2 - t_4 + t_3) \tag{3.4}$$

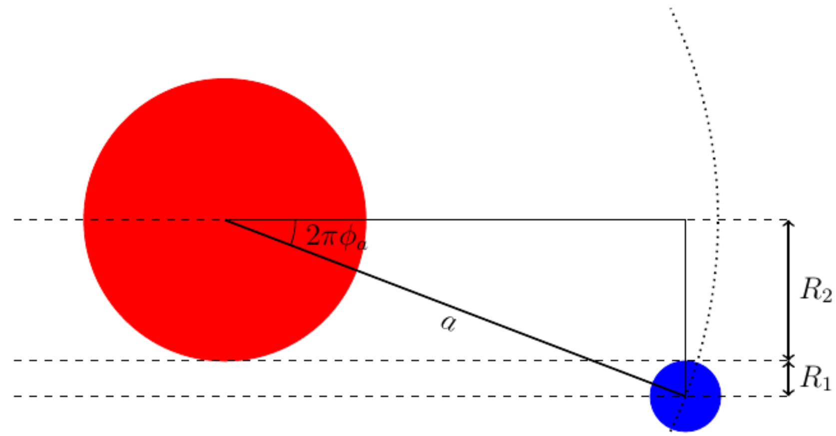
Note: requires extremely accurate photometry

Resulting radii are independent of distance

Temperature and radius ratio

Eclipsing Binaries





Stephan-Boltzmann-Law

$$L_{1/2} = 4\pi R_{1/2}^2 T_{1/2}^4 \tag{3.5}$$

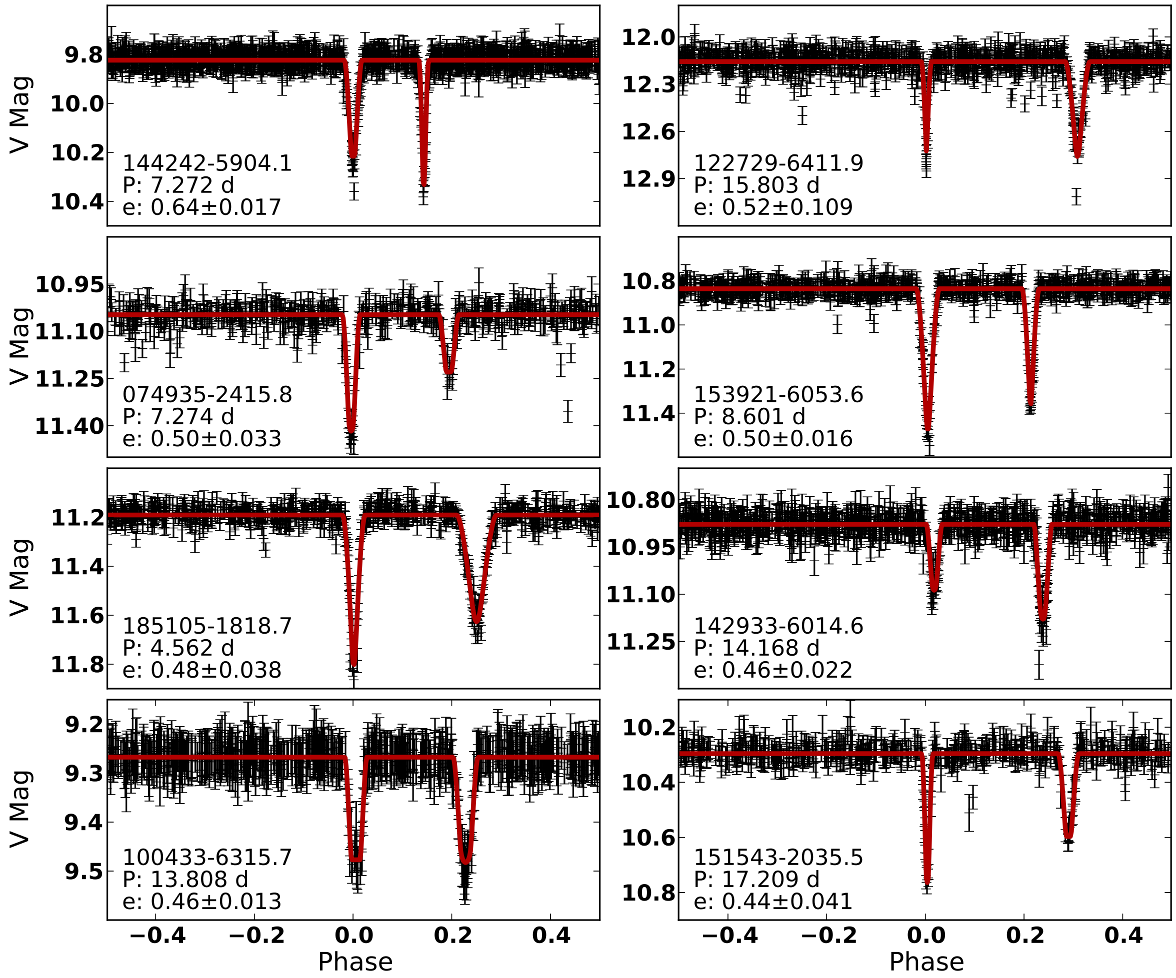
$$\frac{T_1}{T_2} = \left(\frac{F1 - F2}{F_1 - F_3}\right)^{1/4} \tag{3.6}$$

$$\frac{R_1}{R_2} = \left(\frac{F1 - F3}{F_2}\right)^{1/2} \tag{3.8}$$

$$\frac{R_1}{a} = \frac{1}{2}(\sin 2\pi\Phi_a - \sin 2\pi\Phi_b) \tag{3.7}$$

$$\frac{R_2}{a} = \frac{1}{2}(\sin 2\pi\Phi_a + \sin 2\pi\Phi_b) \tag{3.9}$$

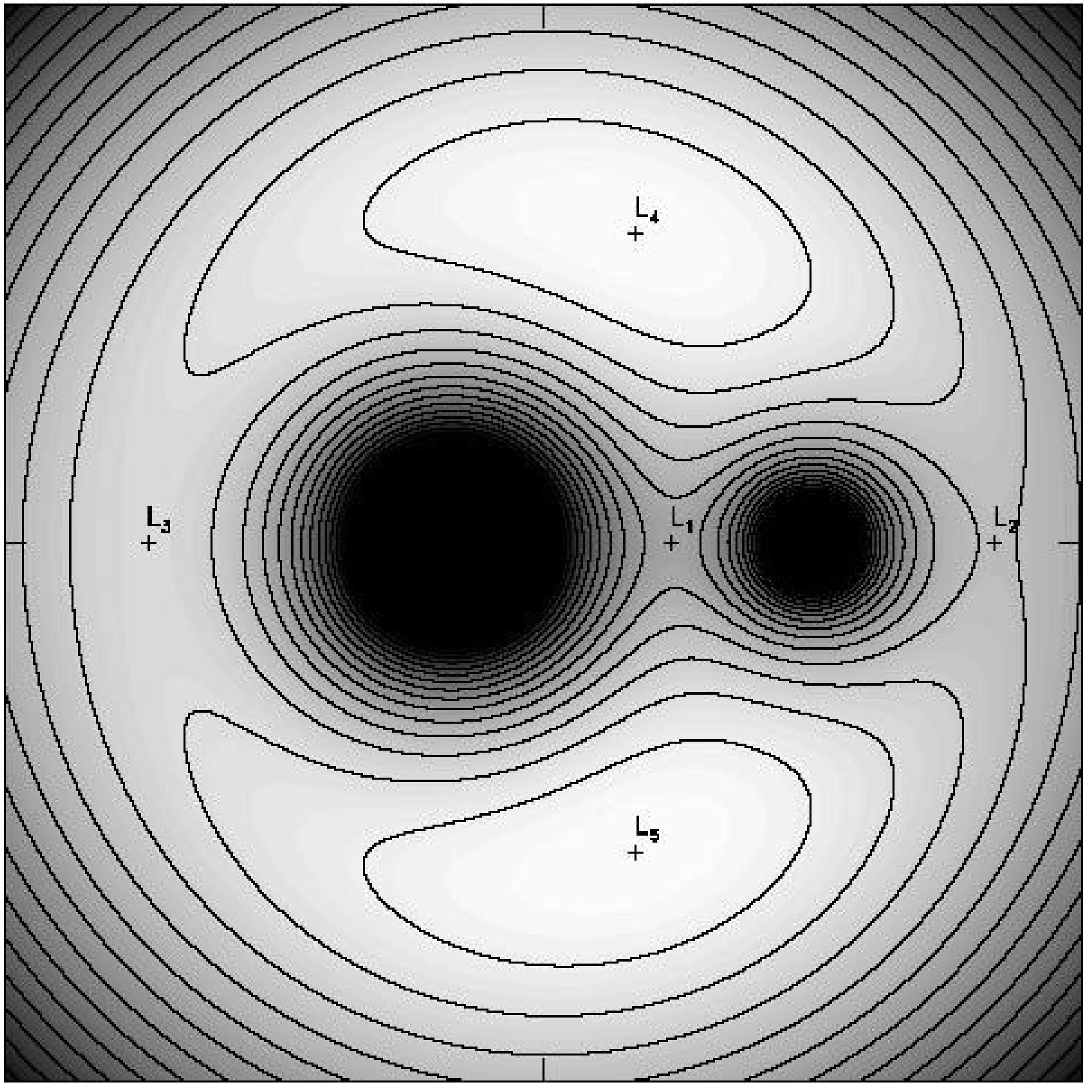
Eccentricity in eclipsing binaries



Shivers et al. 2014

$$\Delta t = \frac{2P}{\pi} e \cos \omega \qquad (3.10)$$

The Roche Model



R. Hynes

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

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

and where

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

Stellar surfaces are isosurfaces of this potential

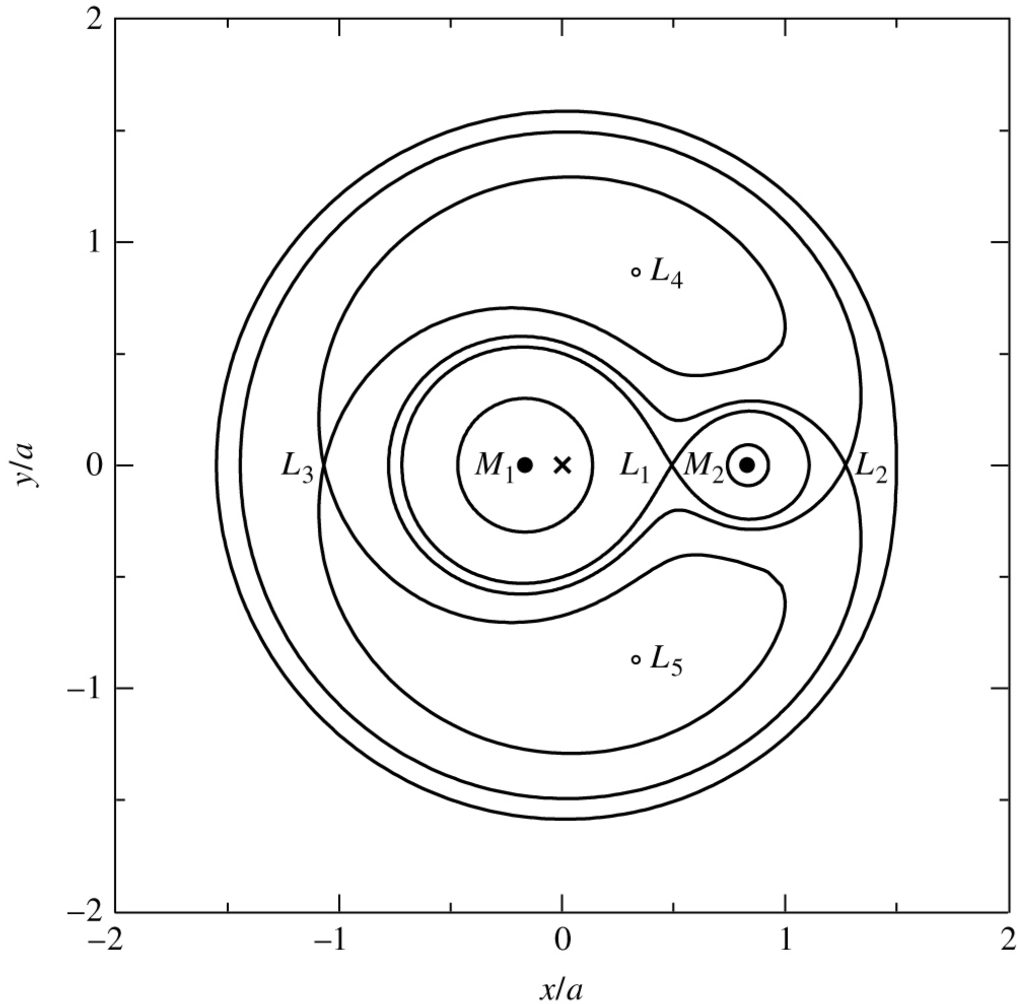
$\Longrightarrow$ stars are non-spherical

$\Longrightarrow$ Stellar magnitude changes with orbit.

