Photometric variability of binaries

Research workshop on evolved stars

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Introduction

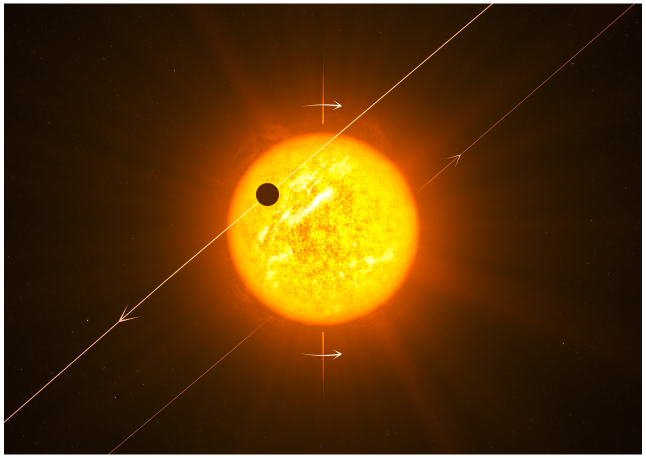
What are variable stars?

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

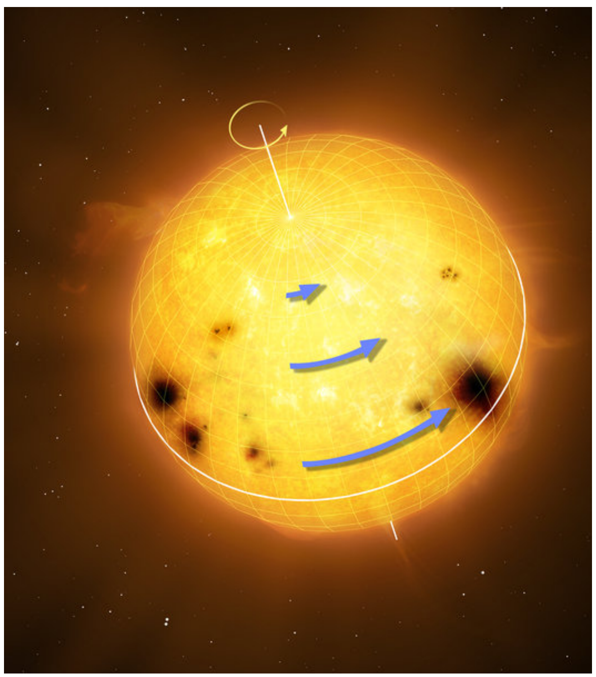
- extrinsic variables: variability is due to the eclipse of one star by another or the effect of stellar rotation
- intrinsic variables: variation is due to physical changes in the star or stellar system

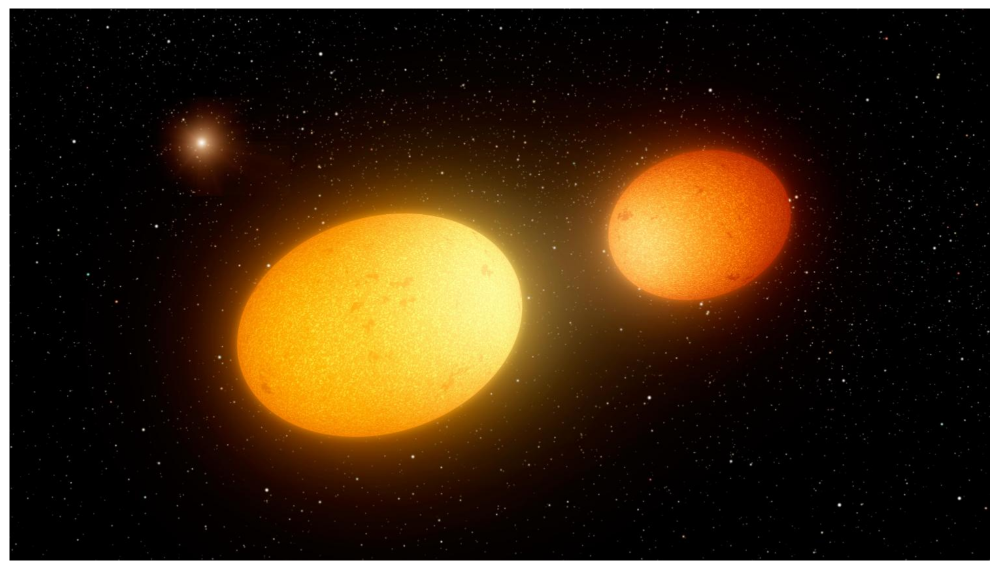
Extrinsic variables

Transiting planets/Eclipsing binaries



Rotating variables

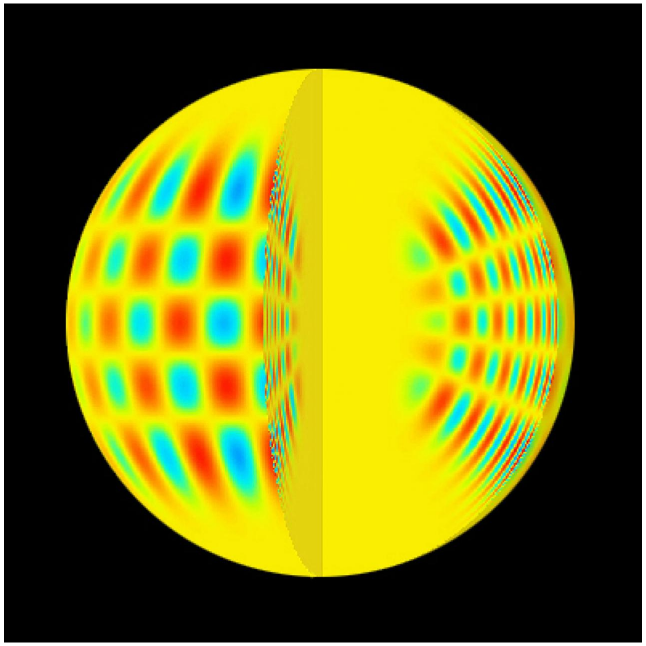


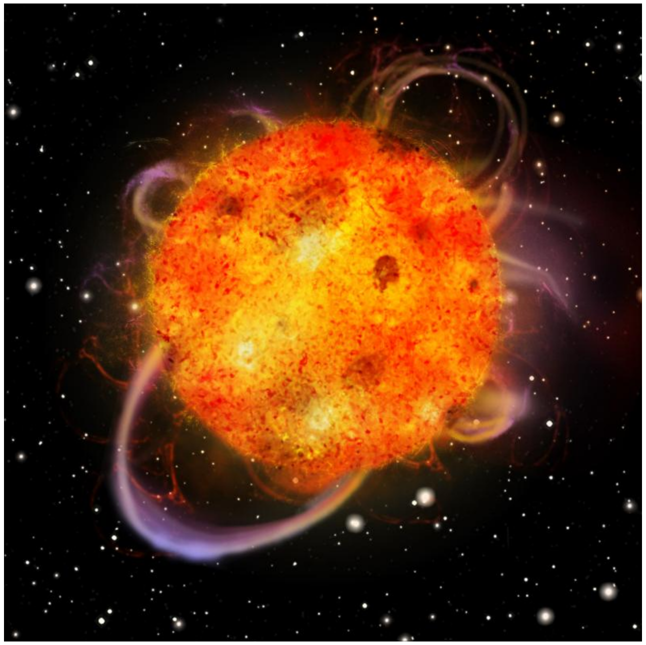


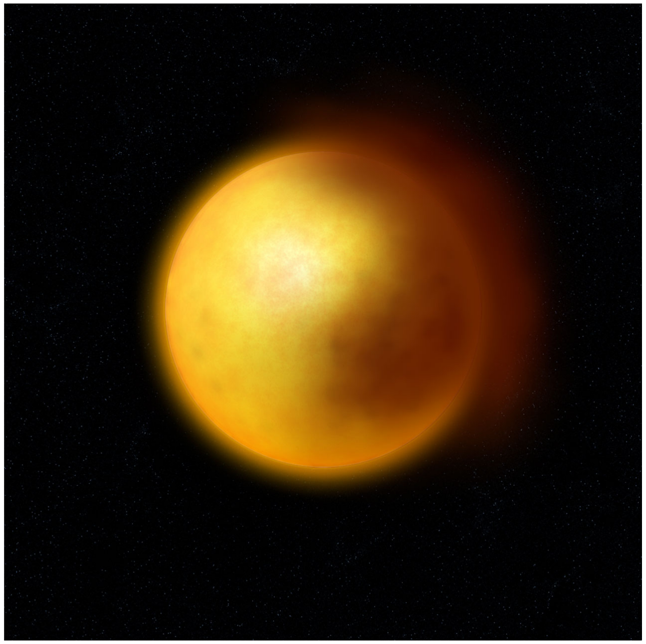
Intrinsic variables

Pulsating variables

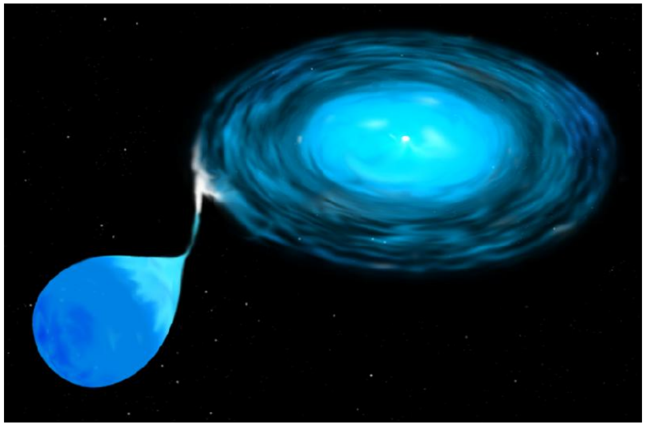
Eruptive variables

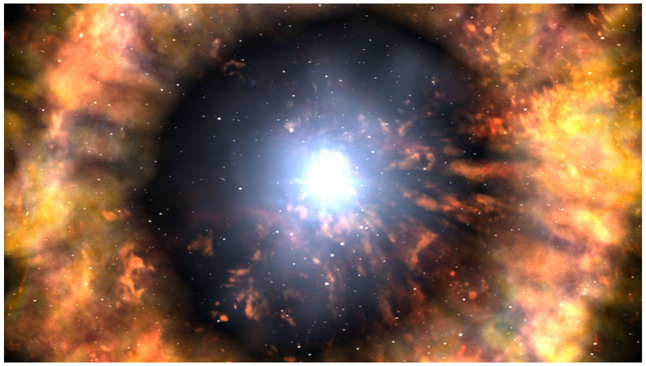






Cataclysmic variables

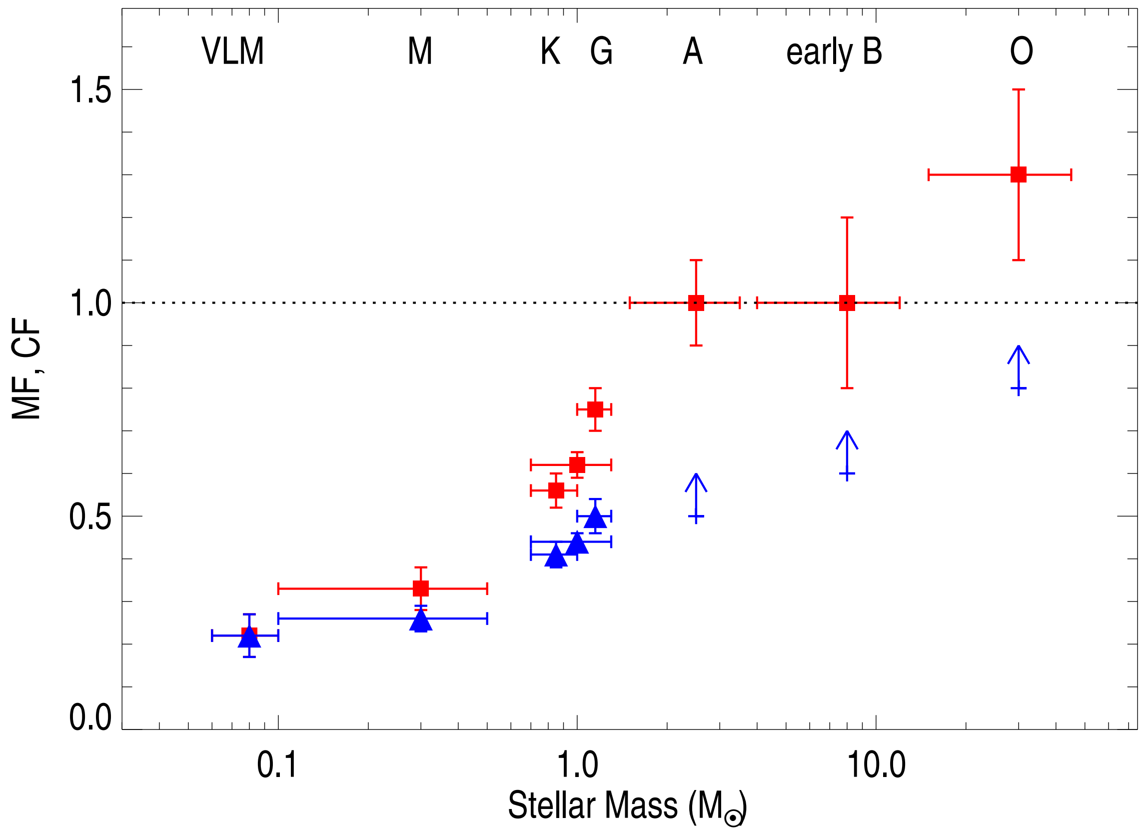




Binary Stars: Overview

Binaries

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



Duchene & Kraus 2013

→ 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:

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

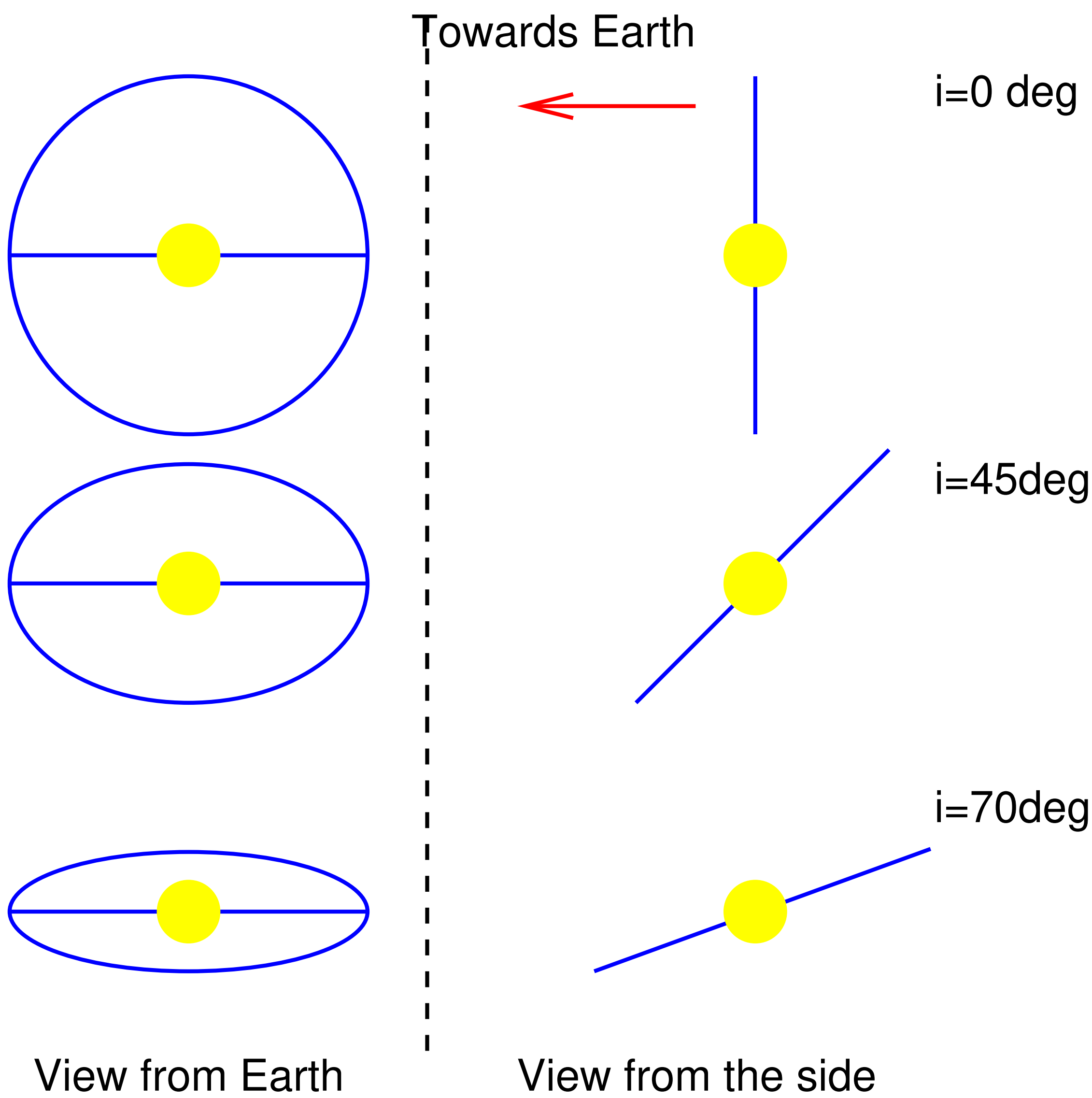
where

- $M_{1,2}$: 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

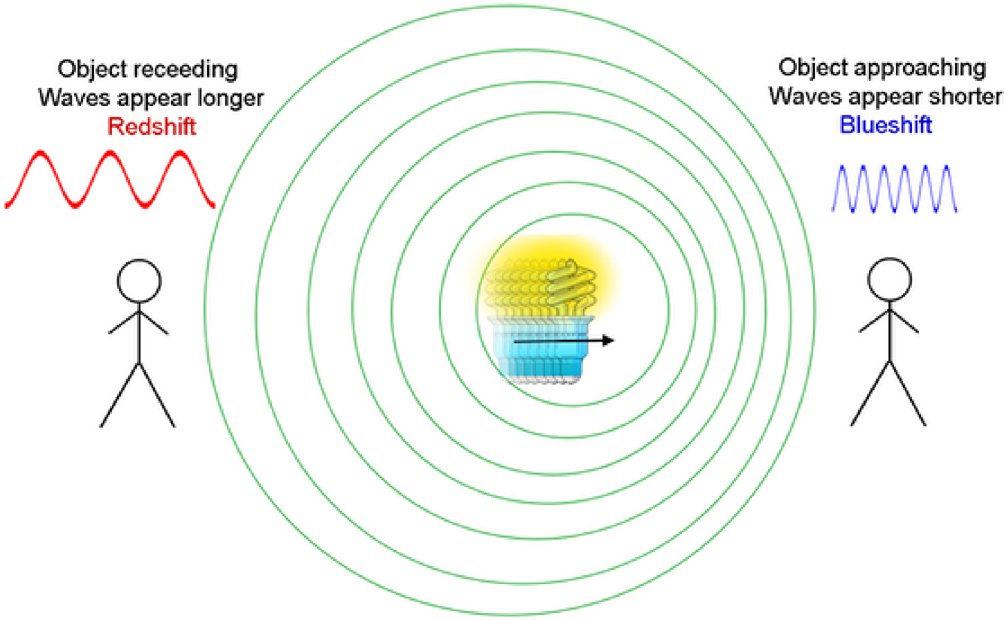


Problem when analysing orbits: orientation of orbit in space: “inclination”

In simplest case: real semi-major axis:

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

Spectroscopic Binaries



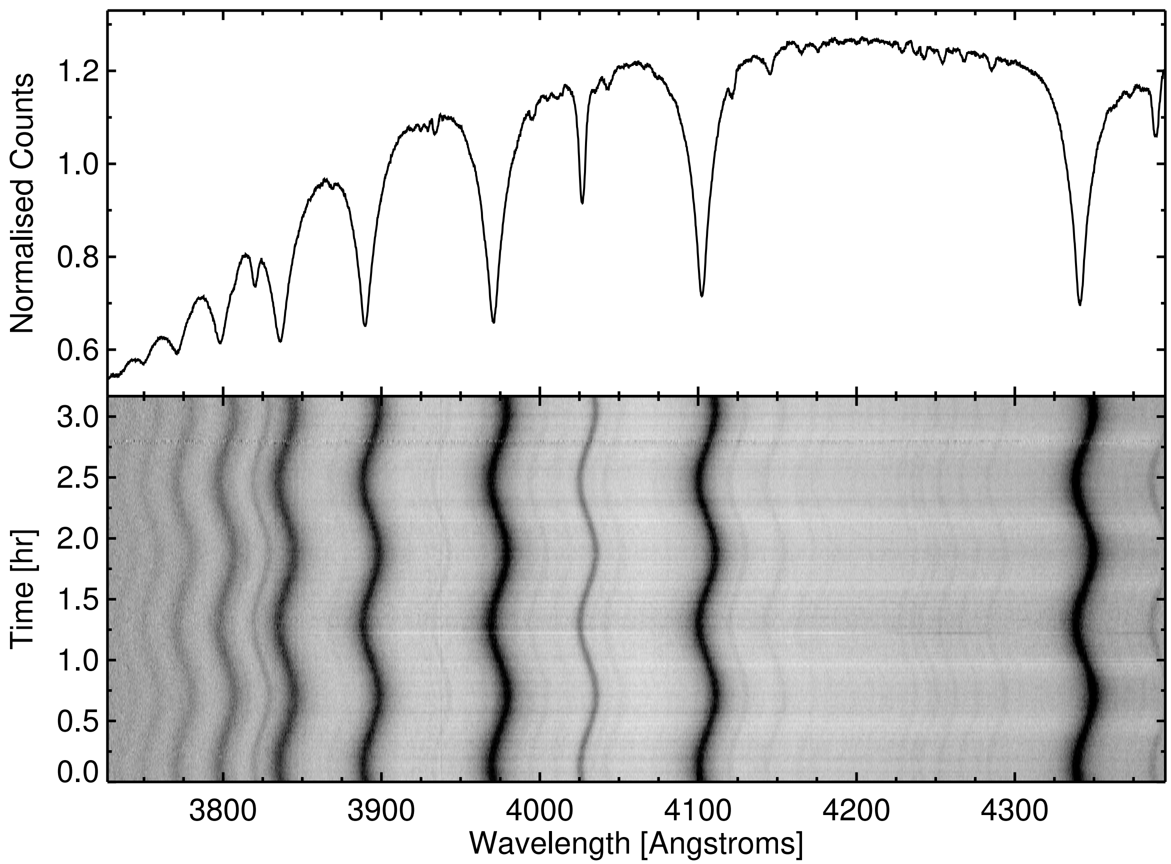
Spectroscopic binaries: Components close together: orbital motion via periodic Doppler shift of spectral lines.

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 ($\star$):

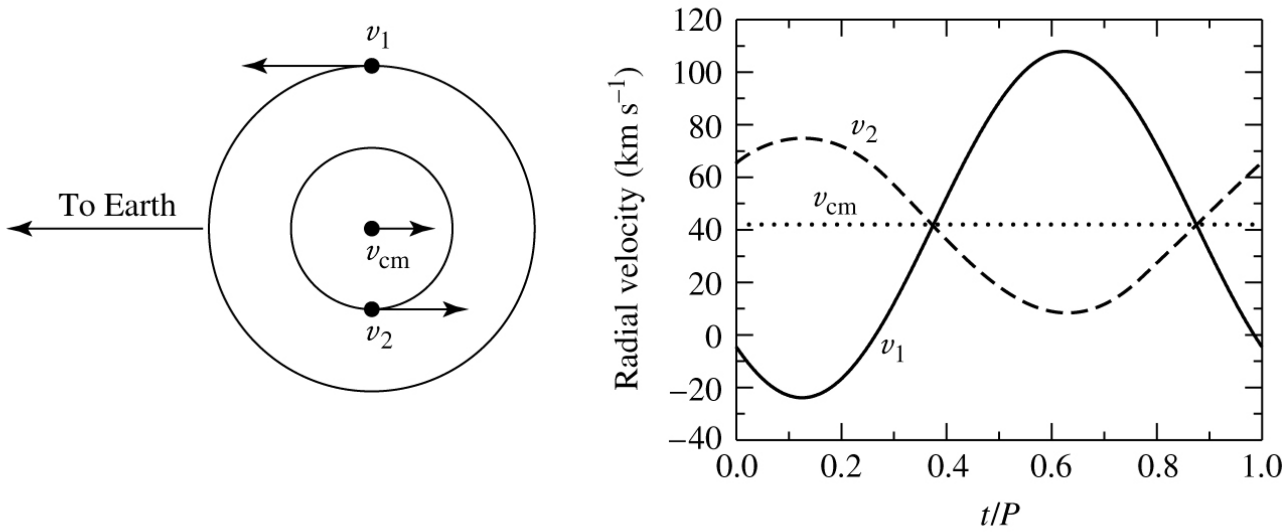
$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}(K_1 + K_1 \frac{M_1}{M_2})^3$$

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

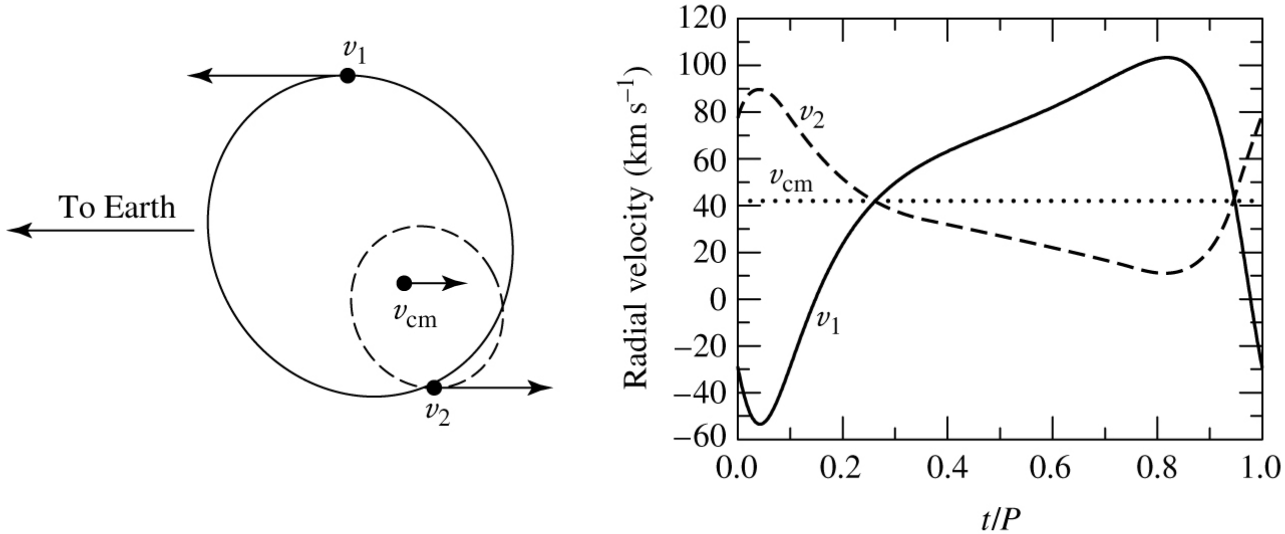
Mass function $f(M)$:

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

Spectroscopic binaries: Radial velocity curve



(a) (b)



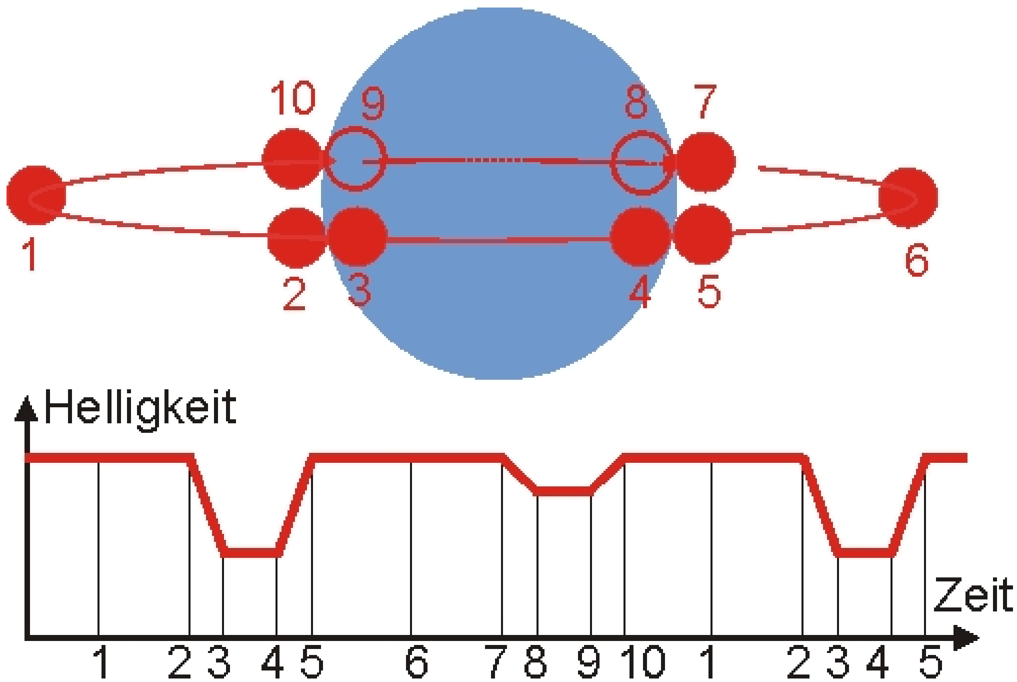
(a) (b)

`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:

$$d_A + d_B = v(t_5 - t_2) \quad (3.1)$$

Duration of eclipse egress:

$$d_A - d_B = v(t_4 - t_3) \quad (3.2)$$

therefore:

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

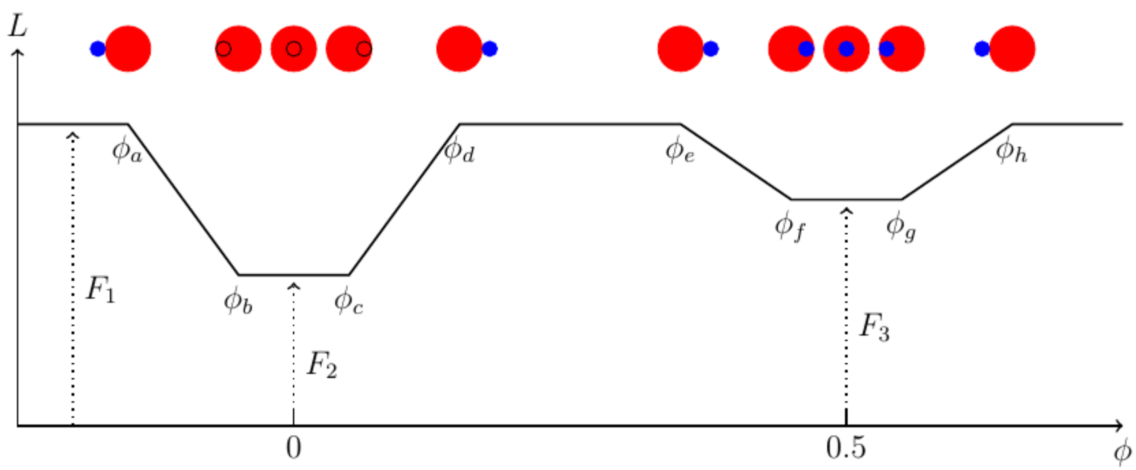
$$d_B = \frac{1}{2} v(t_5 - t_2 - t_4 + t_3) \quad (3.4)$$

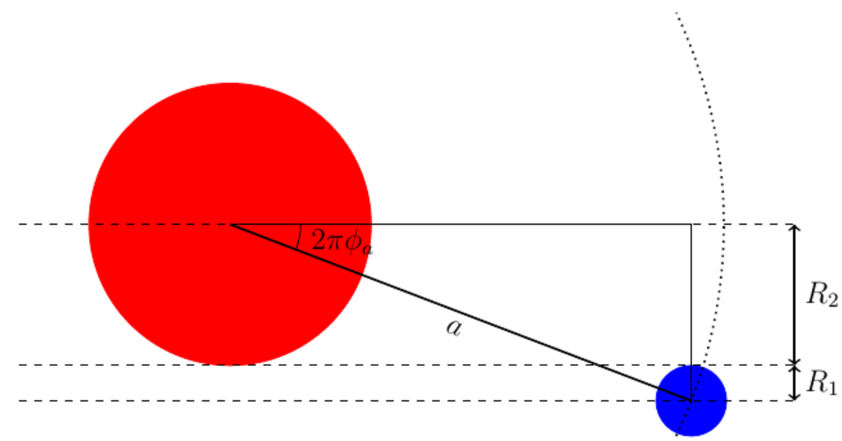
Note: requires extremely accurate photometry

Resulting radii are independent of distance

Temperature and radius ratio

Eclipsing Binaries





Stephan-Boltzmann-Law

$$L_{1/2} = 4\pi R_{1/2}^2 T_{1/2}^4 \quad (3.5)$$

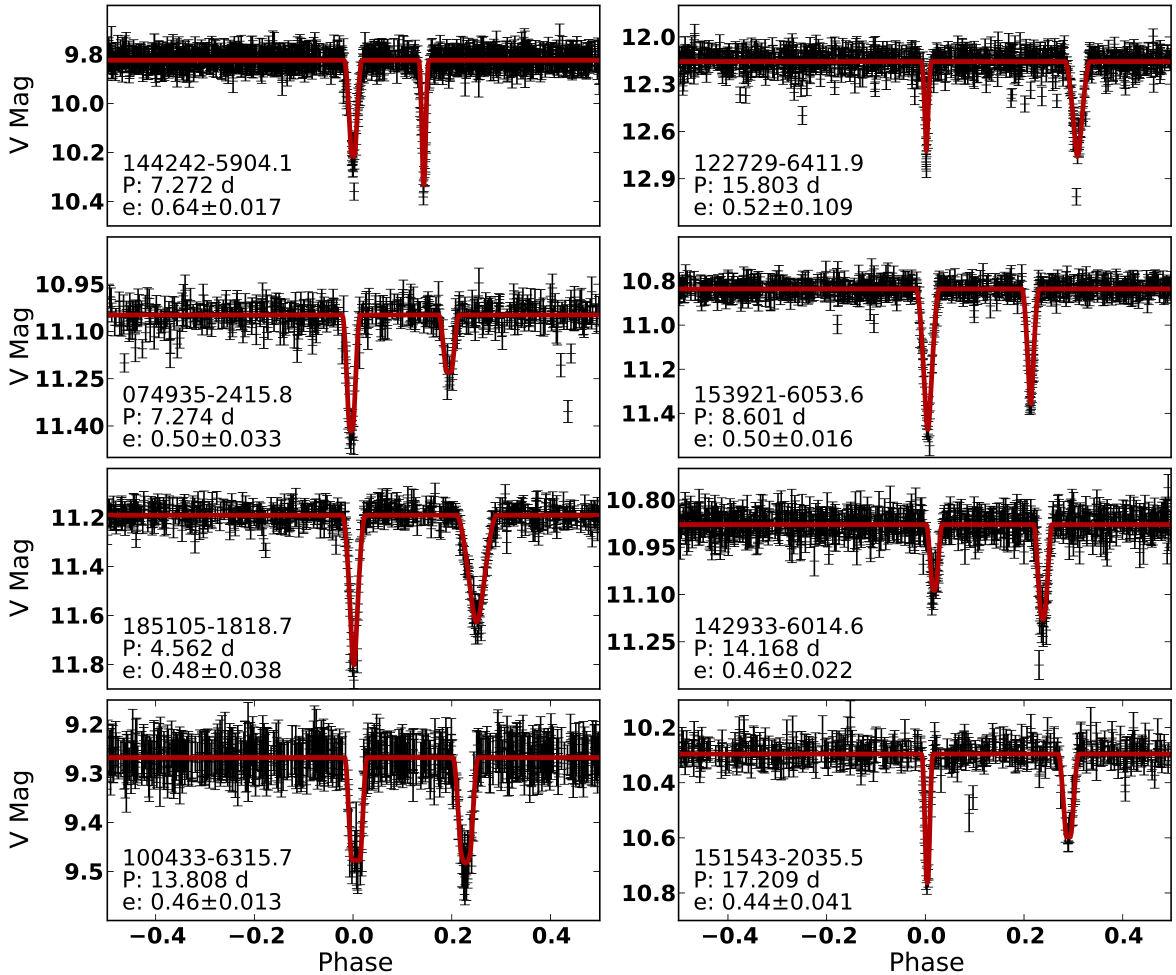
$$\frac{T_1}{T_2} = \left(\frac{F1 - F2}{F_1 - F_3}\right)^{1/4} \quad (3.6)$$

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

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

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

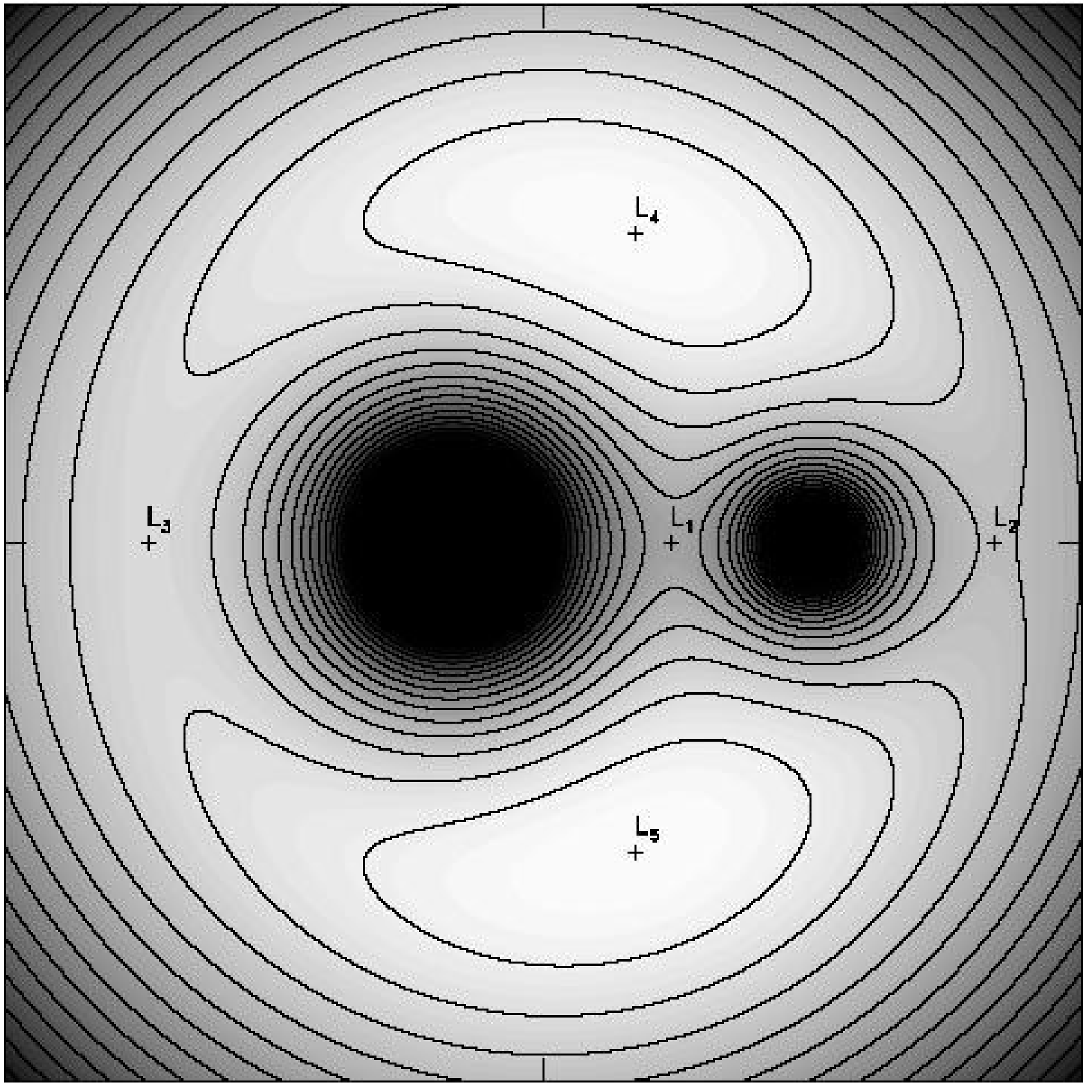
Eccentricity in eclipsing binaries



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:

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

and where

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

Stellar surfaces are isosurfaces of this potential

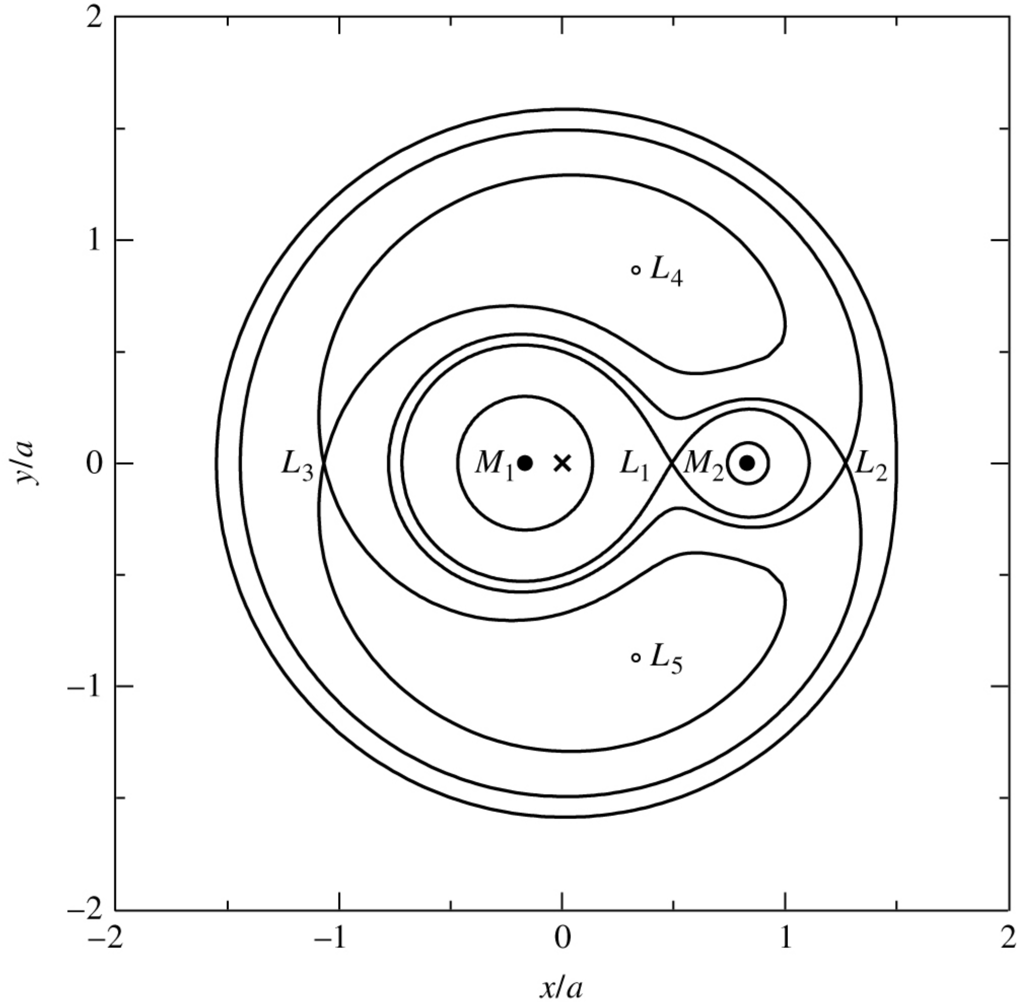
$\Longrightarrow$ stars are non-spherical

$\Longrightarrow$ 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

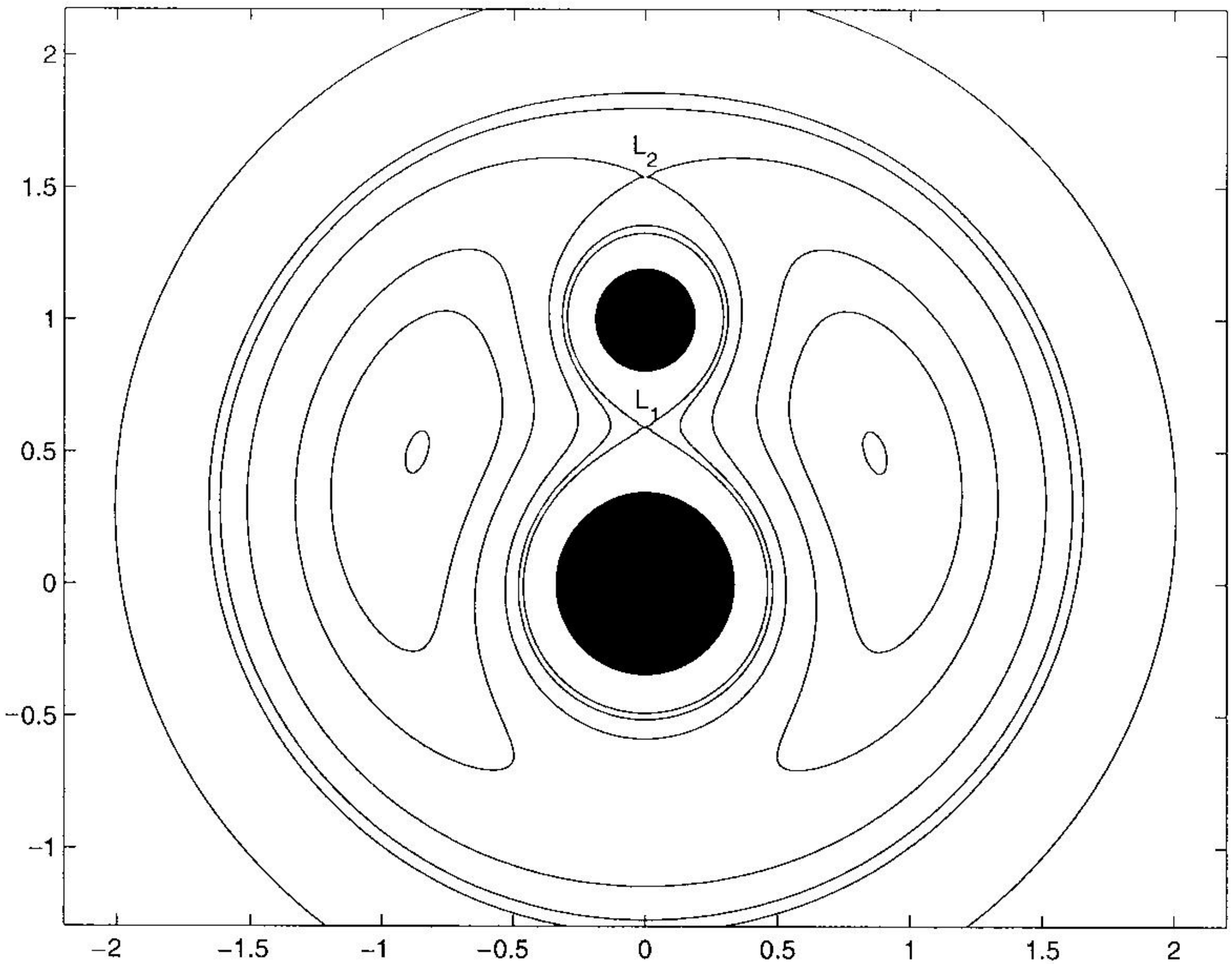


Carroll & Ostlie

Approximations:

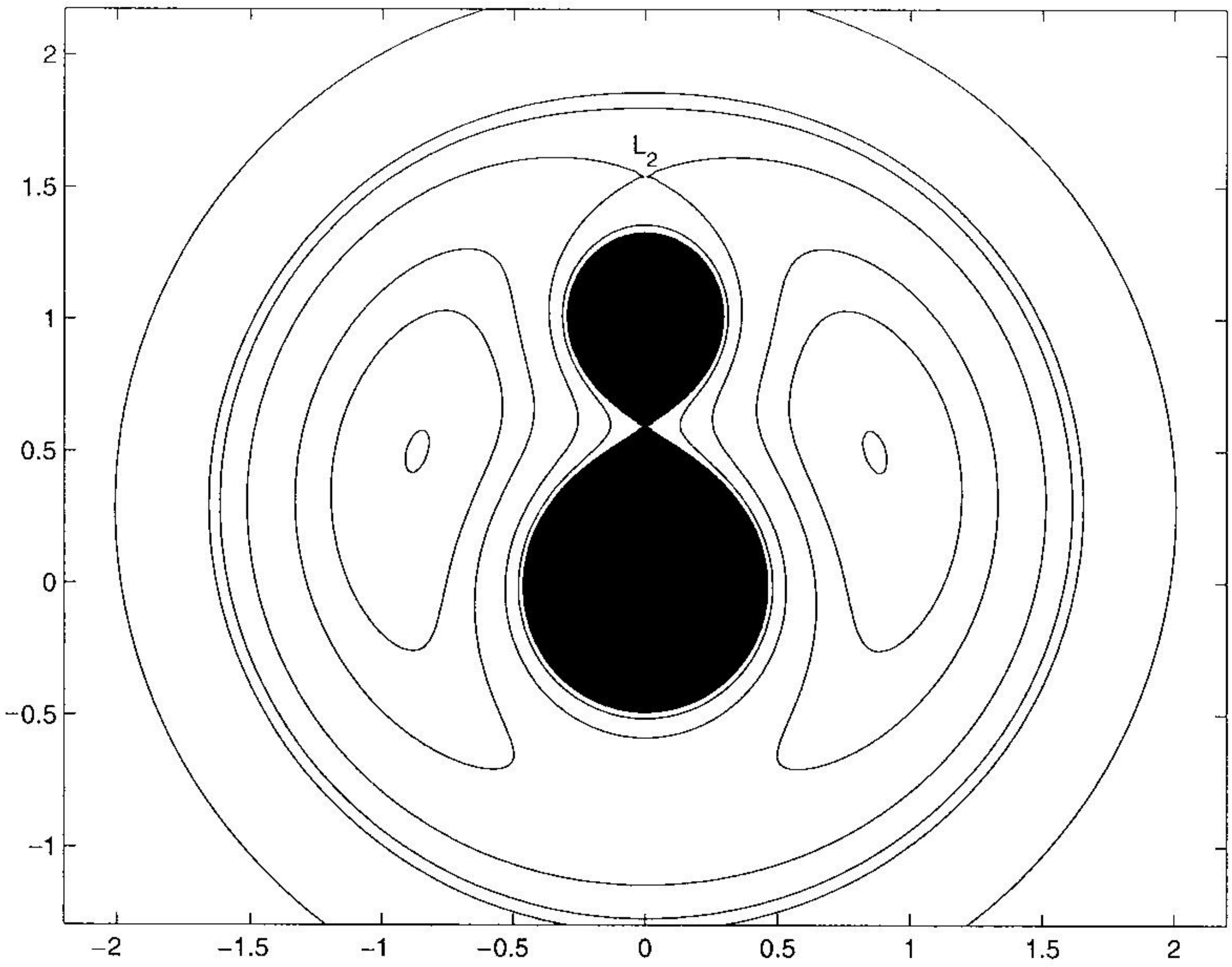
- stellar potentials are point-like (most of the stellar mass in concentrated in its core)
- Orbits are circularised (quickly established by tidal forces)
- rotation axes are perpendicular to the orbital plane
- stellar rotation is synchronous (tidally locked to the orbit)

The Roche Model

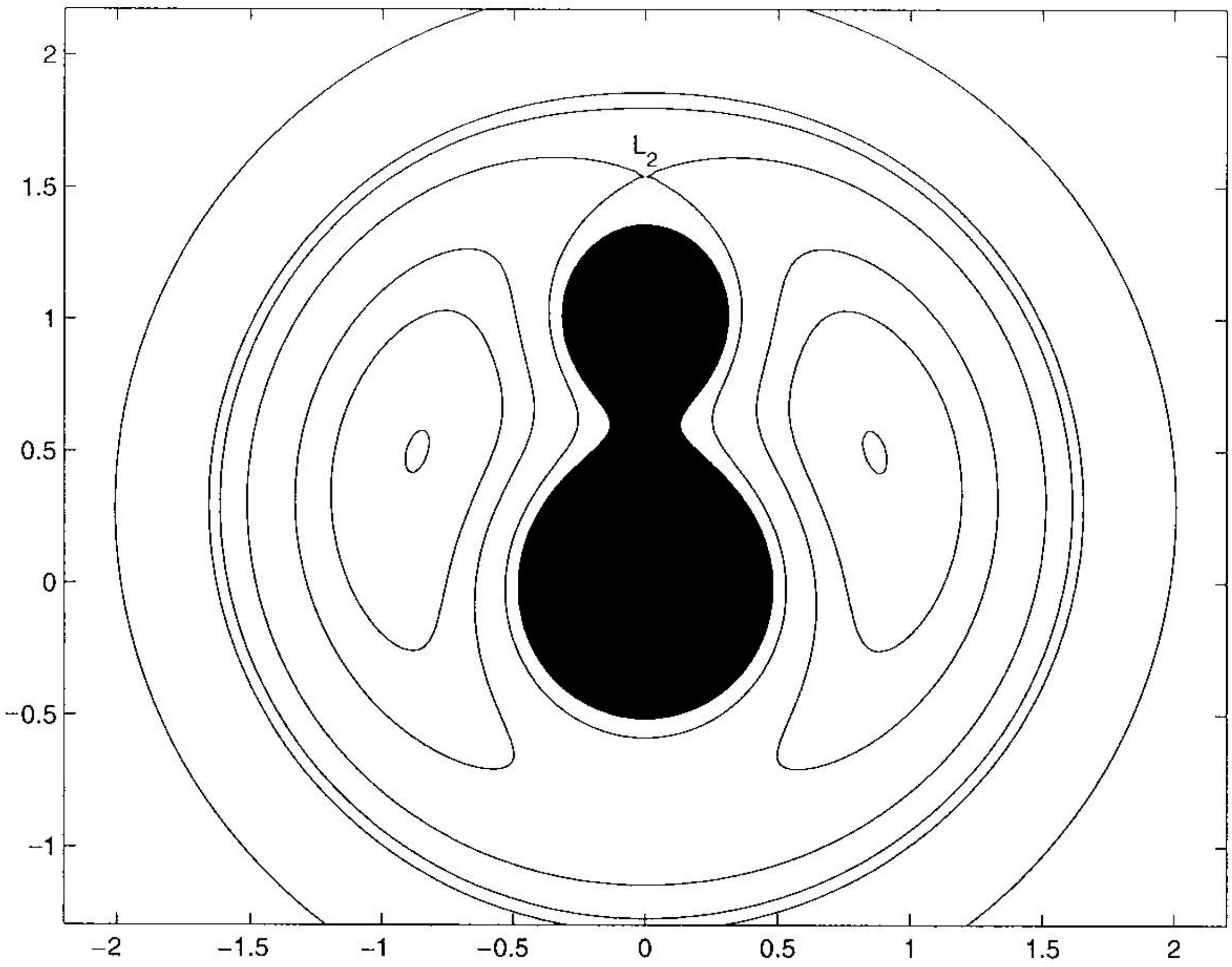


Detached Binaries

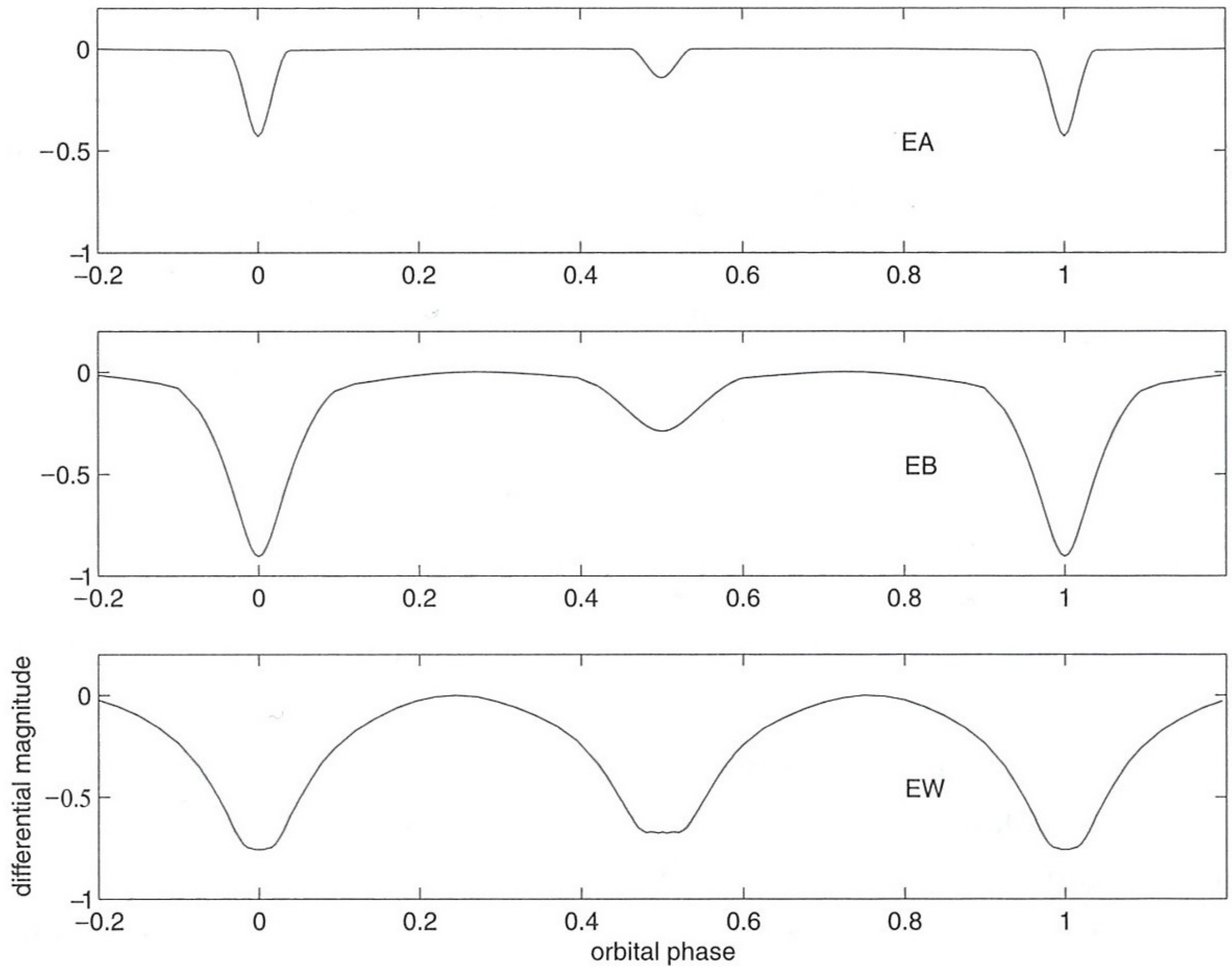
The Roche Model



The Roche Model



The Roche Model



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

Limb darkening

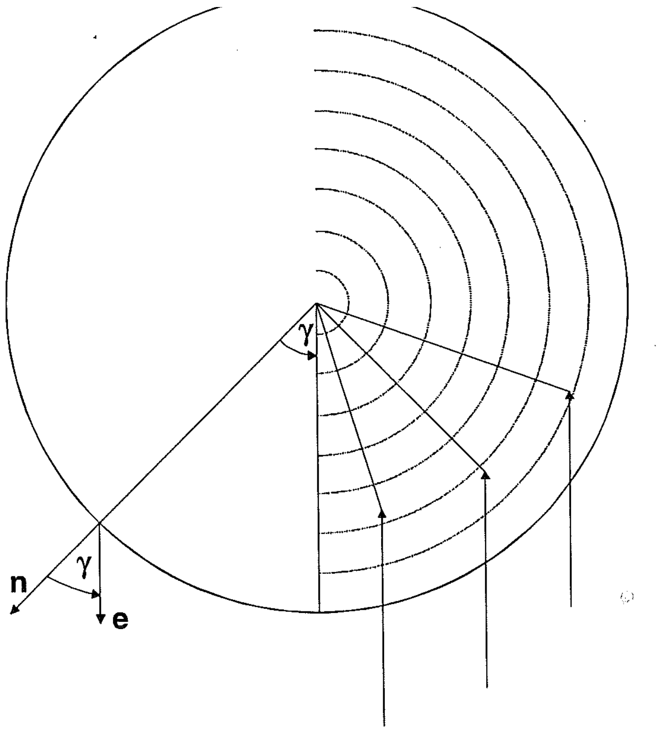
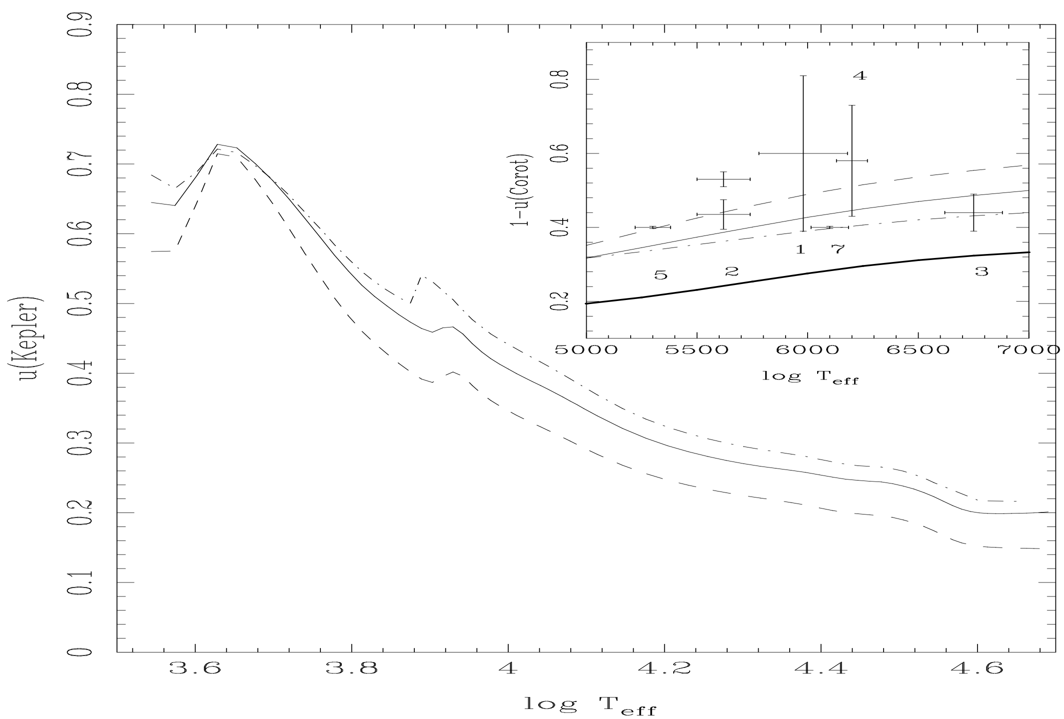


FIGURE 3.17. Center-to-limb variation. This figure shows the aspect angle γ (angle between normal vector **n** and radiation emission direction **e**) appearing in the mathematical formulation of the limb-darkening. The right part of the figure illustrates that the depth of the atmosphere region (and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

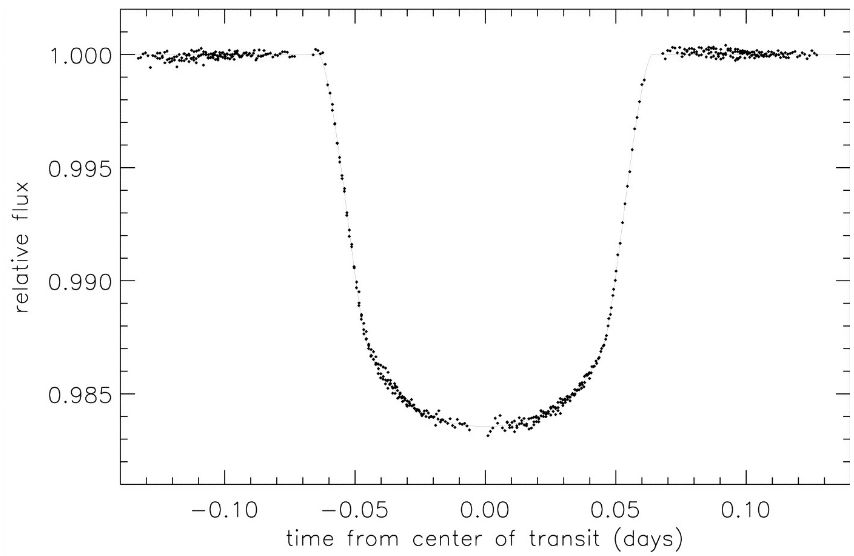
Claret's law:

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

$\mu = \cos\gamma$

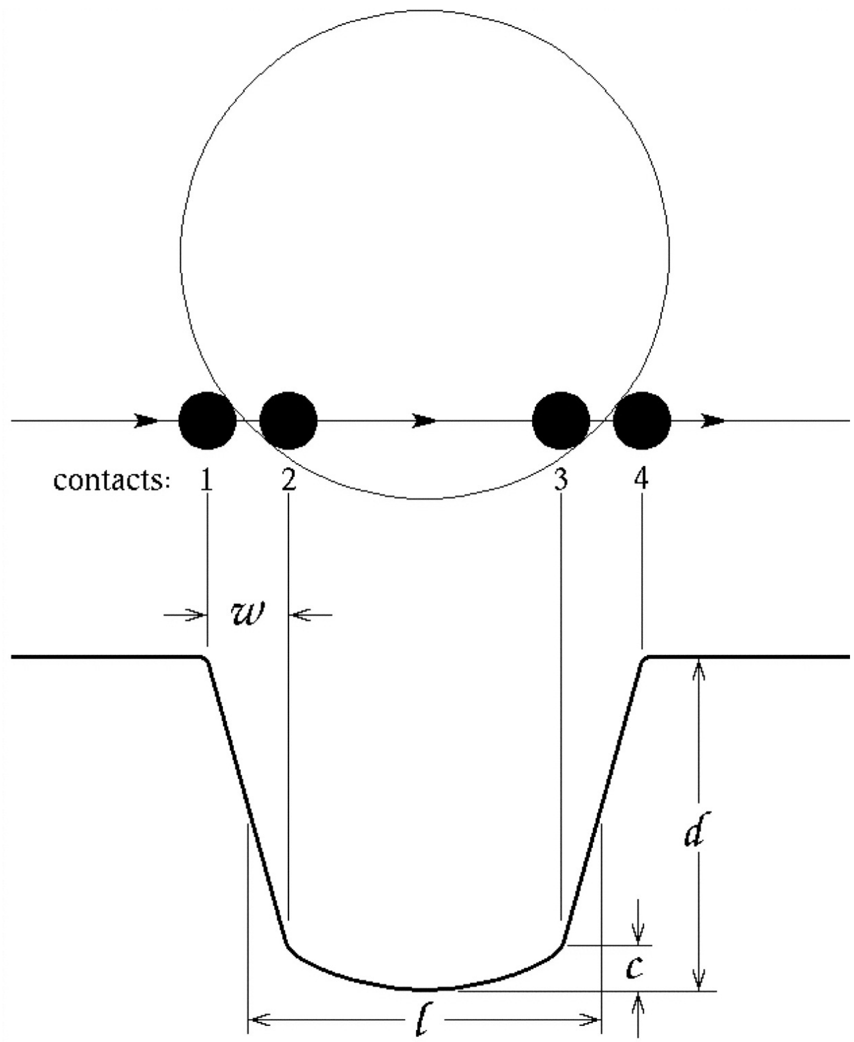
Limb darkening

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

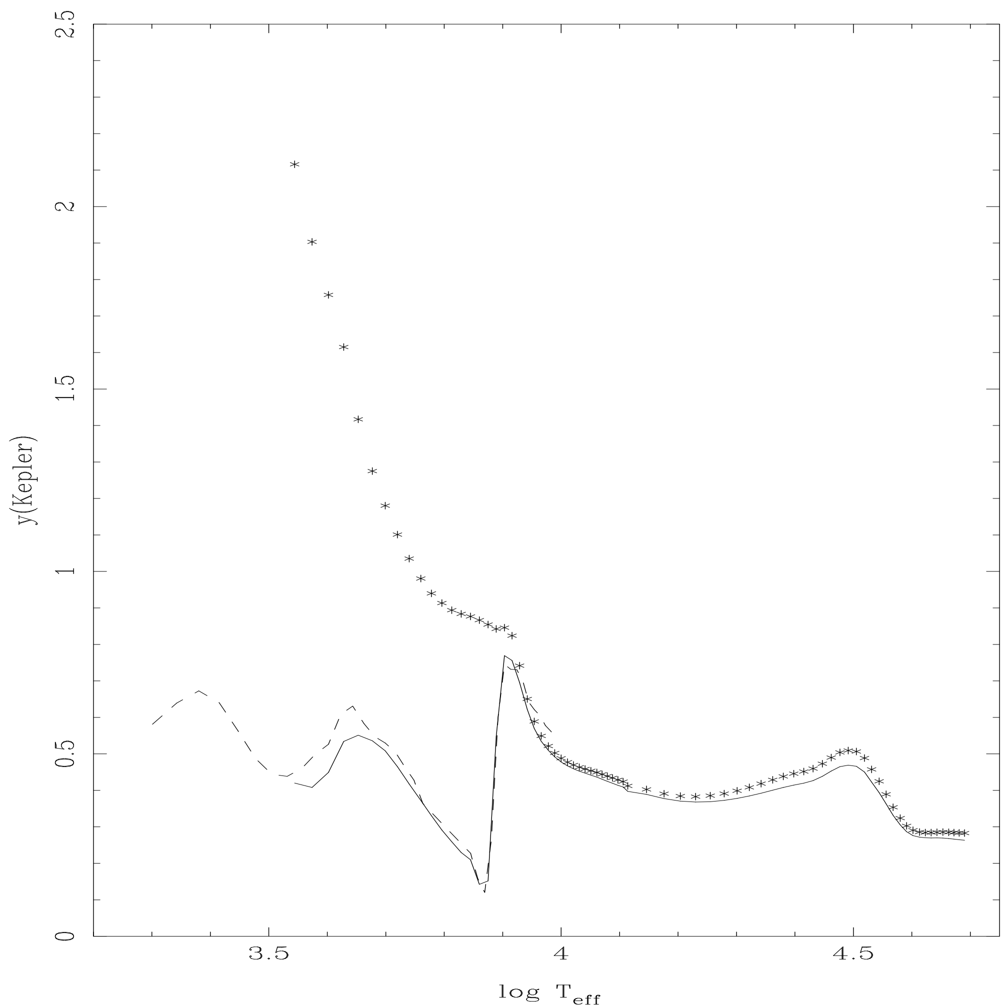


- Transit is not central
- transit depth is not constant
- $\longrightarrow$ caused by limb darkening

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



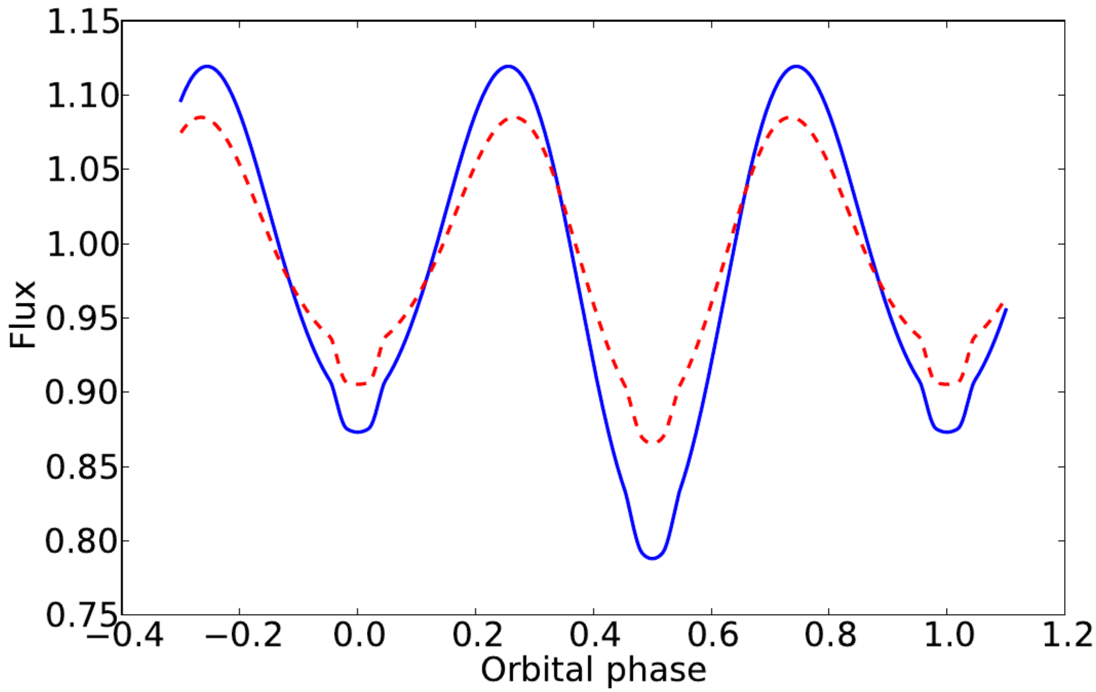
Gravity darkening



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)

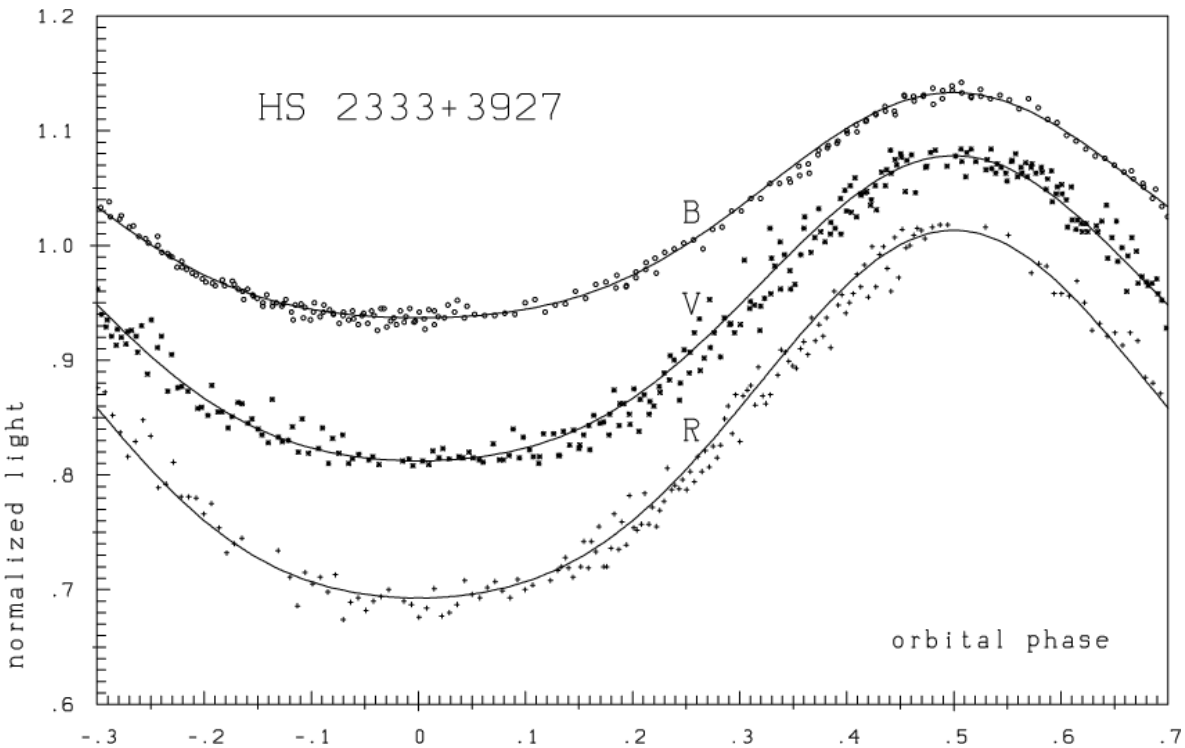
Gravity darkening



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)