Roche radius:

$$\frac{R_L}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})} \qquad (3.11)$$

The Roche Model

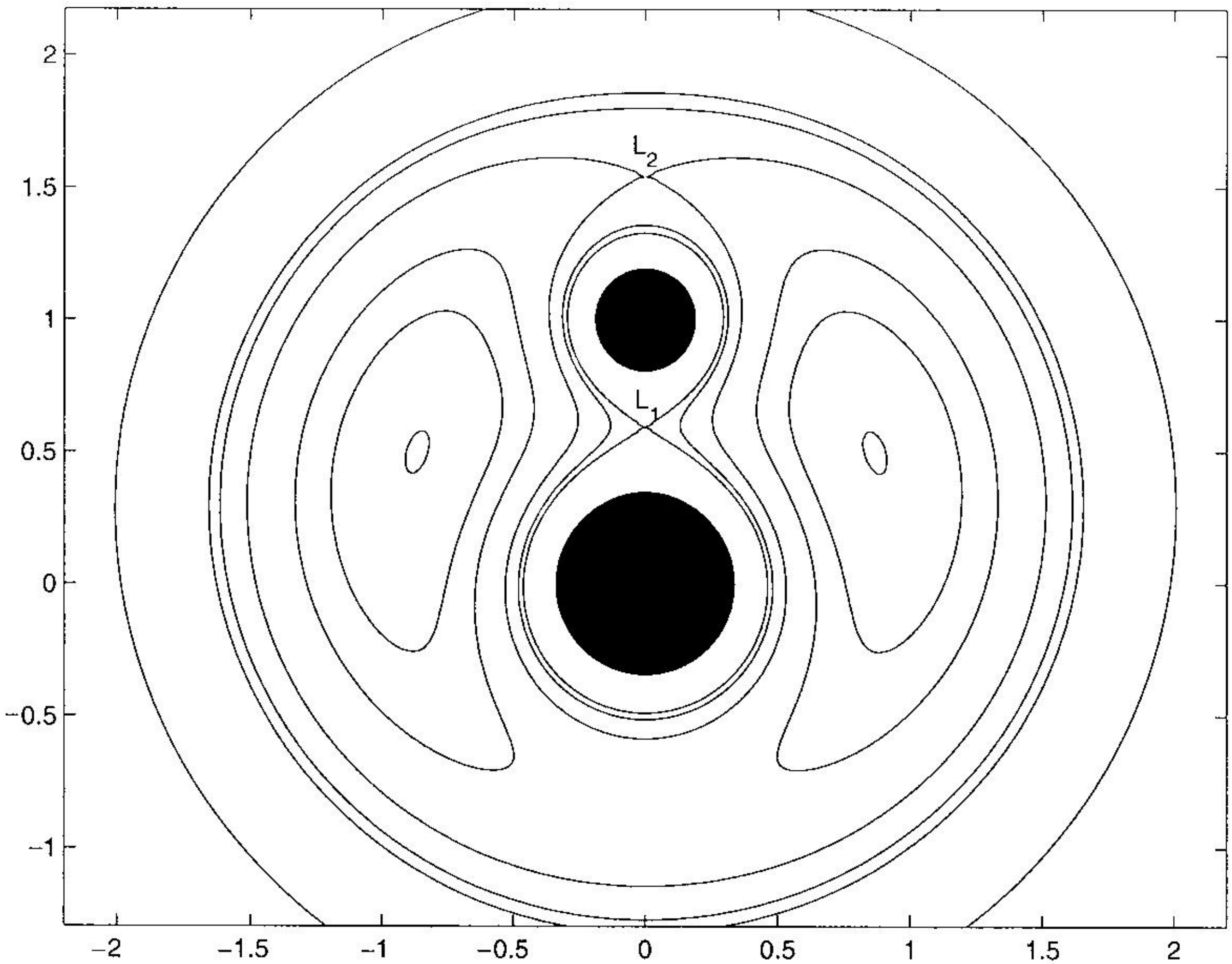


Carroll & Ostlie

Approximations:

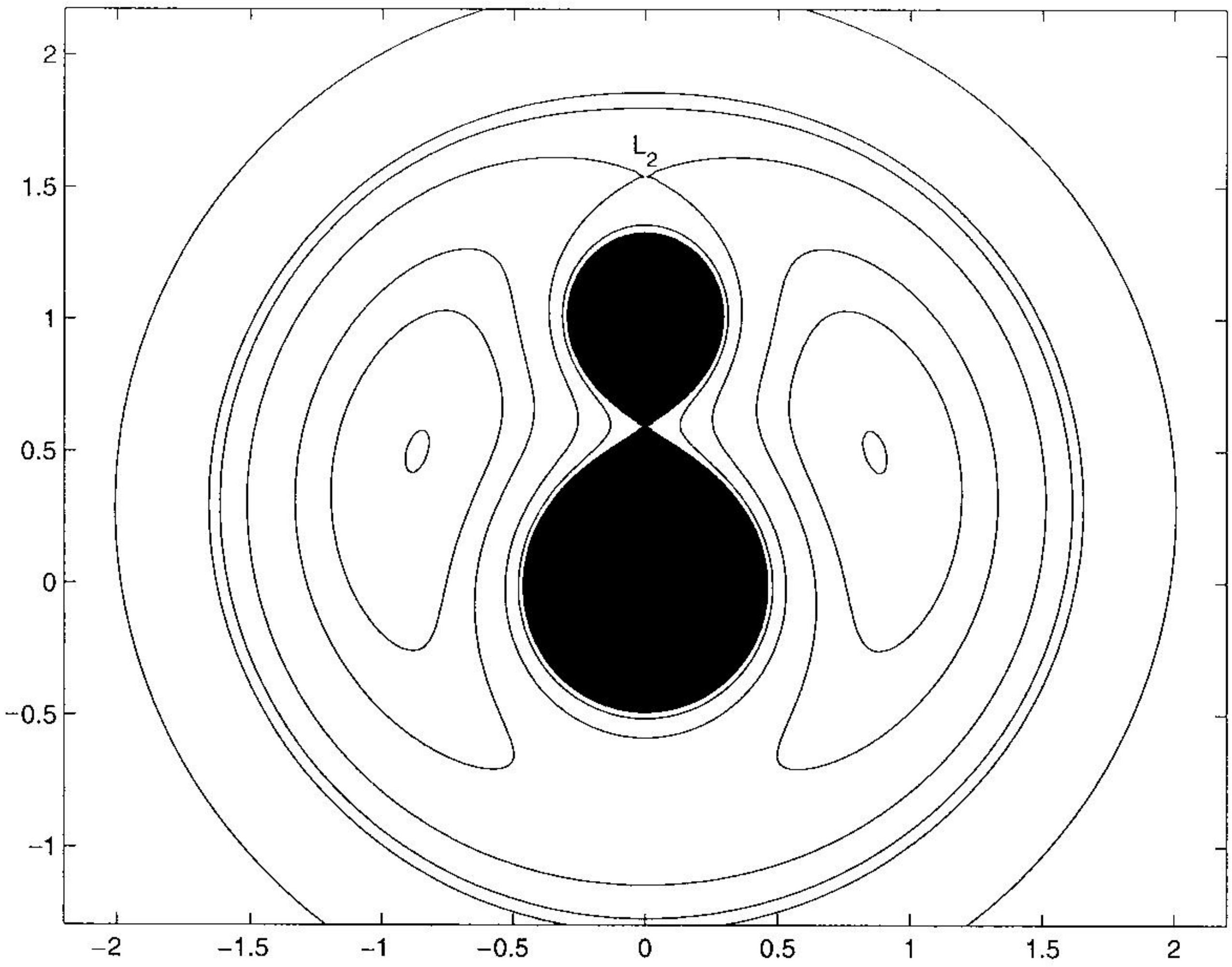
- stellar potentials are point-like (most of the stellar mass in concentrated in its core)
- Orbits are circularised (quickly established by tidal forces)
- rotation axes are perpendicular to the orbital plane
- stellar rotation is synchronous (tidally locked to the orbit)

The Roche Model

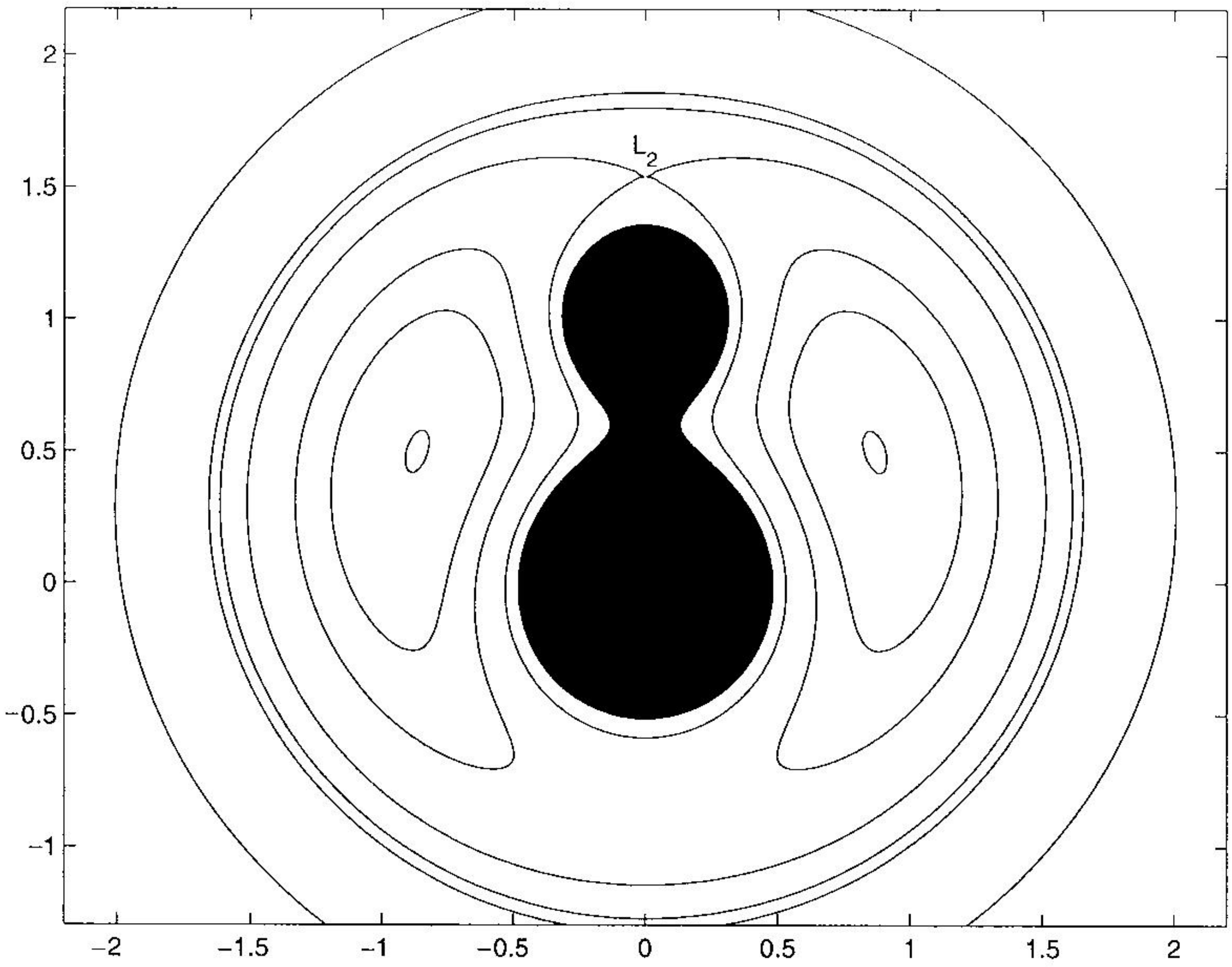


Detached Binaries

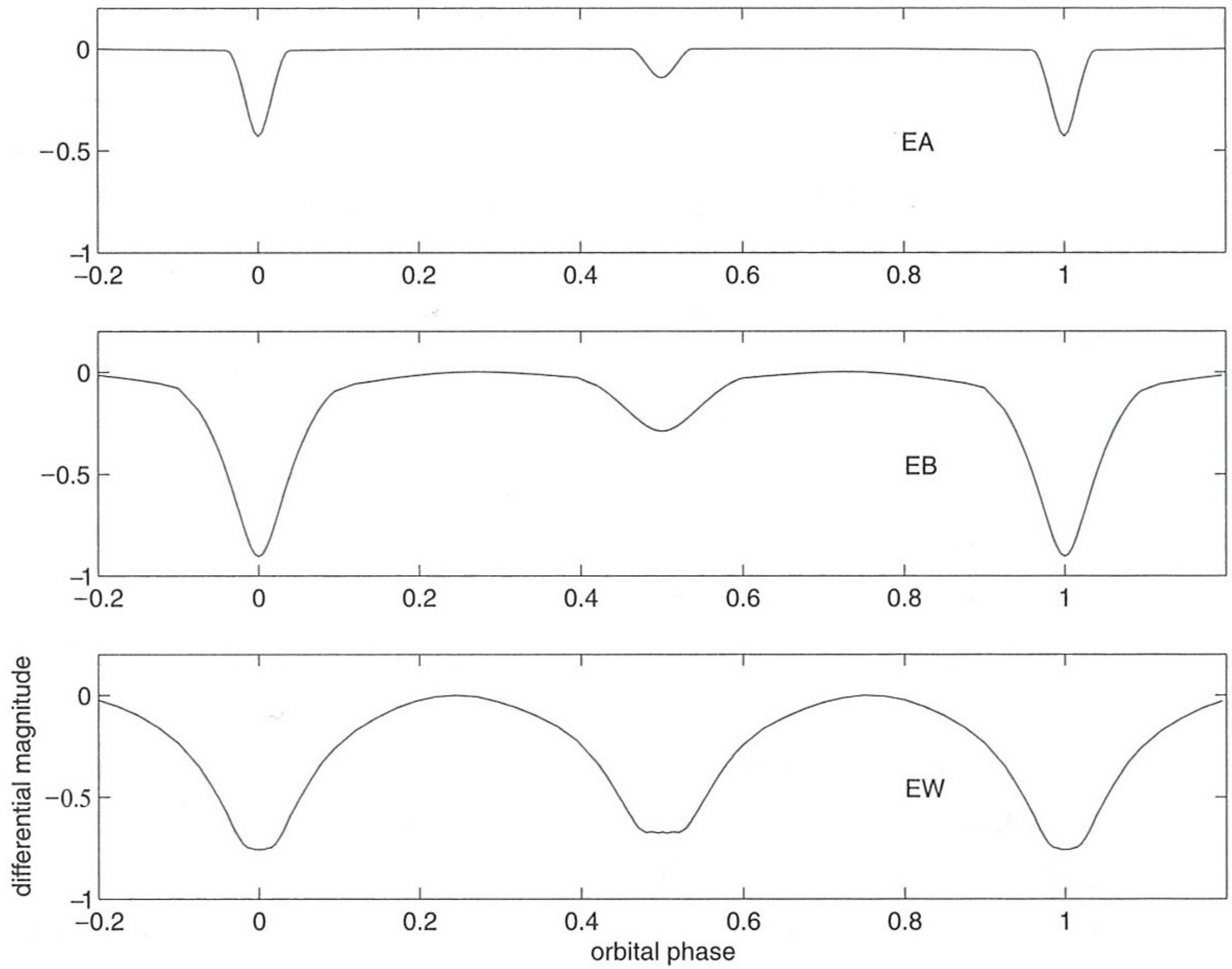
The Roche Model



The Roche Model



The Roche Model



light curves of eclipsing binaries: detached, contact, overcontact (top to bottom)