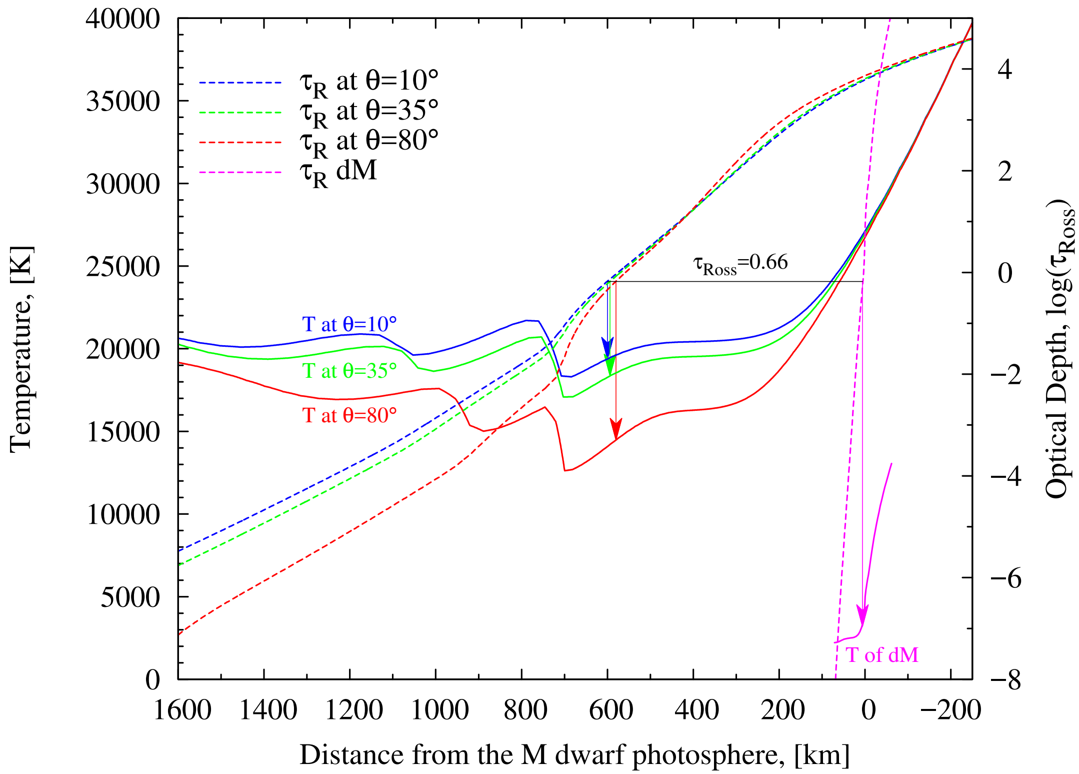
Reflection effect



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 refelected from the irradiated surface.

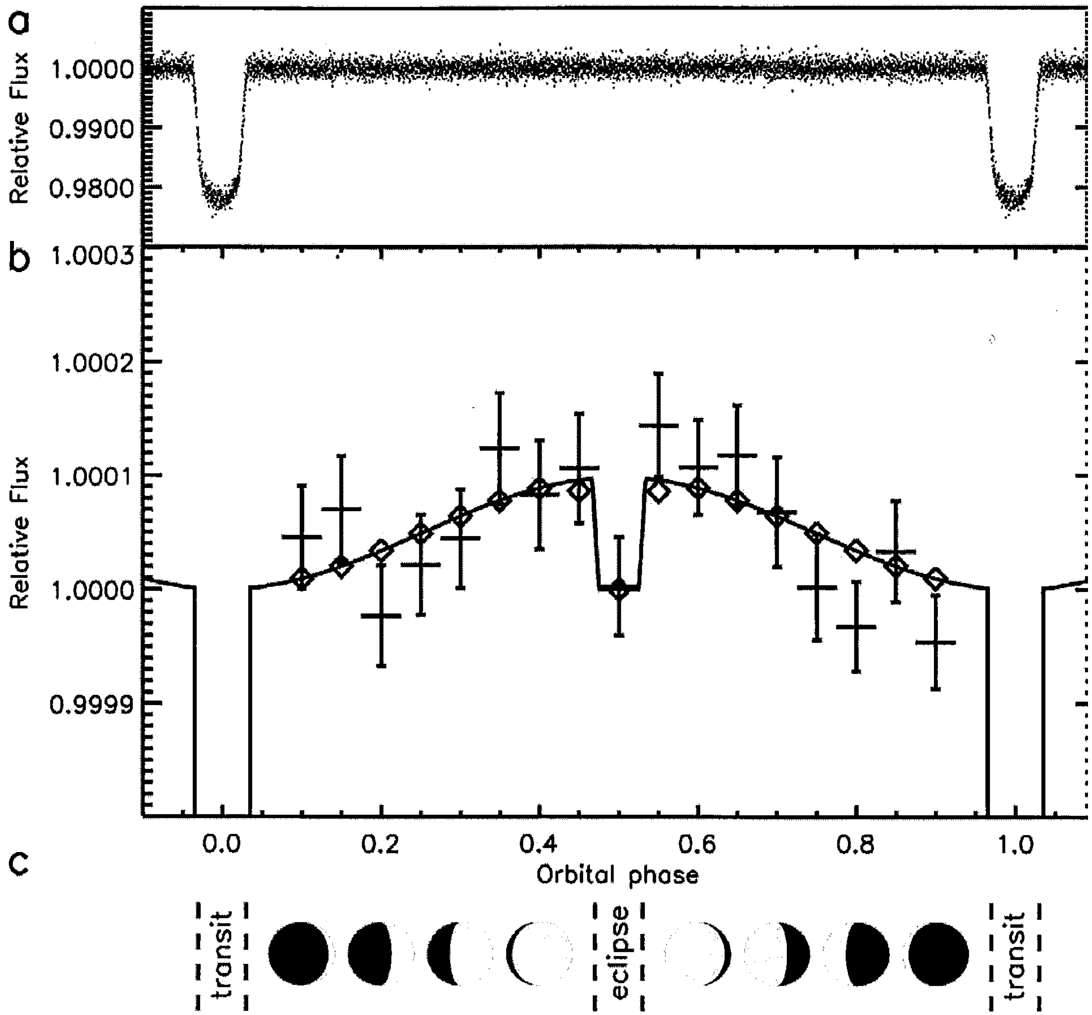
Refection effect



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%

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

Roche model parameters

i	Inclination
q	mass ratio M_2/M_1 for $M_2 \leq M_1$
Ω_1, Ω_2	Surface potentials
T_1, T_2	effecive temperatures
A_1, A_2	albedos
g_1, g_2	gravity darkening coefficients
$L_1(\lambda)$, $L_2(\lambda)$	monochromatische luminosities
$x_1(\lambda)$, $x_2(\lambda)$	linear limb darkening coefficients
$l_3(\lambda)$	third light

- parameters of the Roche model
- observe light curves, preferntially in several filters
- fit synthetic light curves, 17 free parameters!
- degenaracy of solutions, in particular for q
- RV curve $\longrightarrow$ limits q!

Lightcurve analysis of eclipsing sdB+dM systems

Research workshop on evolved stars

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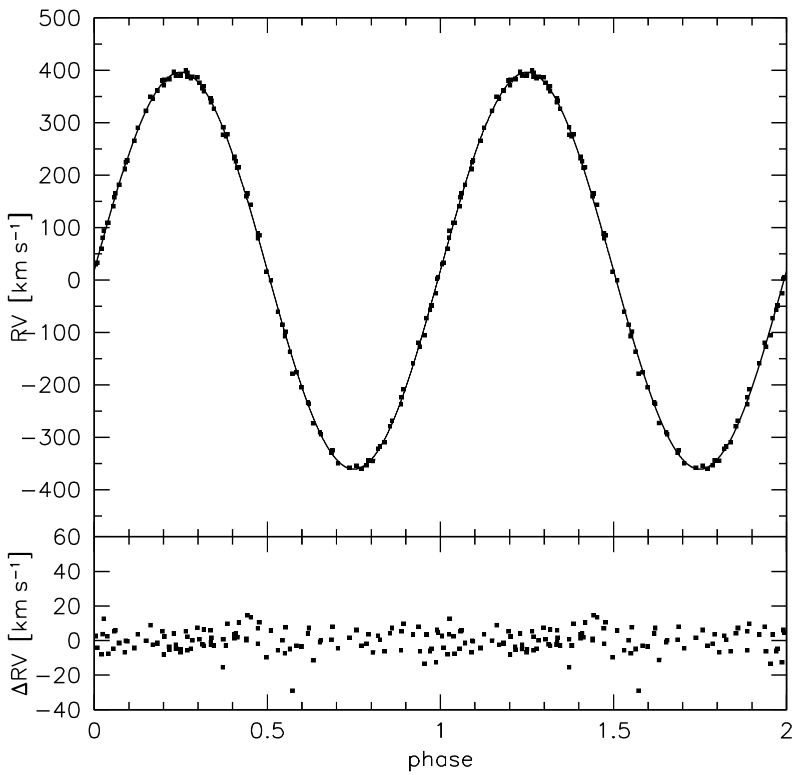
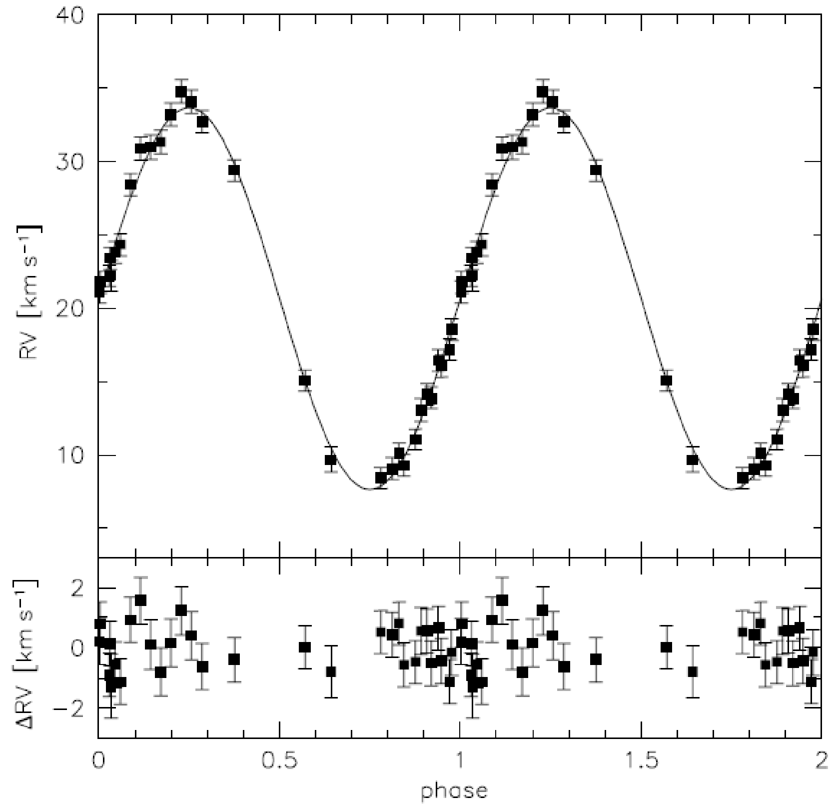
Introduction

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)

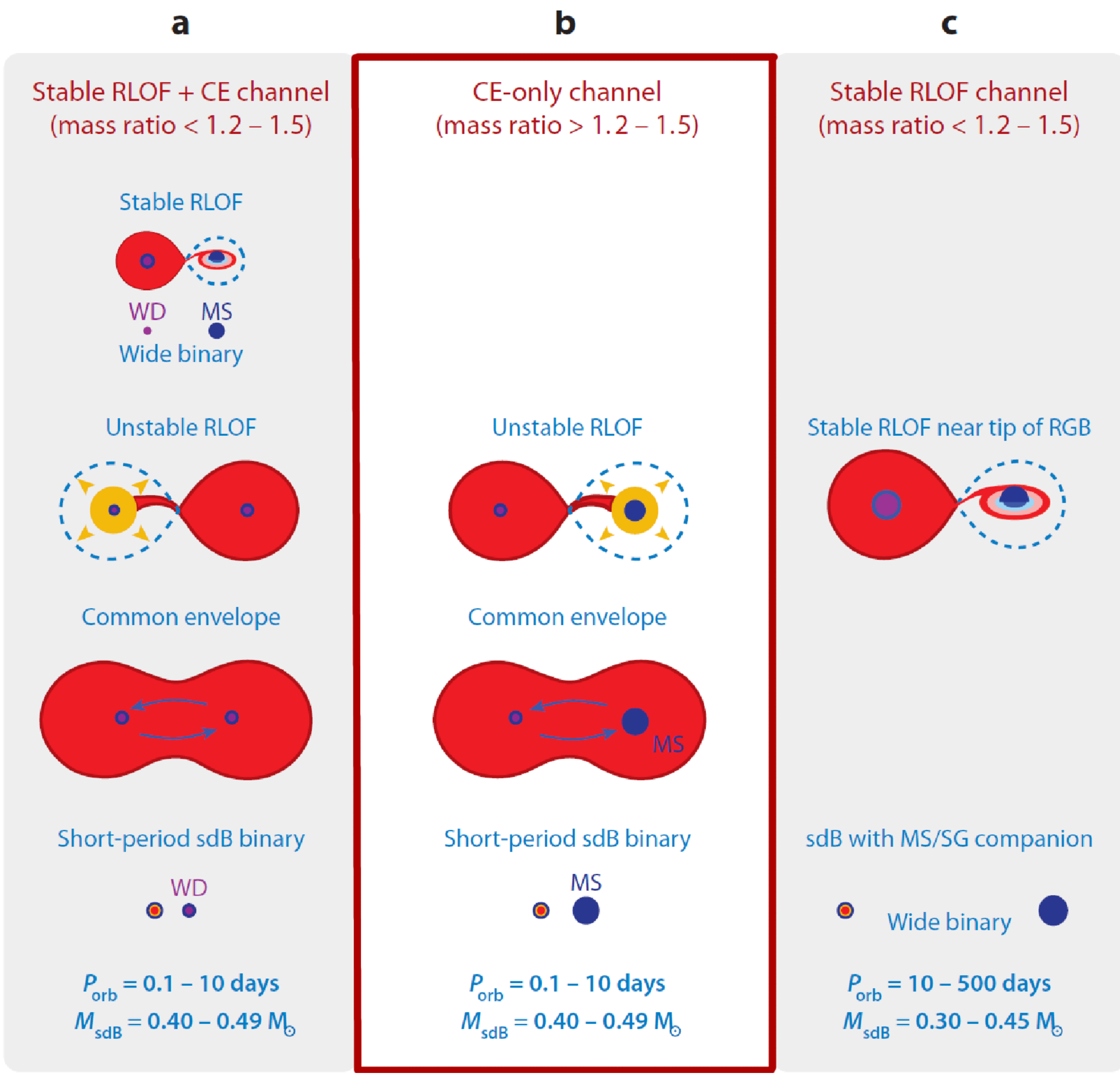


PHL 457, P = 0.3131 d (Schaffenroth et al. 2014)