Limb darkening

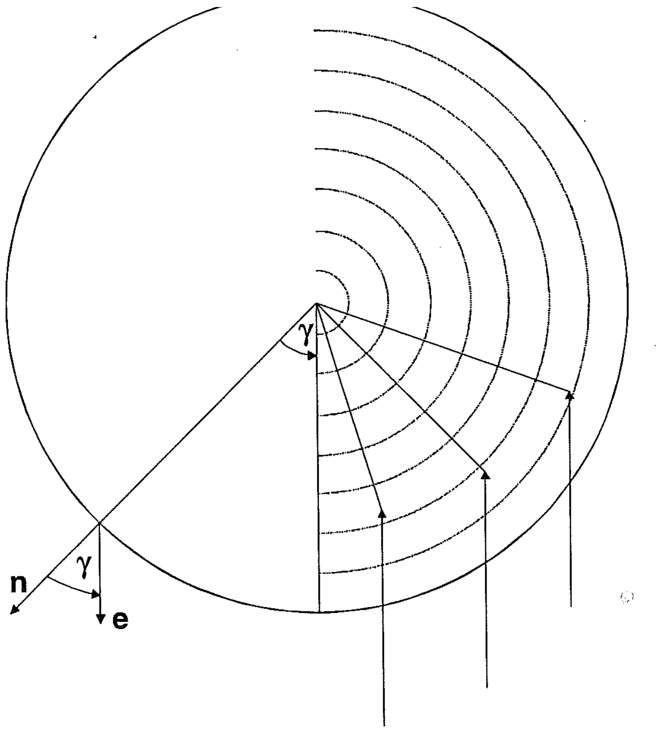
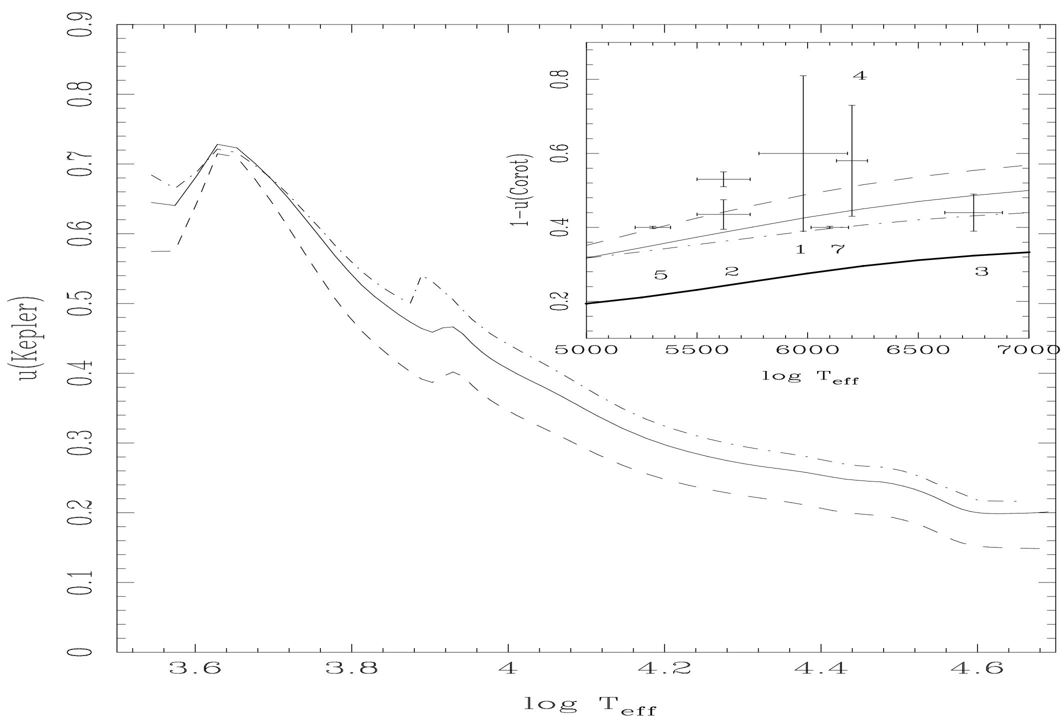


FIGURE 3.17. Center-to-limb variation. This figure shows the aspect angle
(angle between normal vector **n** and radiation emission direction **e**) appearin
in the mathematical formulation of the limb-darkening. The right part of th
figure illustrates that the depth of the atmosphere region (and thus temperature
accessible to an observer varies with the aspect angle γ.

Kallrath & Milone (1999)

- intensity of the stellar disk decreases from the centre to the limb
  temperature is increaing with increasing photospheric depth
- can be measured for the sun
- can be measured by microlensing
- can be calculated from model atmospheres
- linear law: $I = I_0(1 - \epsilon + \epsilon \cos\theta)$
  ϵ = limb darkening factor,
  wavelength dependent
  sun in the UV ($<$ 1600Å): limb brightening due to chromospheric temperature rise

Limb darkening



Claret & Bloemen (2011, A&A 529, A75)

- limb darkening coefficient is temperature dependent
- other laws in use

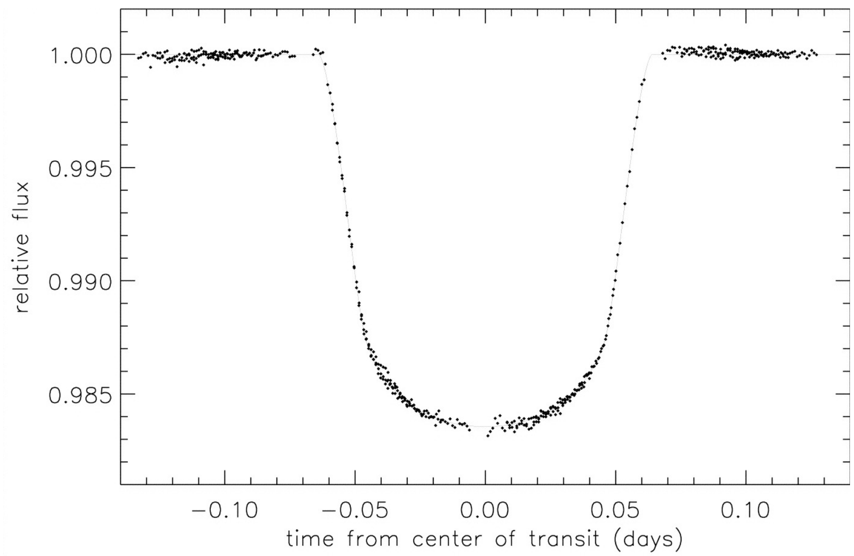
Claret's law:

$$I/I_0 = 1 - a_1(1-\mu^{1/2}) - a_2(1-\mu) - a_3(1-\mu^{3/2}) - a_3(1-\mu^2) \qquad (3.12)$$

$\mu = \cos\gamma$

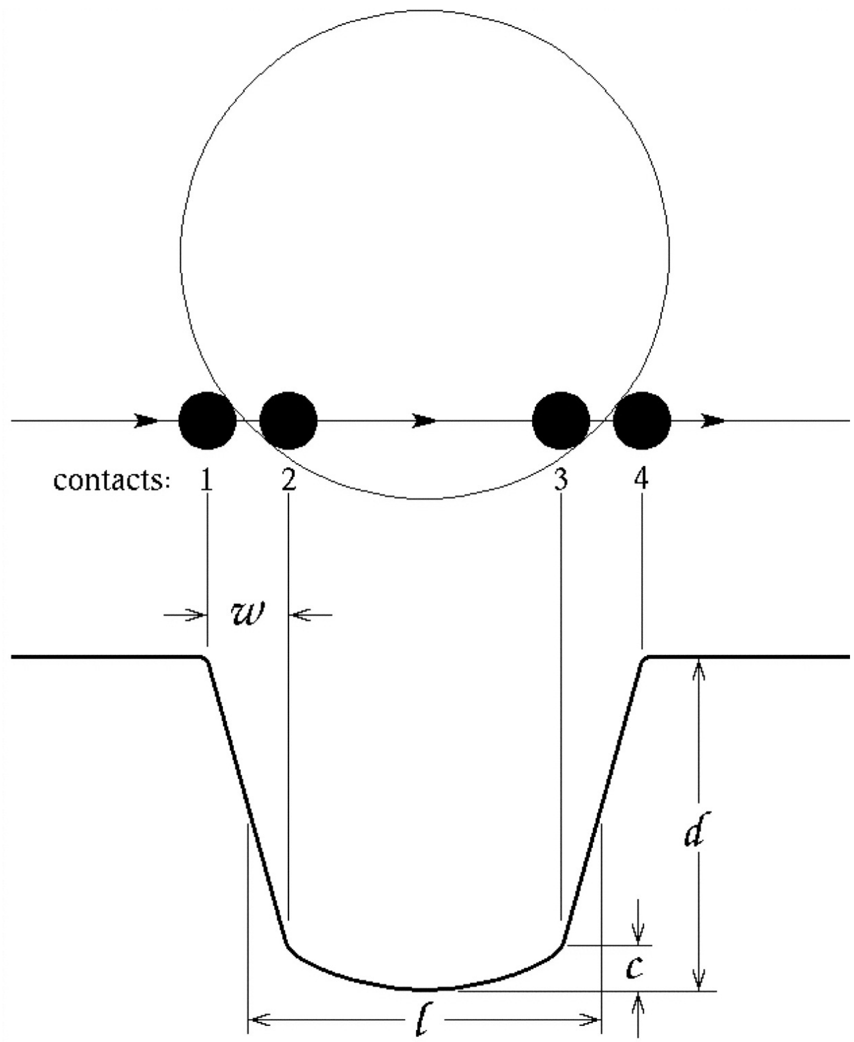
Limb darkening

HD 209458b: the first transiting exo-planet discovered, HST light curve:

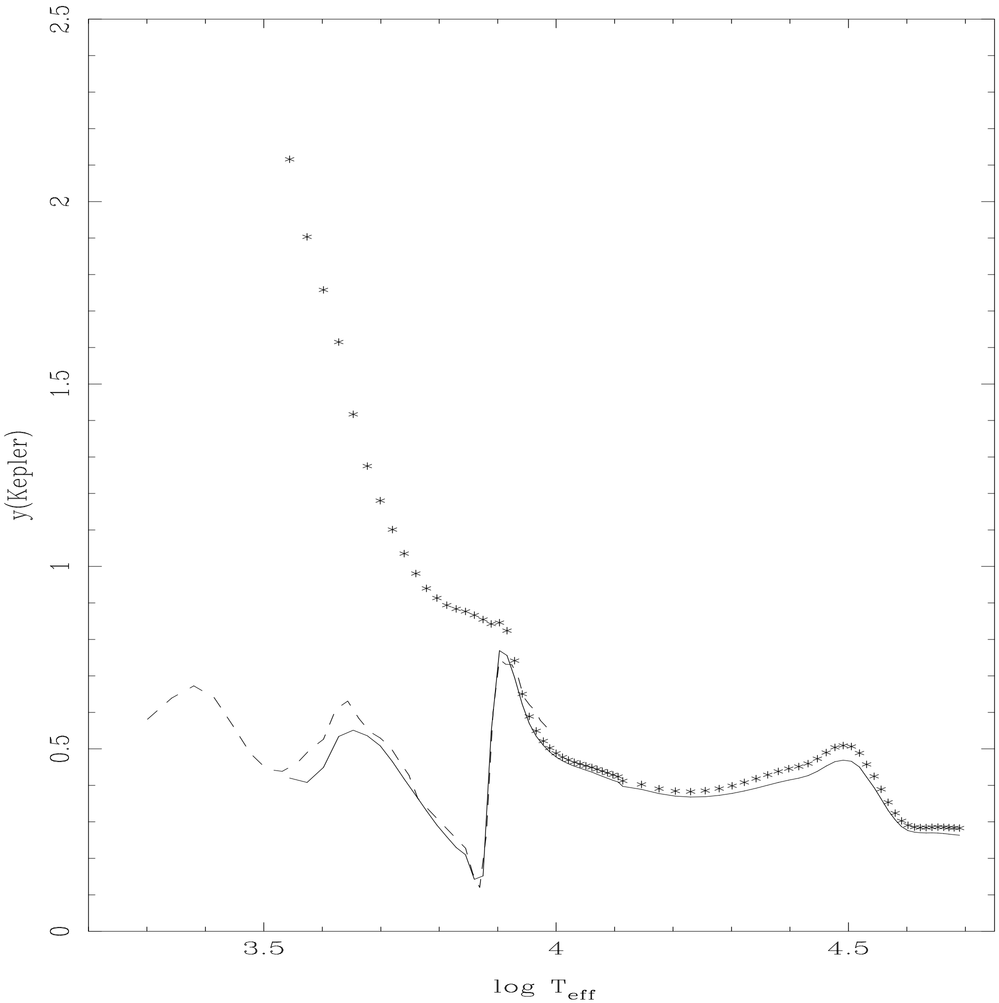


- Transit is not central
- transit depth is not constant
- $\longrightarrow$ caused by limb darkening

Brown et al. (2001, ApJ 552:699)