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

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

Formation of sdB binary

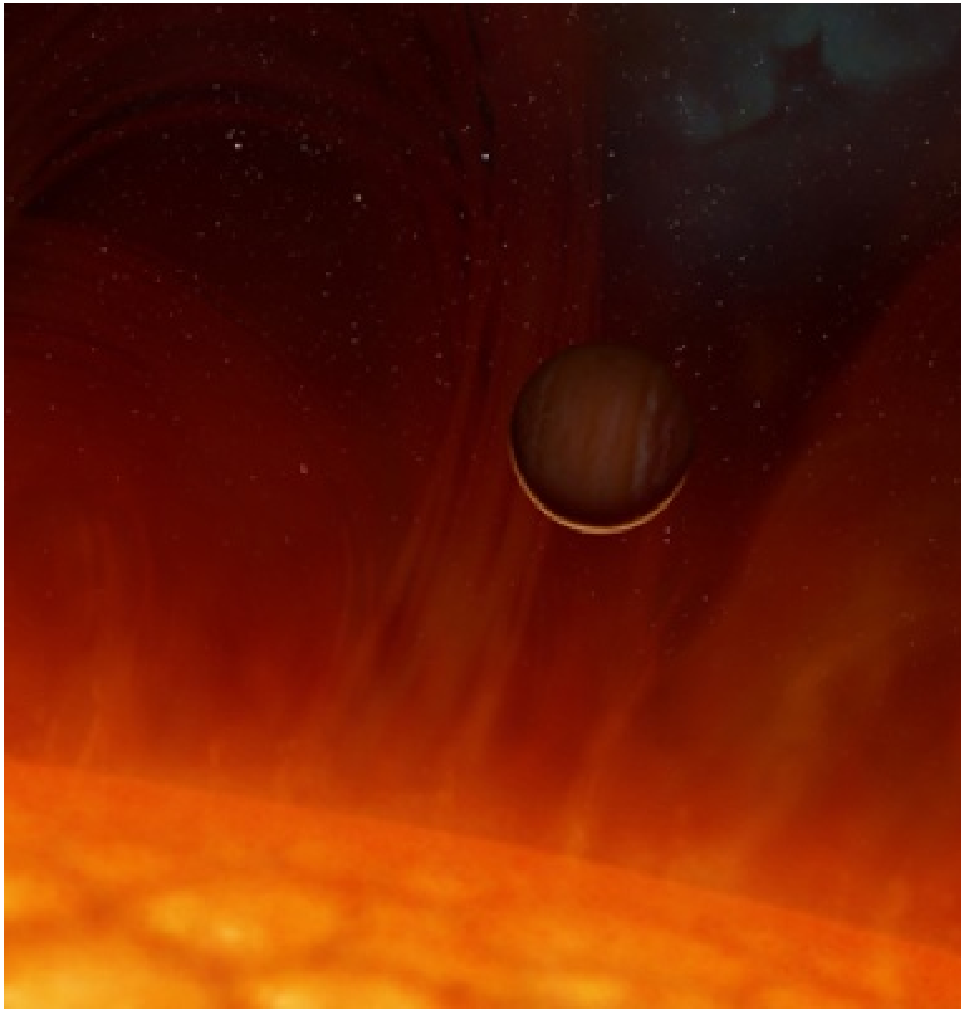


Han et al. (2002,2003)

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 $\geq 10 M_{\mathrm{Jupiter}}$ depending on separation
    $\rightarrow$ ejection of envelope



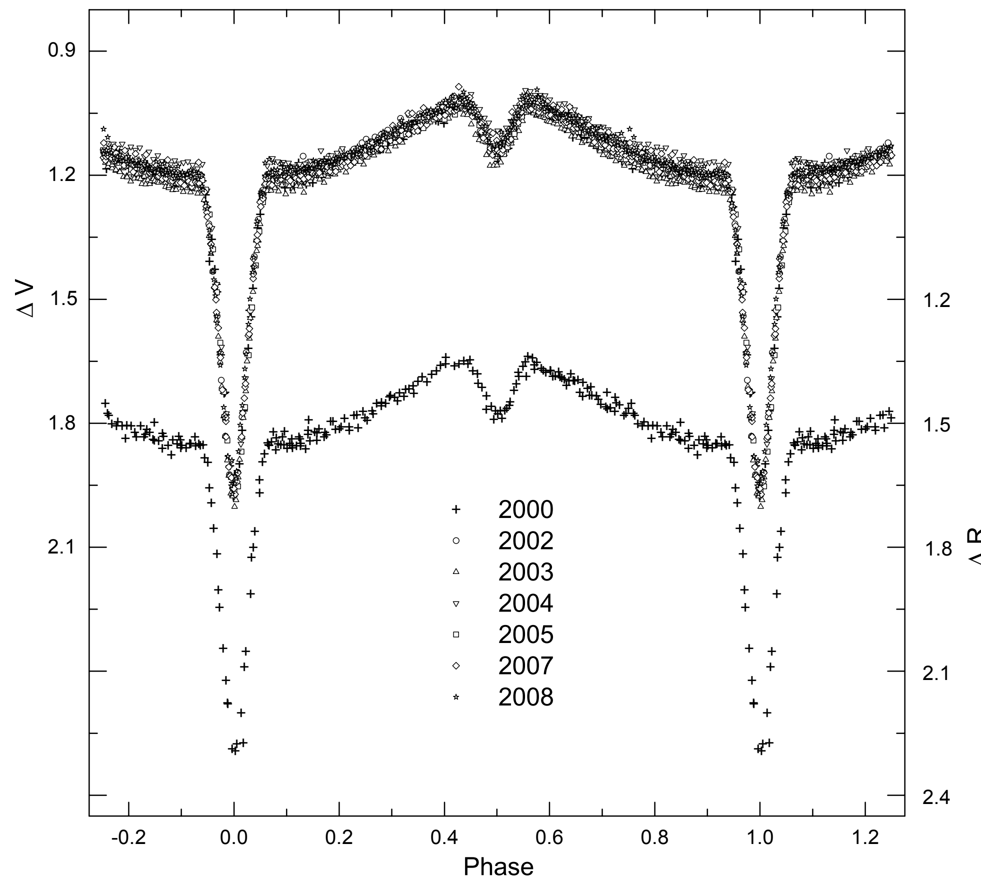
$\rightarrow$ **studying the influence of planets on stellar evolution**

HW Virginis systems

- eclipsing binaries consisting of sdB and cool, low mass stellar or substellar companion
- 20 HW Vir systems published
- very short period ∼ 1.5-6 h (separation ∼ 1 $R_\odot$)

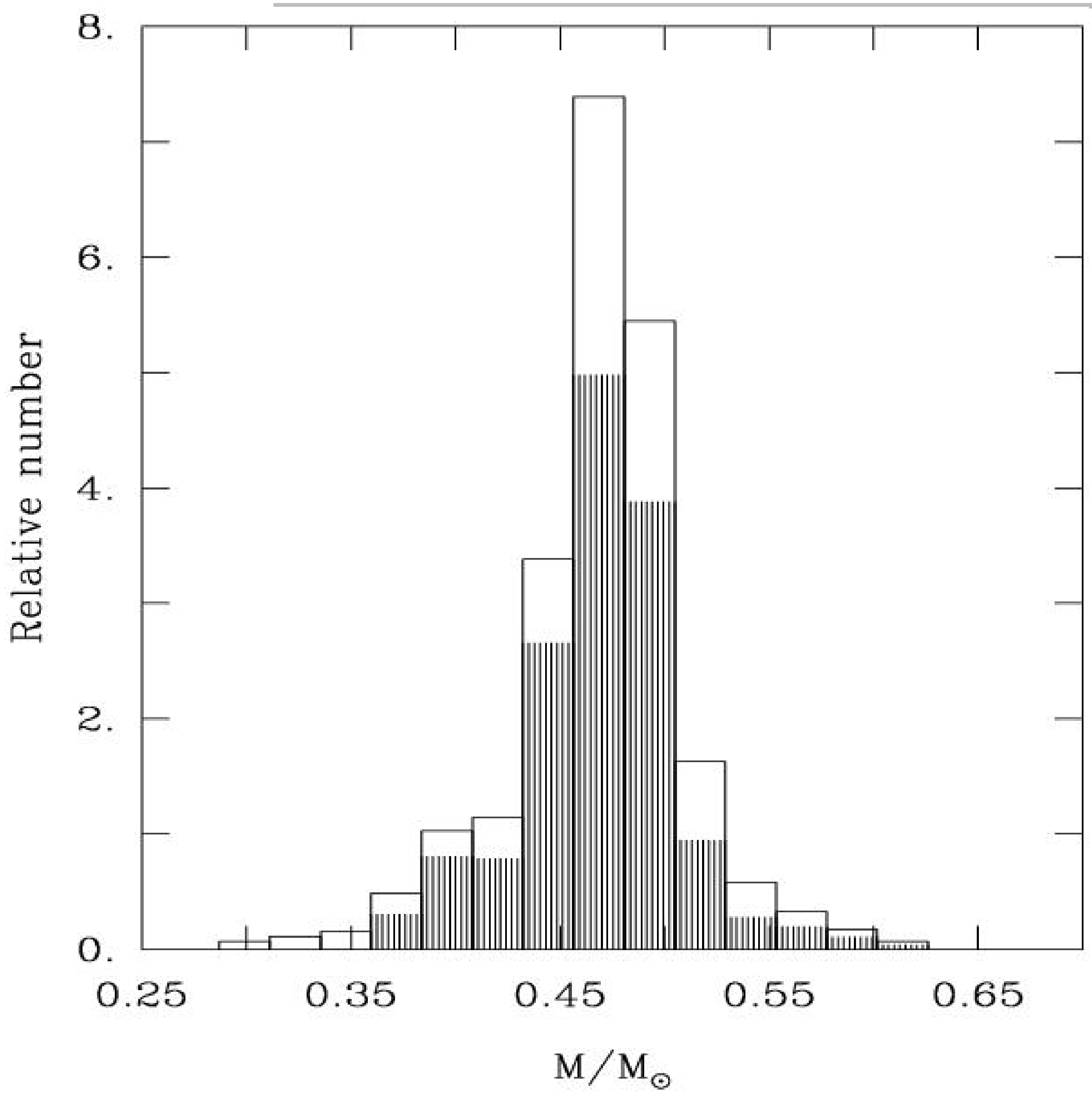
  ⇒ post common envelope system
- only sdB visible in spectrum
- unique lightcurve

  ⇒ huge reflection effect



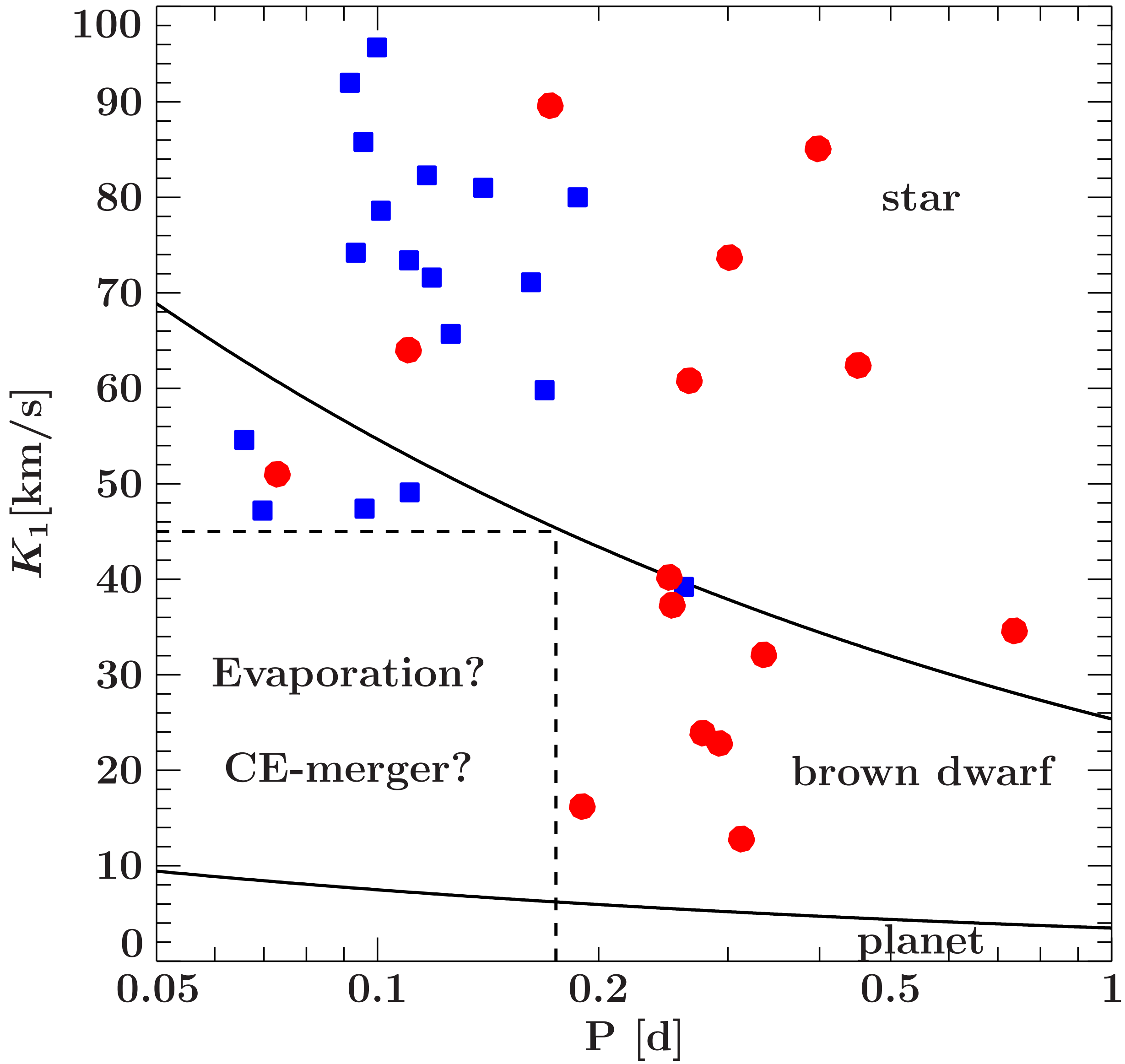
Lightcurve of HW Virginis (Lee et al. 2009)