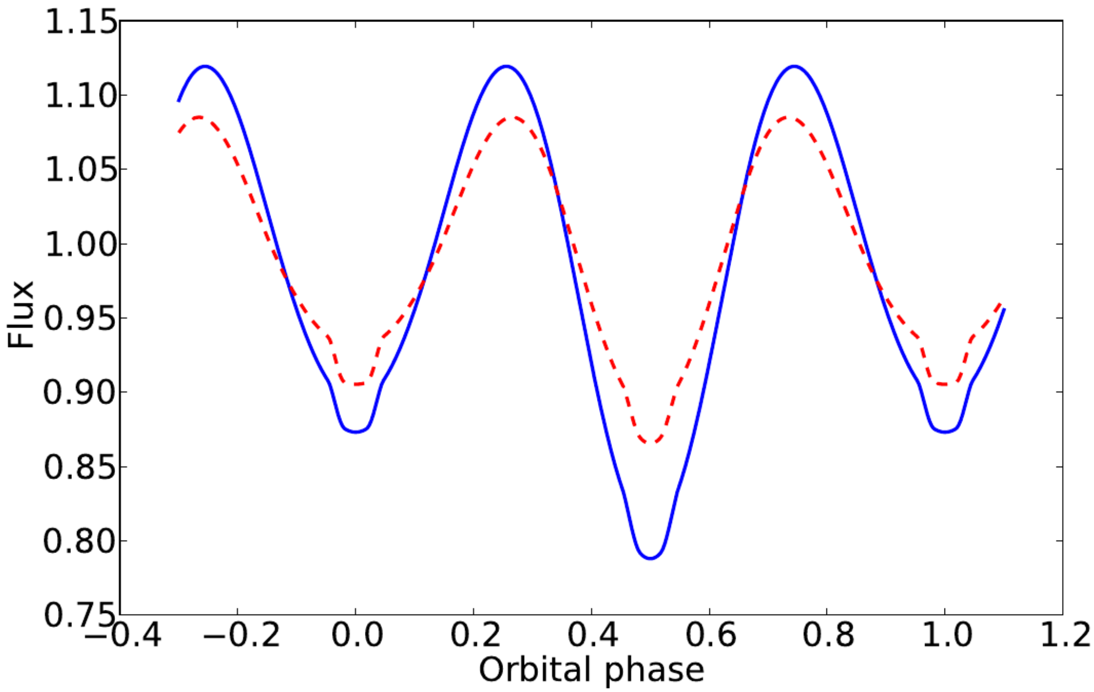
Gravity darkening



Claret & Bloemen (2011, A&A 529, A75)

- non-spherical stars, surface gravity varies across the surface
- von Zeipel's Theorem: radiative atmospheres: black body: diffusion equation
- due to temperature gradient in star Flux $F_R \propto \nabla B \propto \frac{dB}{d\Phi}\nabla\Phi \propto g$
- in the convective case F $\approx$ $g^{0.32}$ (Lucy's law, 1967)
- derive numerically from appropriate model atmospheres
- $F \propto g^y$ (tables by Claret & Bloemen, 2011)

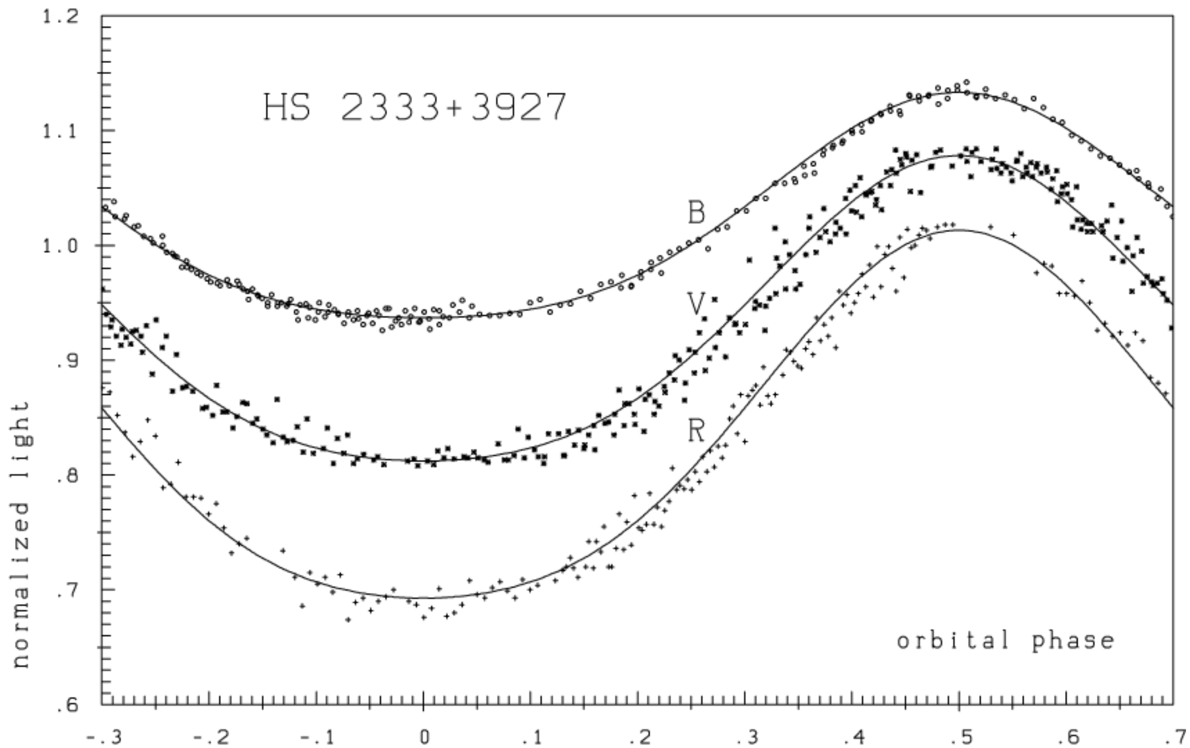
Gravity darkening



Tidally-distorted, limb-darkened, eclipsing, with and without gravity darkening.

- non-spherical stars, surface gravity varies across the surface
- derive numerically from appropriate model atmospheres
- $F \propto g^y$ (tables by Claret & Bloemen, 2011)

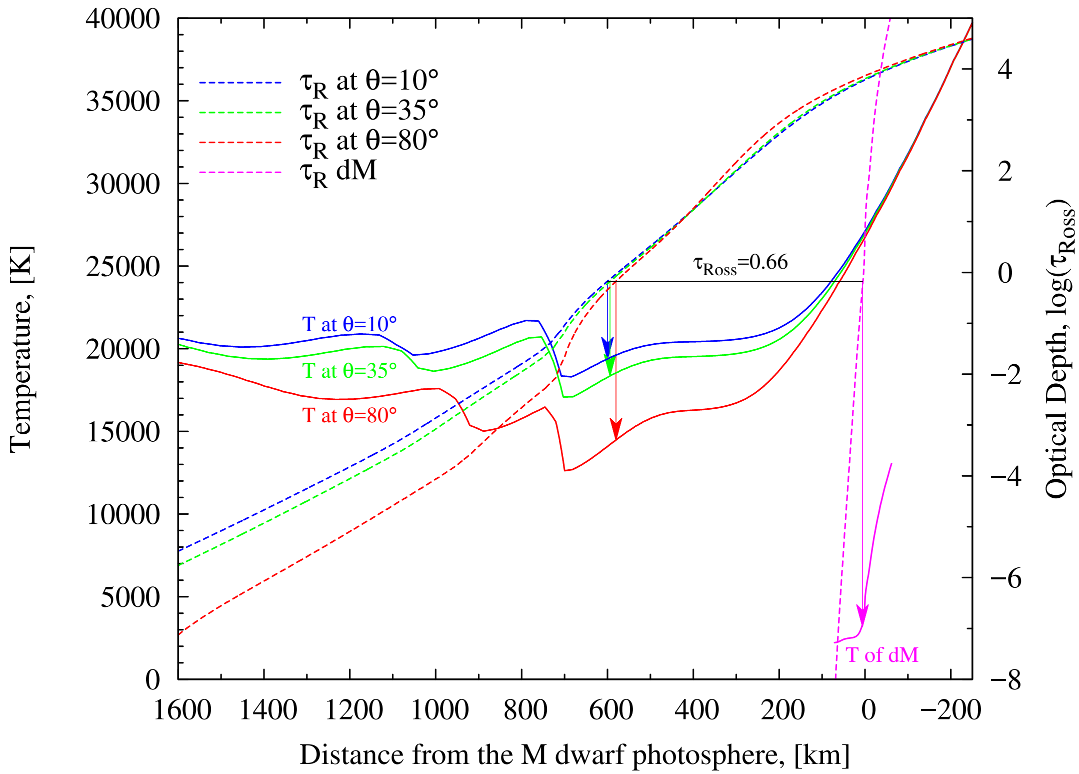
Reflection effect



Heber et al. 2004, A&A 420, 251

- light variation by irradiated hemisphere of the companion
- companion has phases like the moon or Venus
- e.g. HS2333+3927: Hot star (33000K) & cool star (3000K)
- Albedo: percentage of light reflected from the irradiated surface.

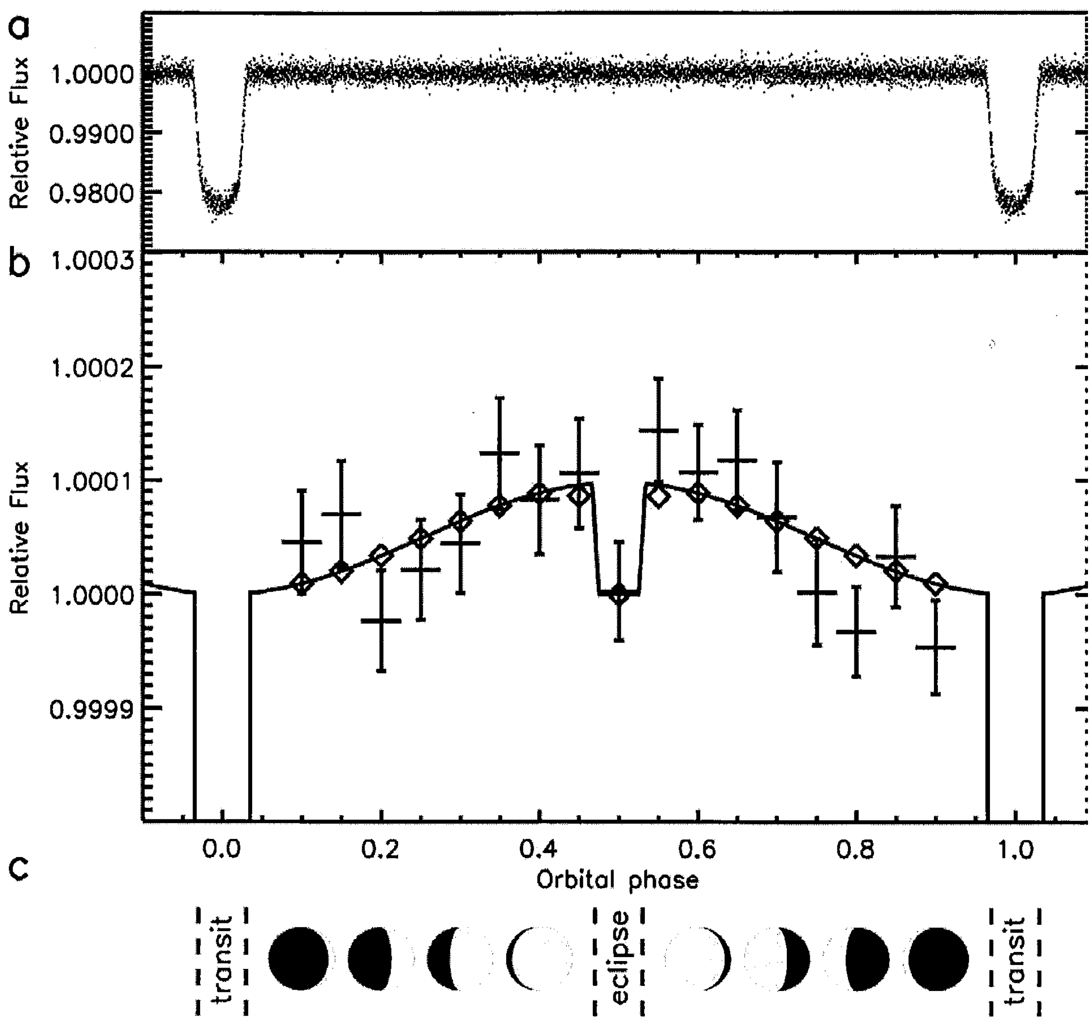
Refection effect



Vuckovic et al. 2016

- The refelction effect is not simply reflected light
- the irradiated hemisphere is strongly heated
- e.g. AA Dor: A hot subdwarf (40000K) & brown dwarf (3000K)
- hemisphere is heated to more than 20000K
- redistribution of flux from one wavelengths range to the other
  $\longrightarrow$ albedo can be larger than 1 (100%)
- synchronised rotation, no heat exchange expected

Reflection effect



Snellen et al., 2009, Nature 459,543

- CoRoT 1b: Hot Jupiter: mass $M=1.03M_{Jup}$; radius: $R=1.49\ R_{Jup}$
- CoRoT 1b: Reflection effect and eclipse of a transiting planet discovered for the first time (Snellen et al. 2009)
- Orbital period 1.509 d, light variation 0.01%

$$T_{2,new} = T_2 \left(1 + \alpha \left(\frac{T_1}{T_2}\right)^4 \left(\frac{R_1}{a}\right)^2\right)^{0.25} \tag{3.13}$$

The search for and analysis of new sdB binaries as well as the classification of variable hot subdwarf candidates

Research workshop on evolved stars

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10.09.2021

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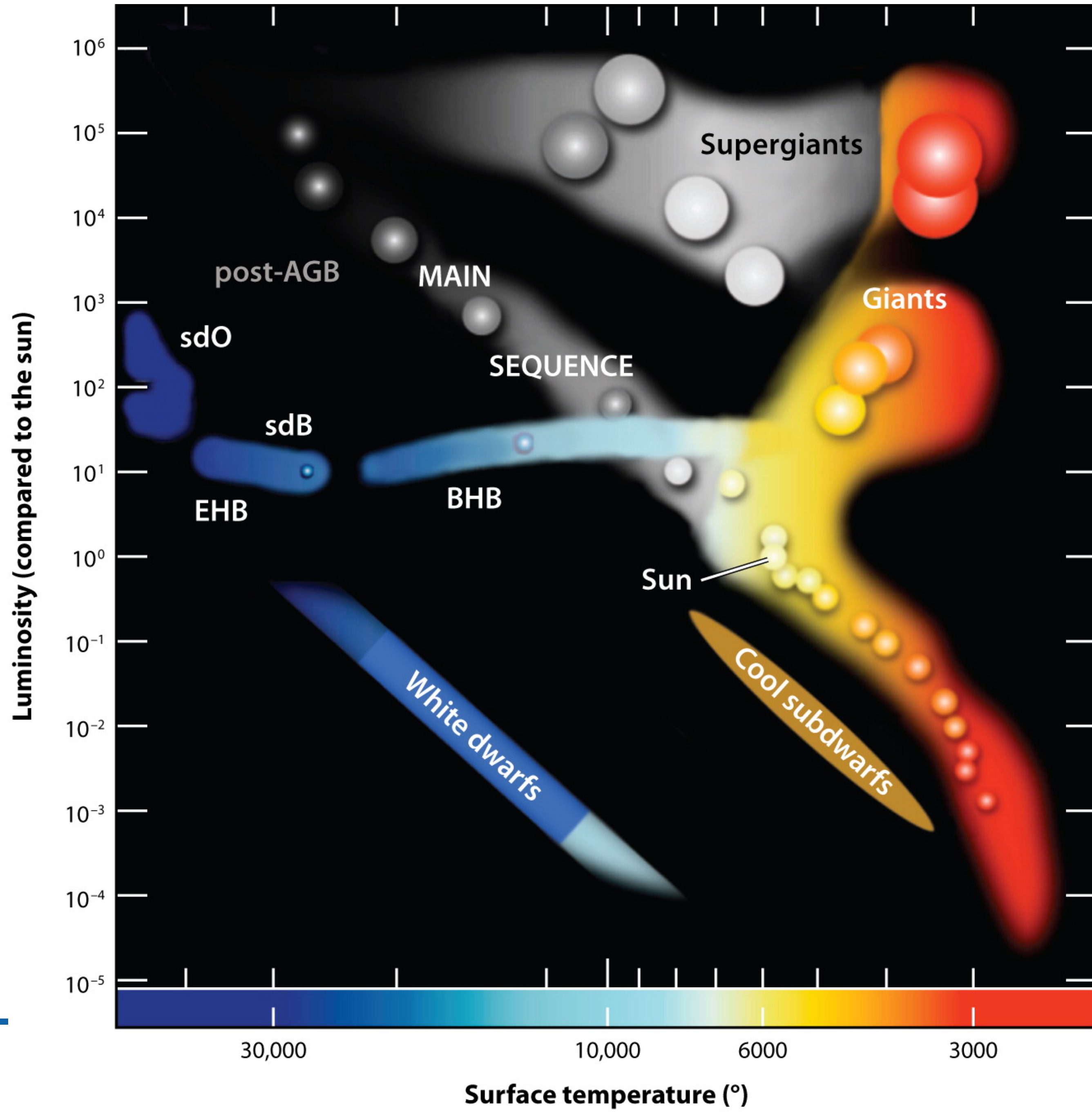
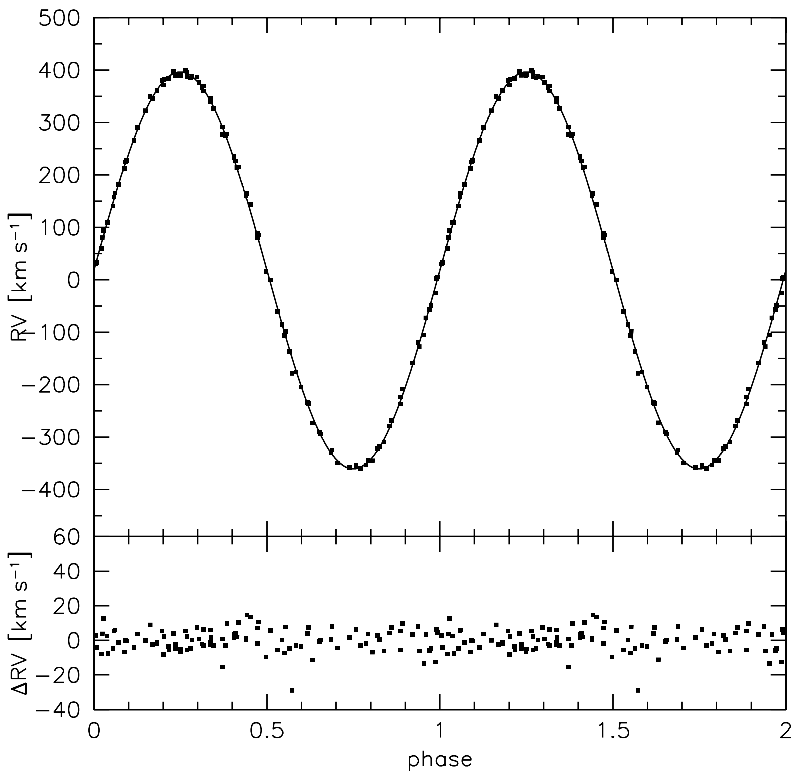
Introduction

Hot subdwarf stars of spectral type B (sdB)

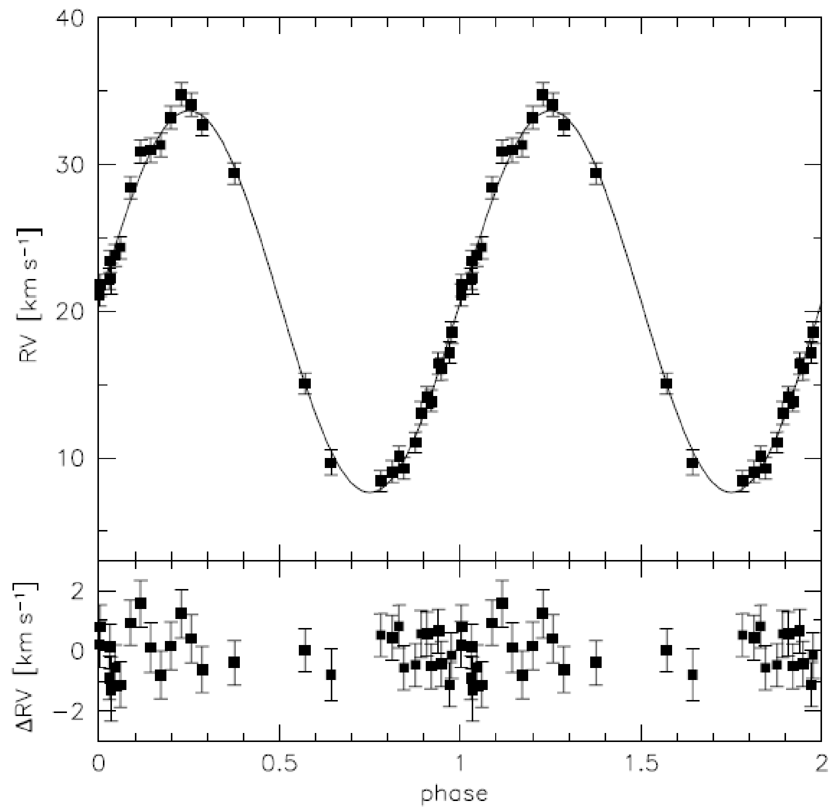


Hot subdwarfs in binaries

Hot subdwarfs in binaries with unseen companion discovered by RV method



CD-30°1122, P = 0.0498 d (Geier et al. 2013)

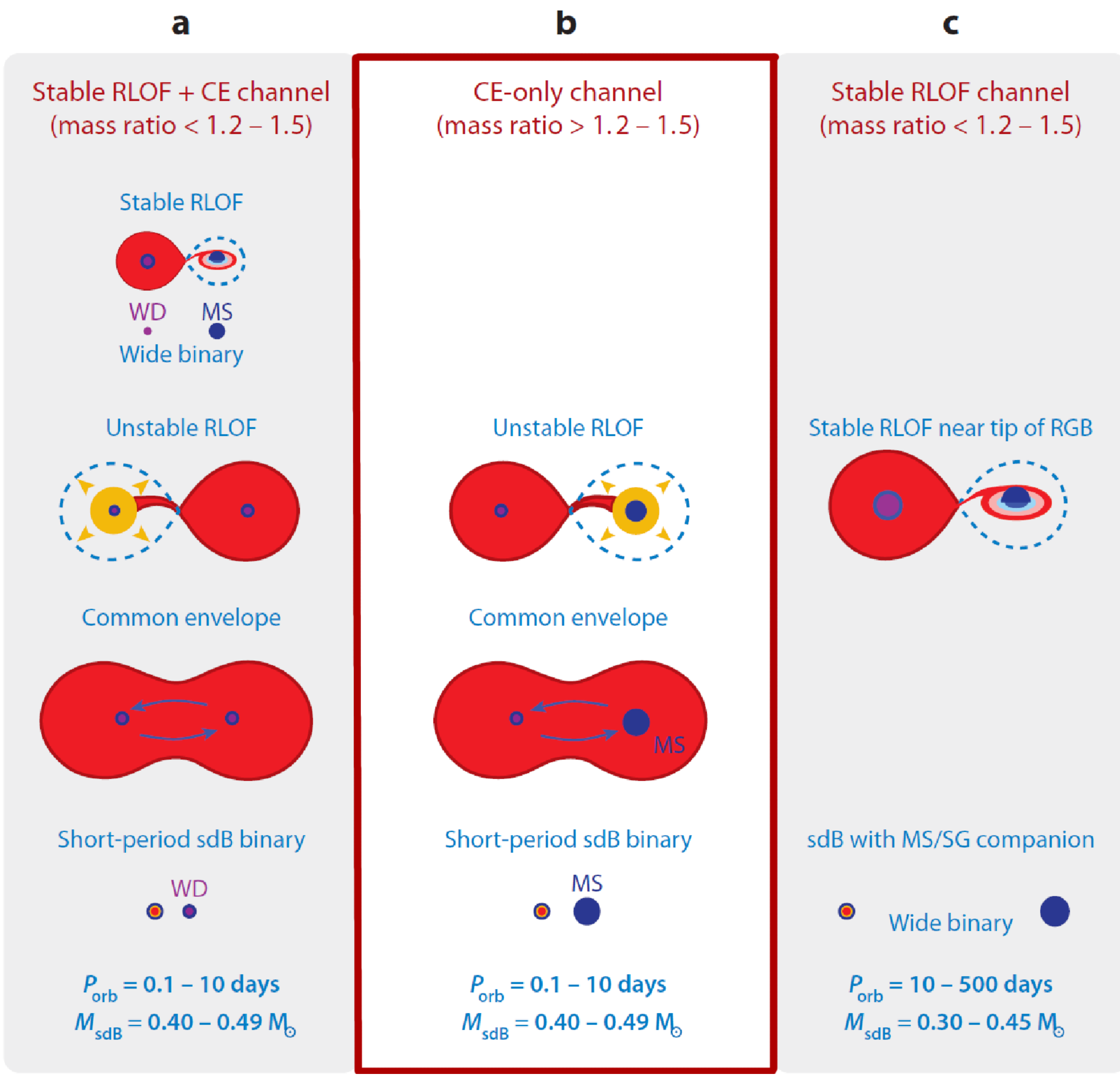


PHL 457, P = 0.3131 d (Schaffenroth et al. 2014)

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{K_1^3 P}{2\pi G}$$

more than 50% of sdBs in close binaries ($P < 1$ d)

Formation of sdB binary

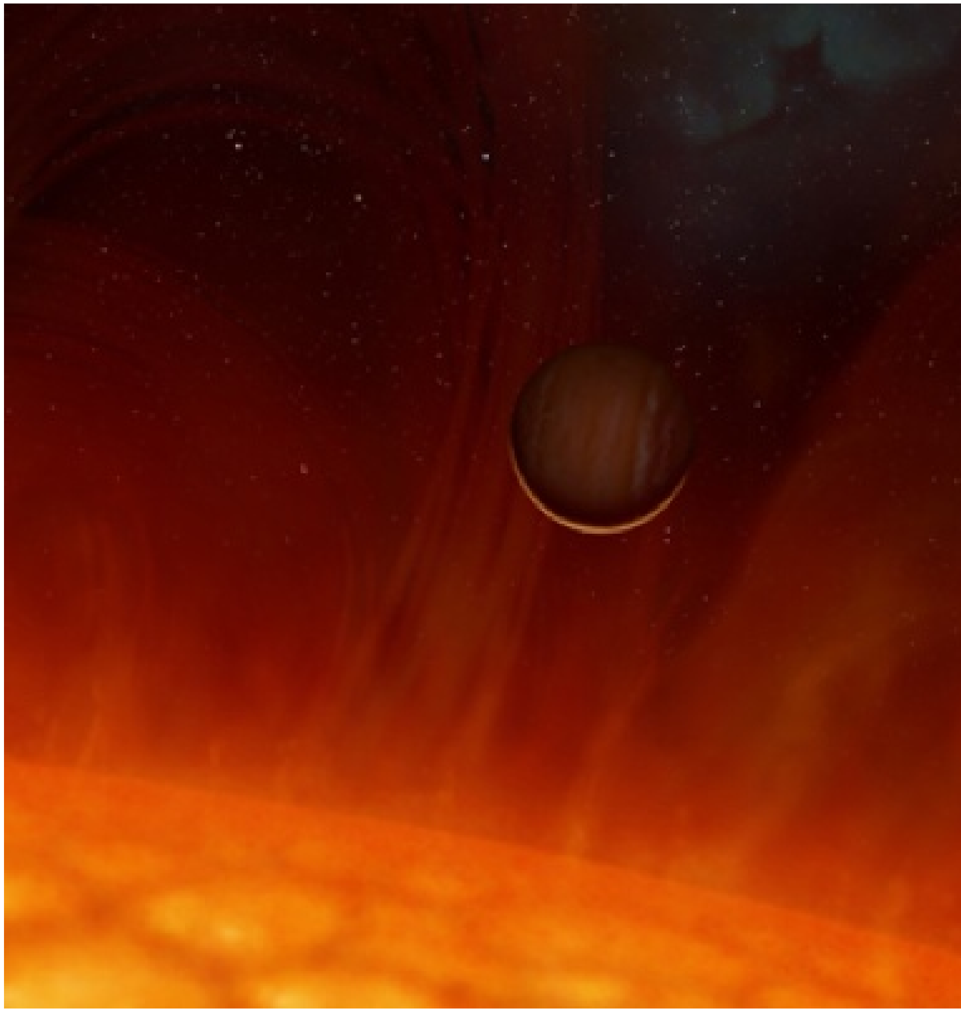


Han et al. (2002,2003)

Formation of sdBs by substellar objects

Soker 1998 AJ

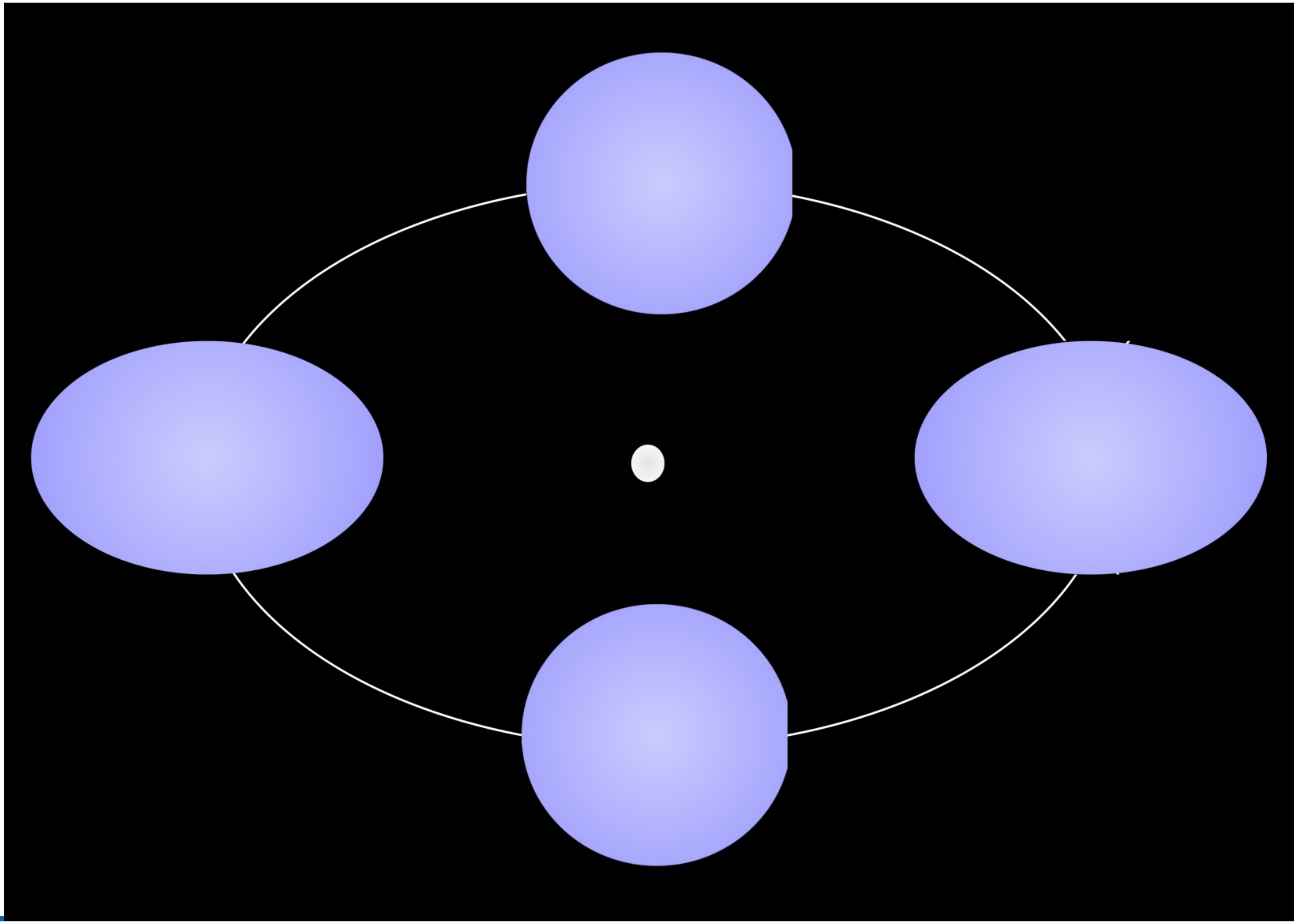
- Orbit of planet in envelope of evolved star
- fate of planet:
  - evaporation
  - merger with the core
  - survival for $\geq 10 M_{\text{Jupiter}}$ depending on separation
    $\rightarrow$ ejection of envelope



Â© Mark Garlick / HELAS

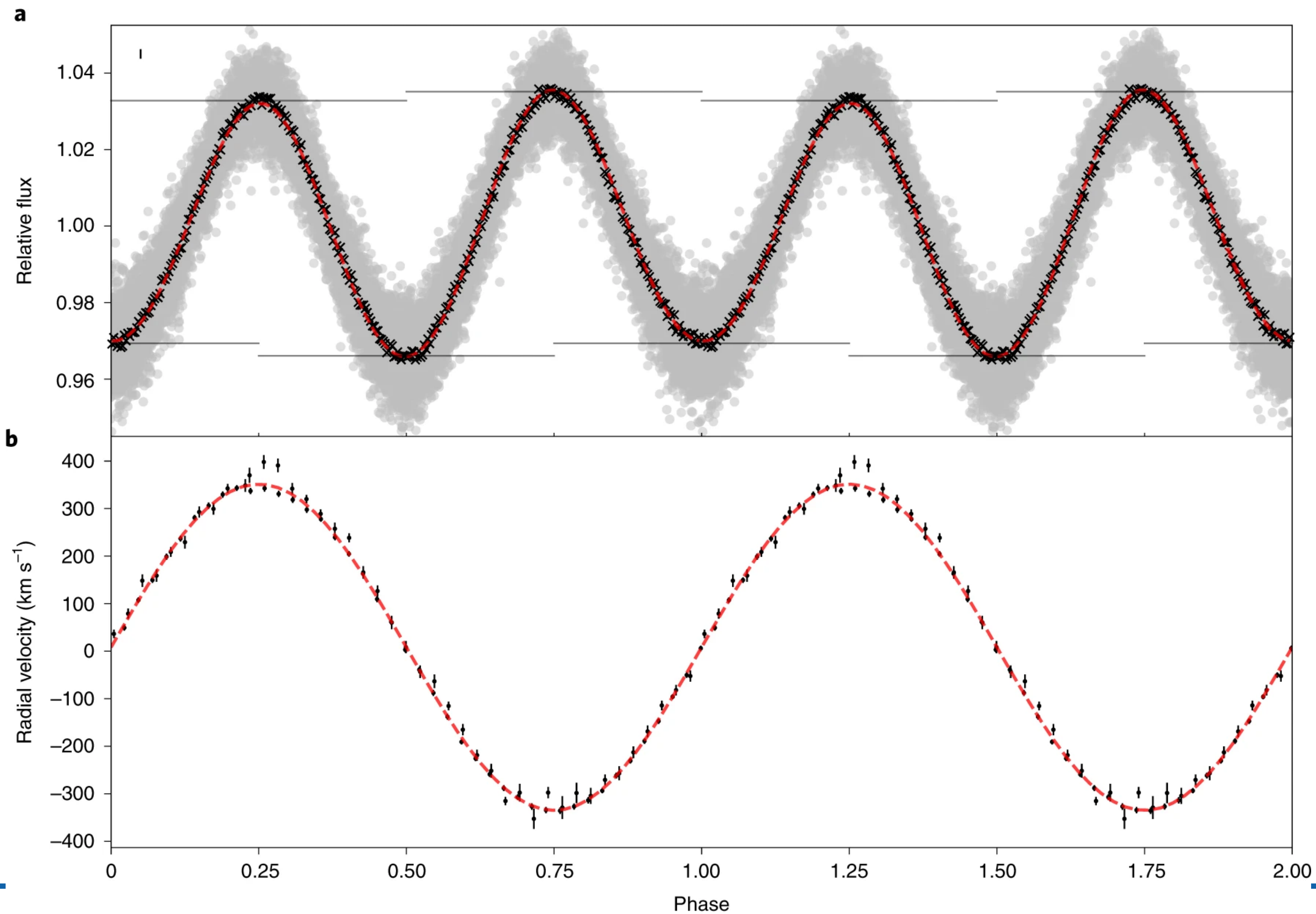
$\rightarrow$ **studying the influence of planets on stellar evolution**

Light variation of compact sdB binaries



Ellipsoidal Variations

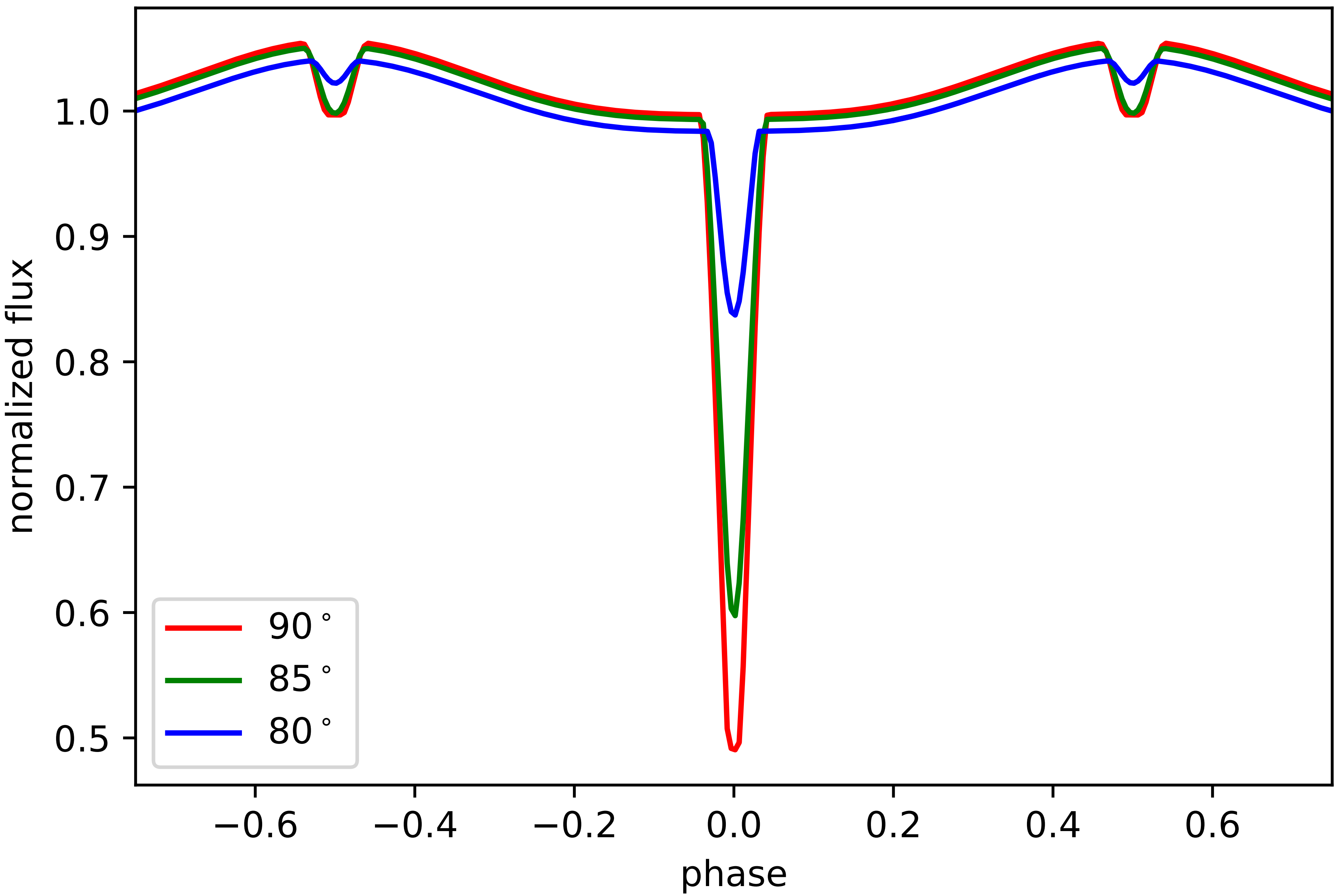
Ellipsoidal modulation and Doppler beaming (sdB+WD)



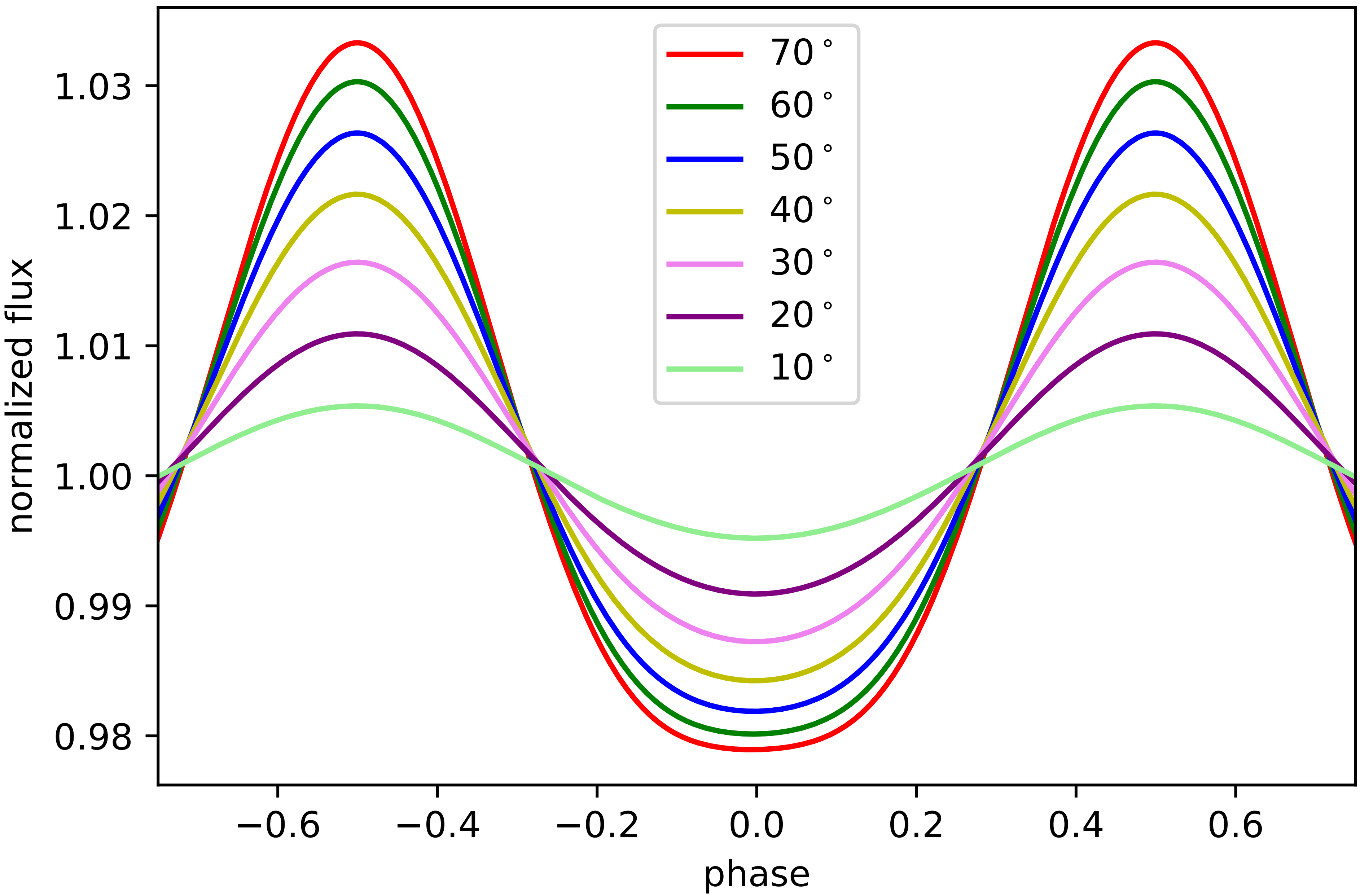
Pelisoli et al. (2021)

Eclipsing Reflection effect (sdB+dM/BD) systems

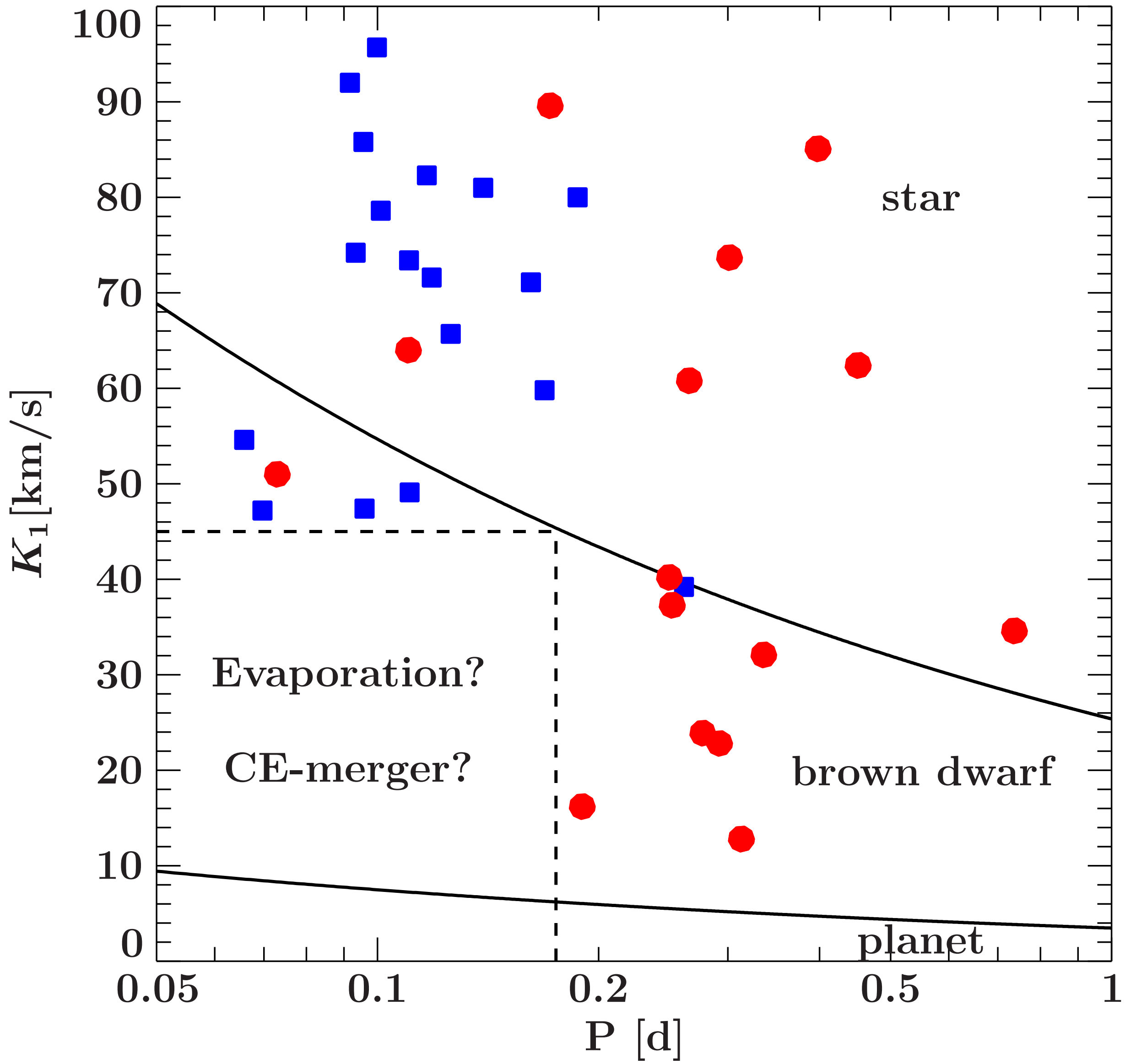
Eclipsing Reflection effect (HW Vir systems)



Reflection effect



Minimum companion masses of hot subdwarfs with cool companions



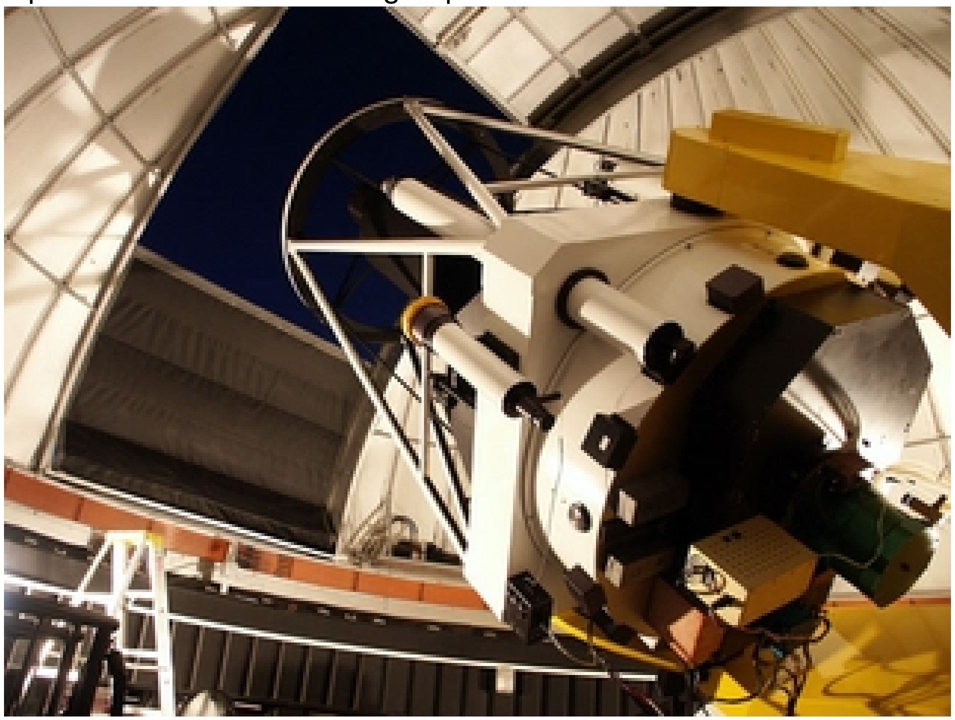
Schaffenroth et al. 2019 in press

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{K_1^3 P}{2\pi G}$$

Ground-based lightcurve surveys

OGLE

Optical Gravitational Lensing Experiment

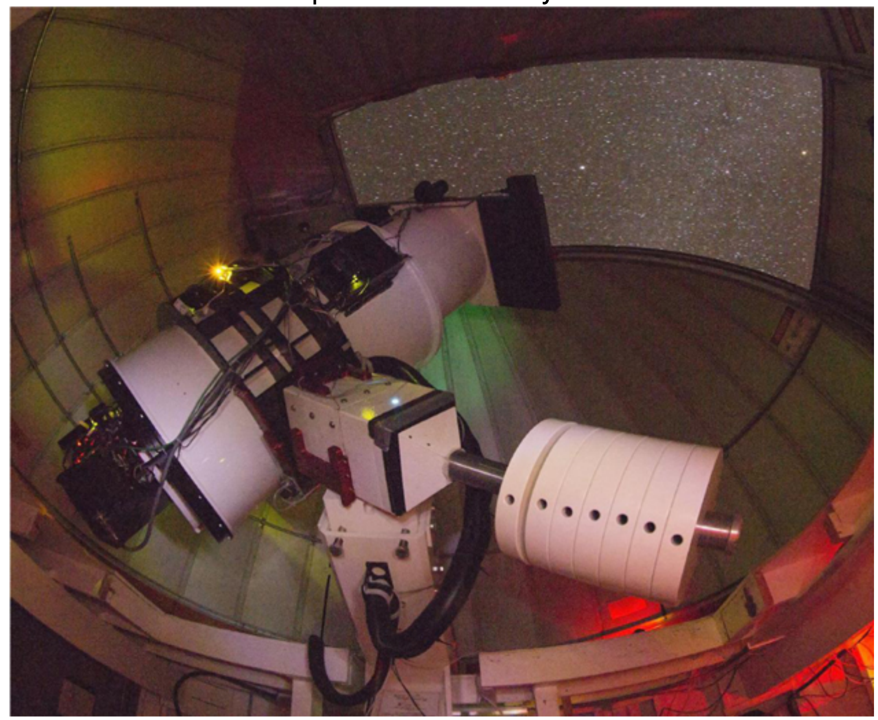


→ observation of the lightcurve of many stars in different fields
→ discovery of planetary transits, pulsators, eclipsing binaries

CRTS, PTF, ZTF, BlackGEM, ...

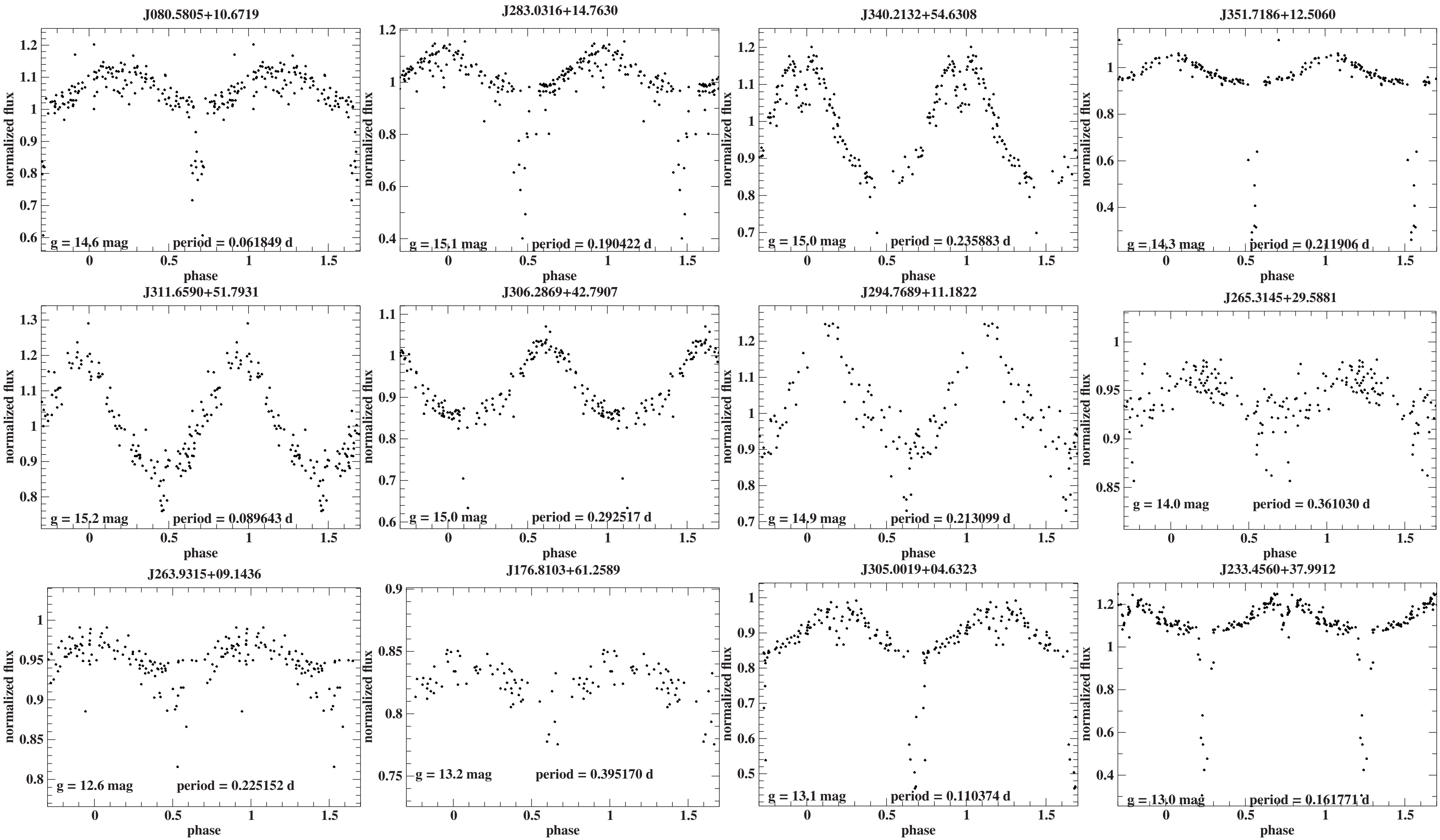
ATLAS

Asteroid Terrestrial-impact Last Alert System



→ a robotic astronomical survey looking for near-earth objects
→ located in Hawaii, planned in the southern hemisphere

150 HW Vir candidate systems: $P = 0.05 - 1.26$ d



The EREBOS project

EREBOS (Eclipsing Reflection Effect Binaries from **Optical** Surveys)

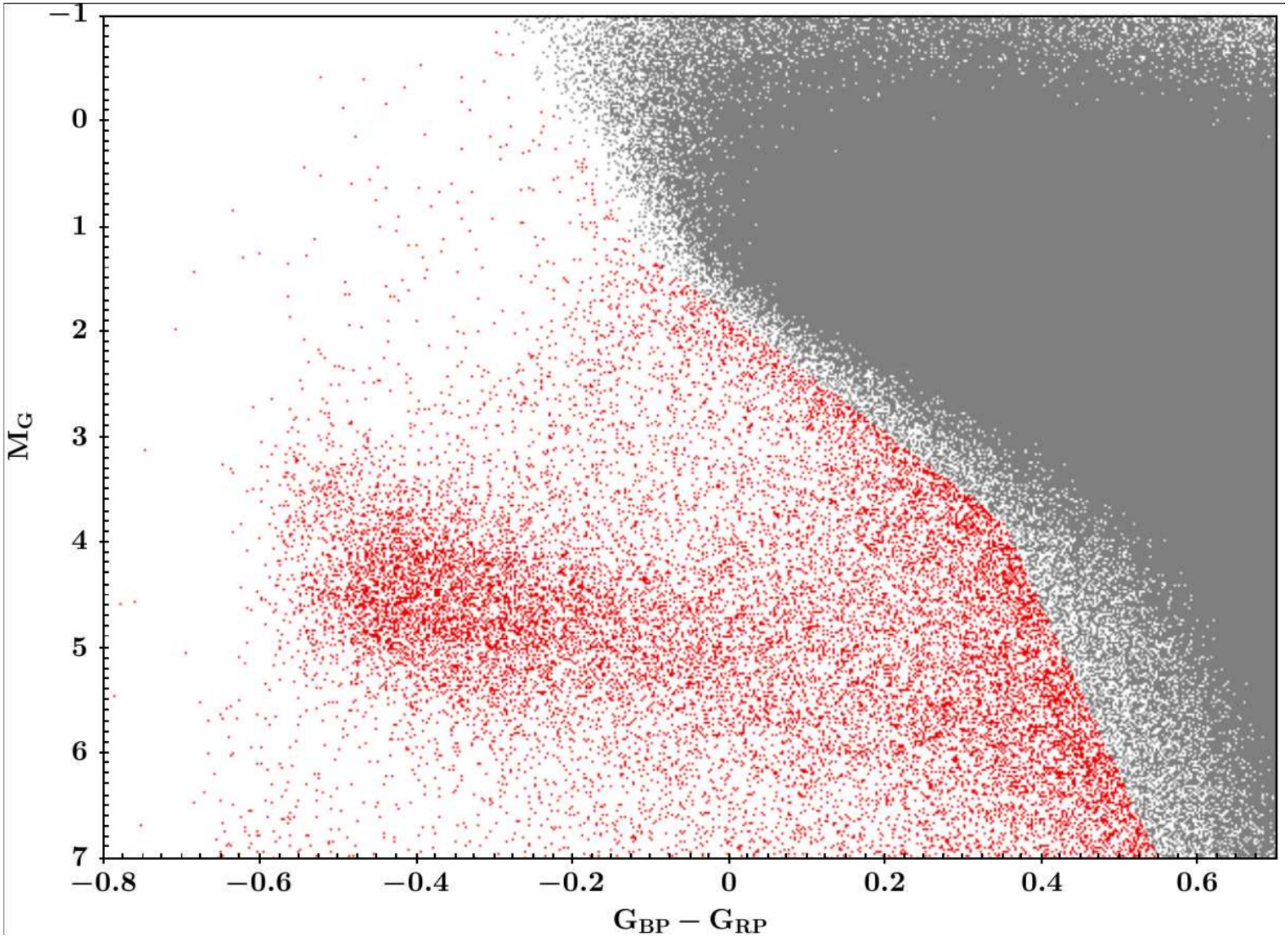
- homogeneous data analysis of all newly discovered HW Vir systems
- photometric and spectroscopic follow-up of all targets to determine fundamental (M, R), atmospheric ($T_{\rm eff}$, $\log g$) and system parameters (a, P)
- spectroscopic and photometric follow-up

Key questions:

- minimum mass of the companion necessary to eject the common envelope?
- fraction of close substellar companions to sdB stars
- better understanding of the CE phase and the reflection effect

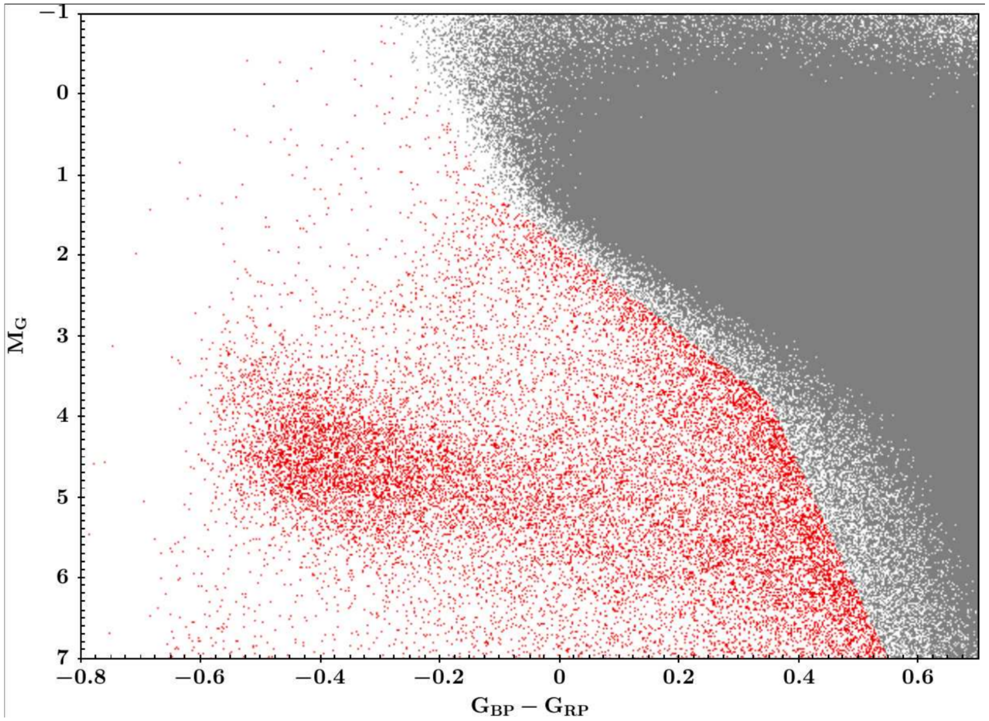
EREBOS
God of darkness

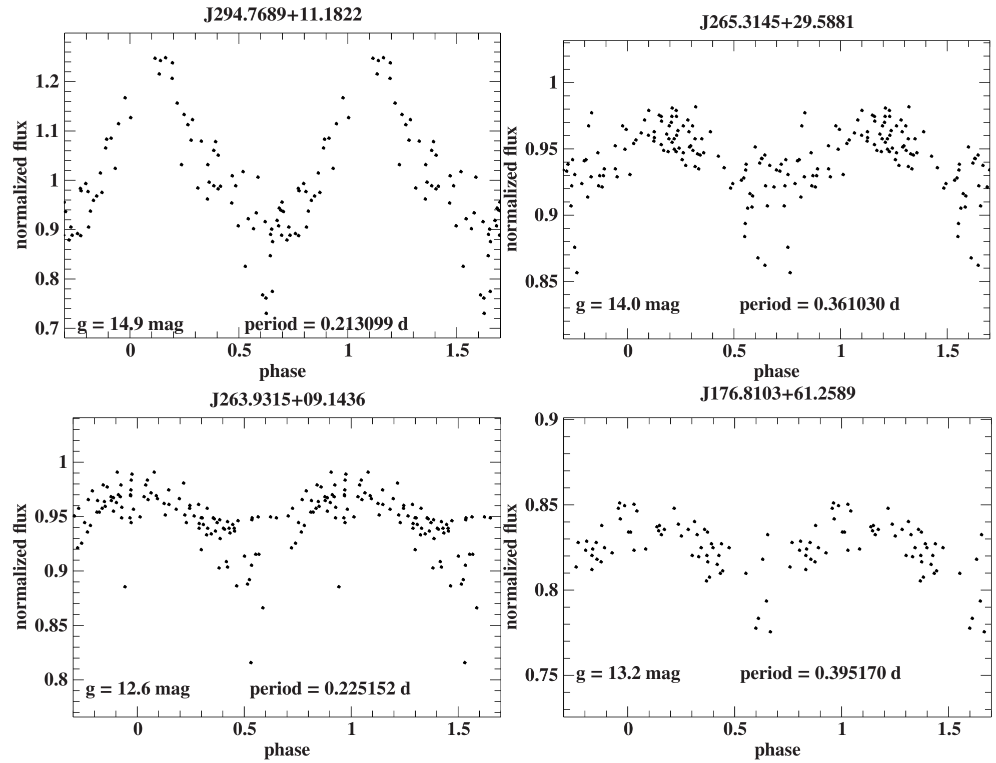
Target selection – Gaia catalogue of hot subdwarf candidates



Geier et al. 2019

Photometric project I

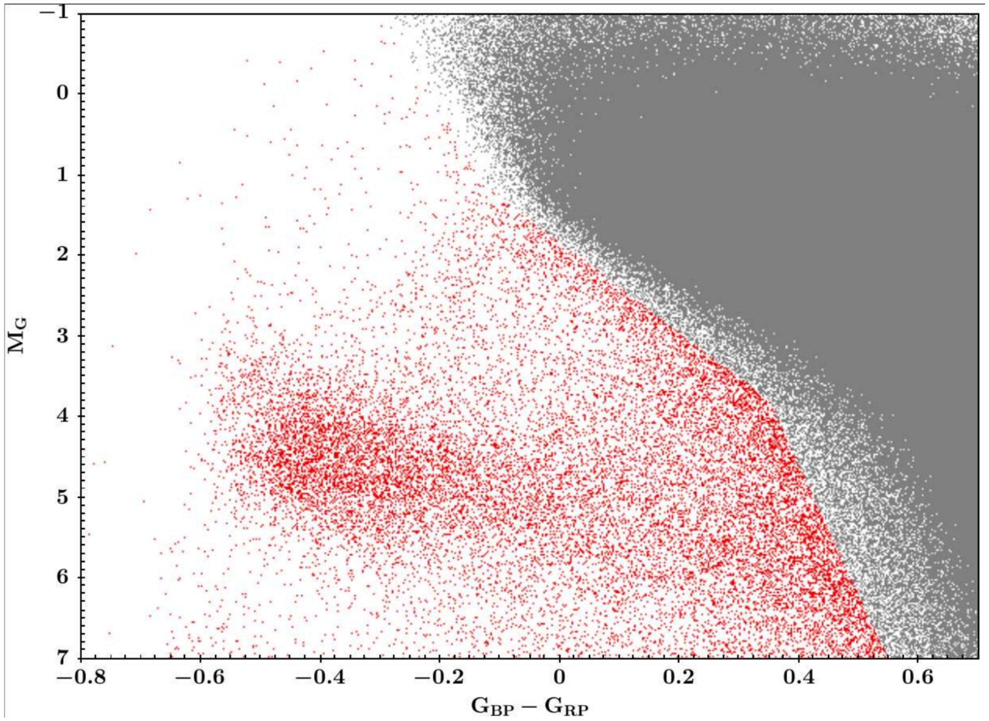


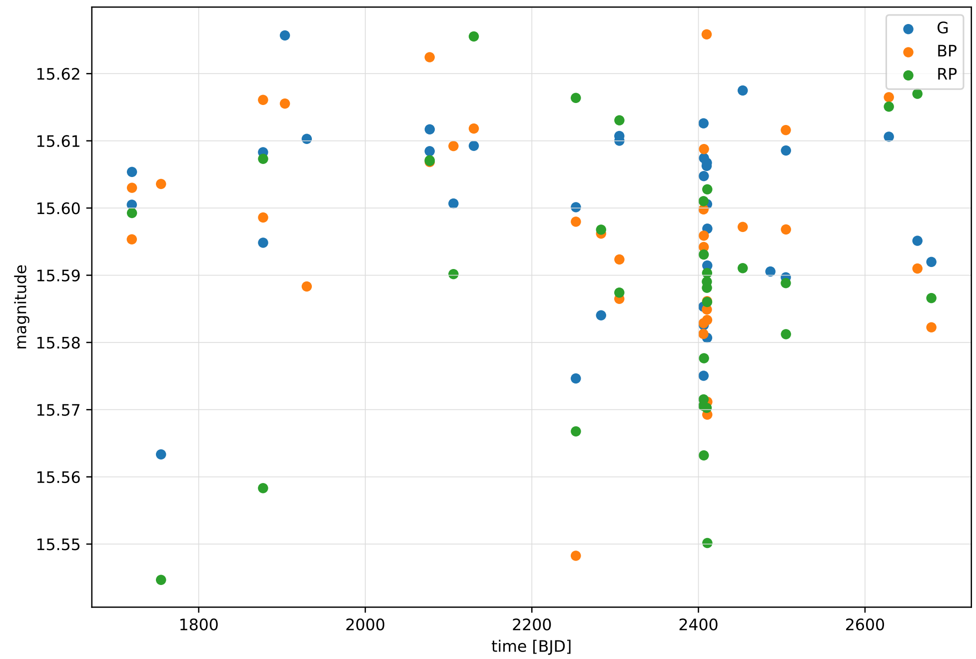


Geier et al. 2019

$\rightarrow$ Crossmatch with photometric surveys – search for, follow-up observation of and light curve analysis of HW Vir system candidates to derive fundamental parameters

Photometric project II





Geier et al. 2019

→ Crossmatch with new Gaia photometric variable catalogue – search for, follow-up observation of and classification of light curves of variable hot subdwarf candidates

→ amplitude, period, light curve shape