Observed mass distribution of sdBs



Fontaine et al. 2012

Minimum companion masses of hot subdwarfs with cool companions



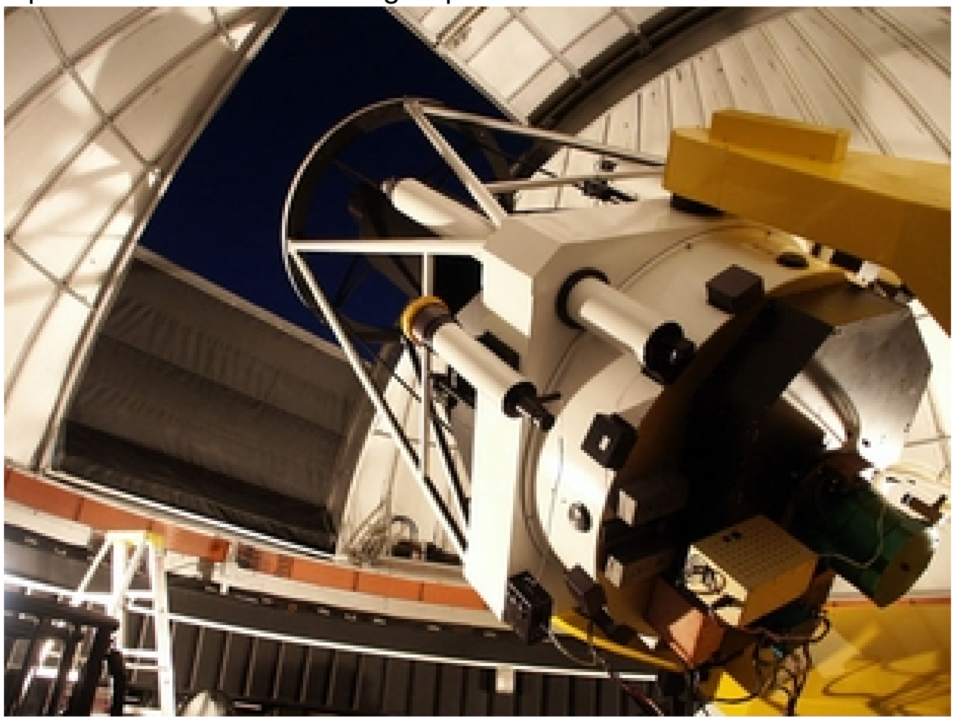
Schaffenroth et al. 2019 in press

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

Ground-based lightcurve surveys

OGLE

Optical Gravitational Lensing Experiment



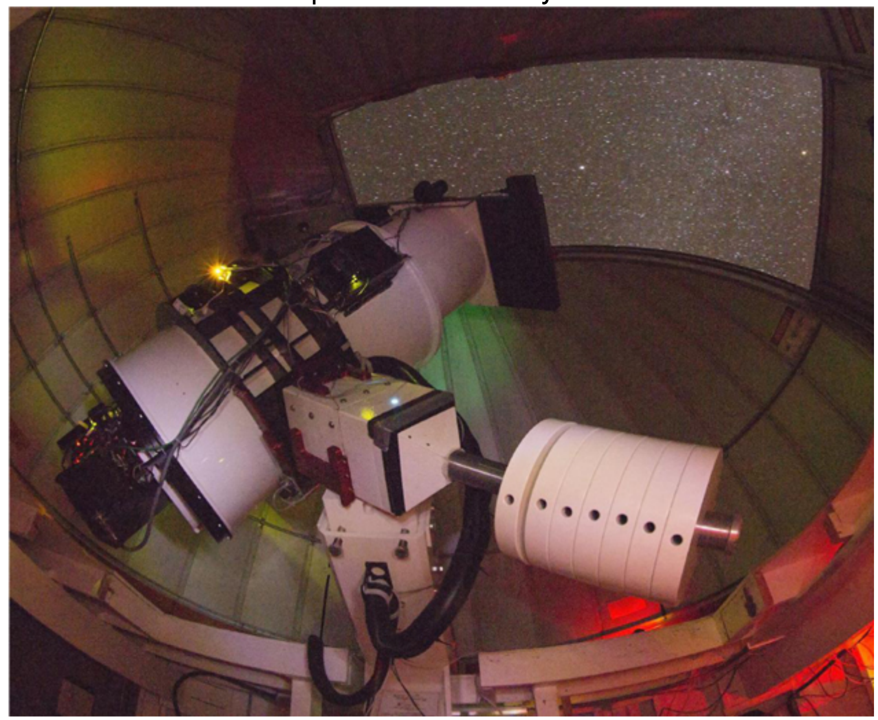
→ observation of the lightcurve of many stars in different fields

→ discovery of planetary transits, pulsators, eclipsing binaries

CRTS, PTF, ZTF, BlackGEM, ...

ATLAS

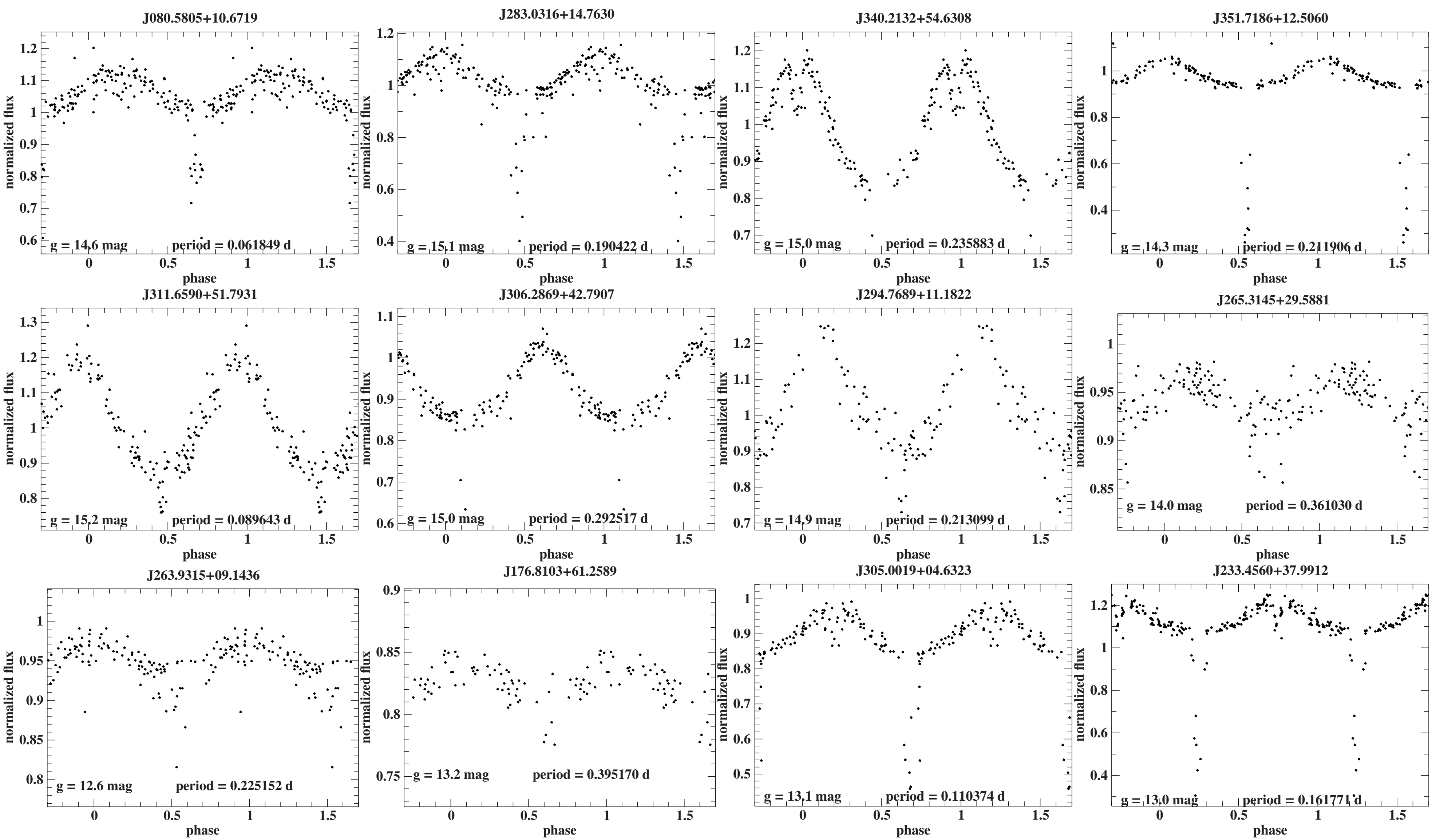
Asteroid Terrestrial-impact Last Alert System



→ 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



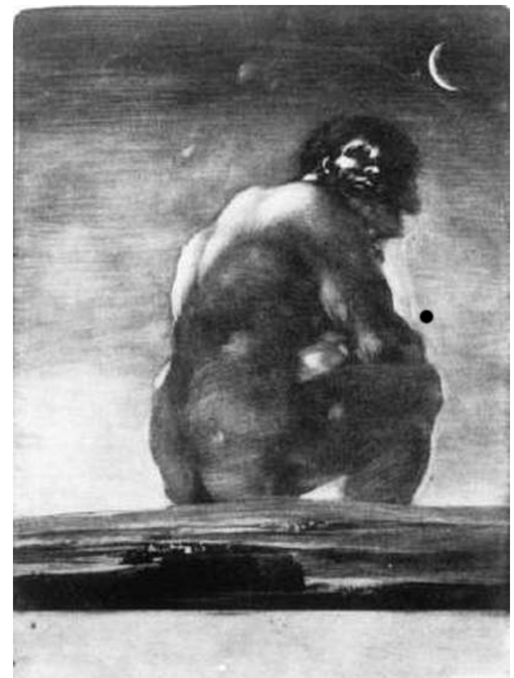
The EREBOS project

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:

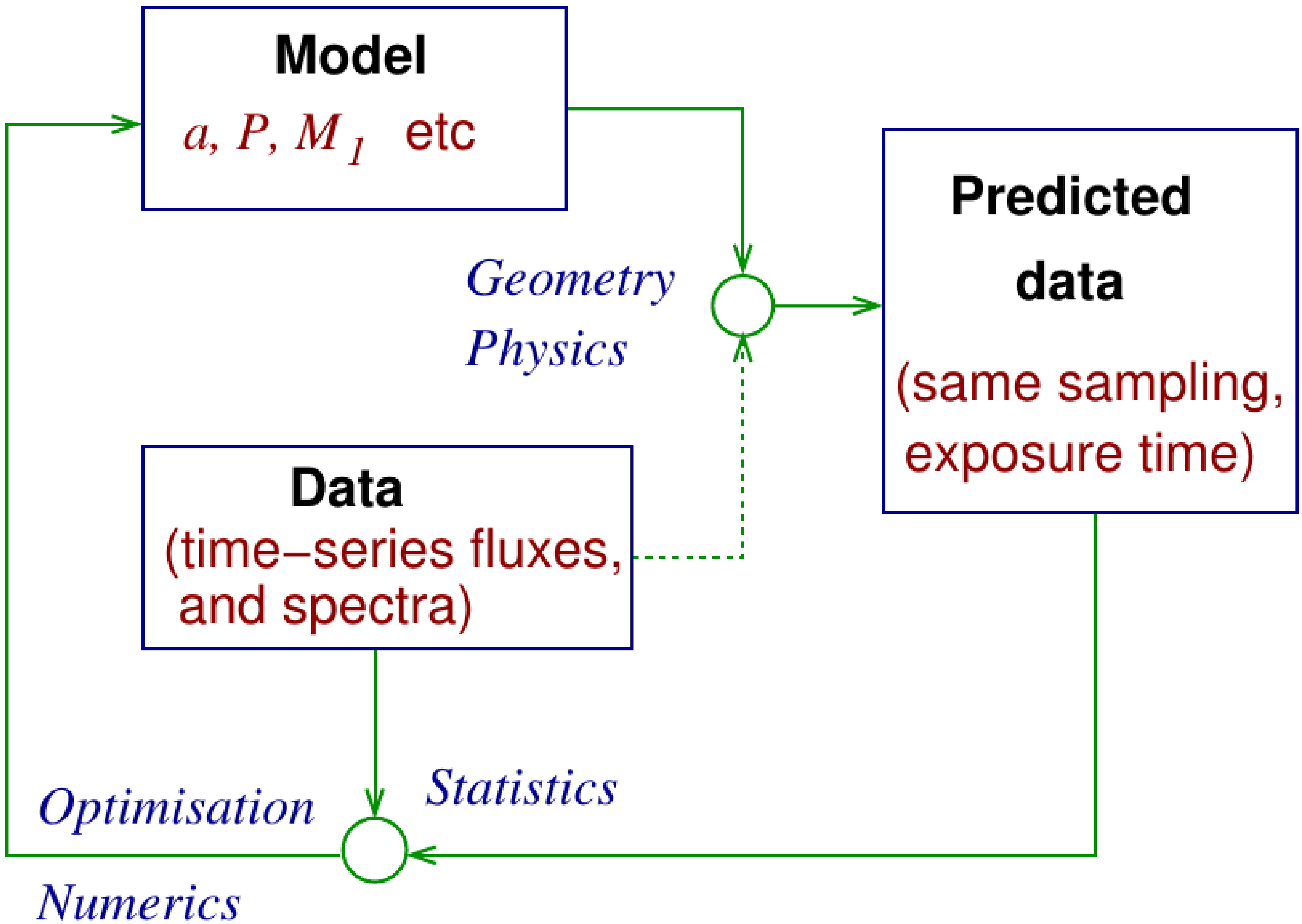
- minimum mass of the companion necessary to eject the common envelope?
- fraction of close substellar companions to sdB stars
- better understanding of the CE phase and the reflection effect



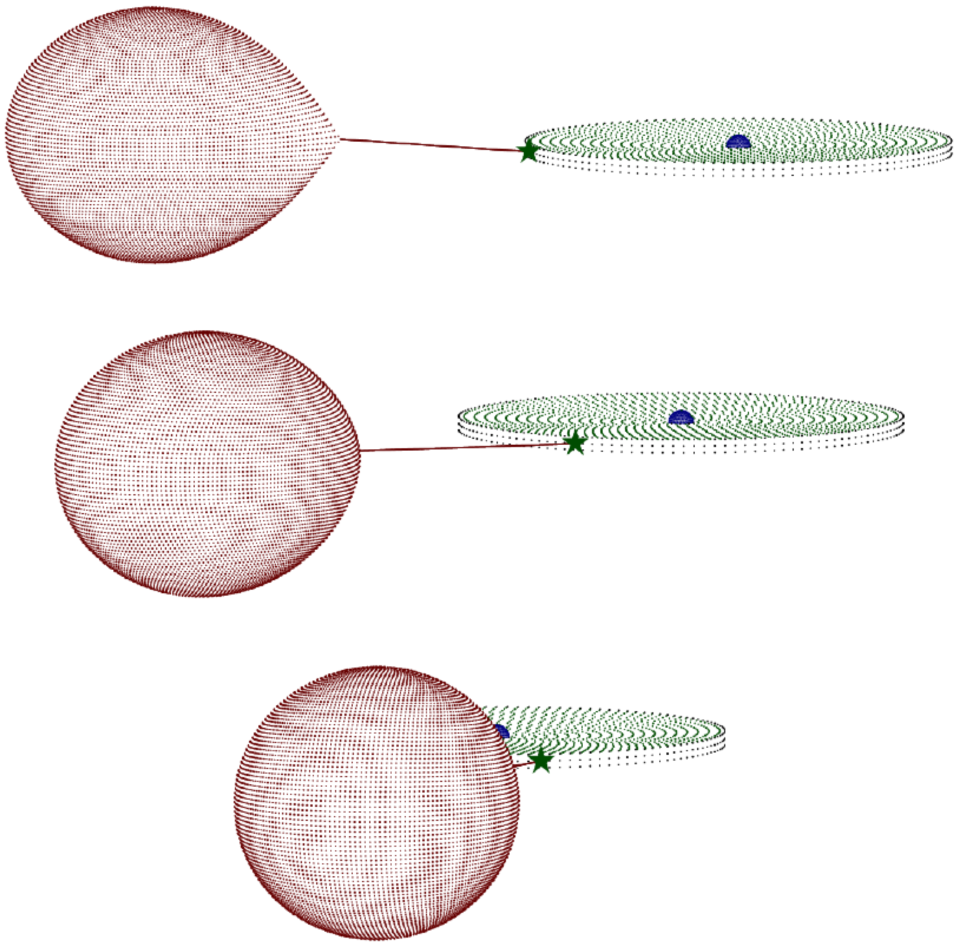
EREBOS
God of darkness

Lightcurve analysis with ***lcurve***

The circle of binary analysis



Generating a lightcurve



A light curve can be generated as follows:

- Generate grids covering all objects (stars, disc, ...)
- set their surface brightness including all effects, e.g. limb darkening, gravity darkening, reflection effect, Doppler beaming, ...
- At every phase compute what can and cannot be seen, add up the fluxes.

Computation of the light-curve of a Roche distorted star

lroche computes the light curve equivalent to a model of a sphere and a Roche-distorted star to model a white dwarf or subdwarf/main-sequence binary and can optionally include a disc and bright-spot as well.
Other physics included: Doppler beaming, gravitational lensing, Roemer time delays, asynchronous rotation of the stellar components

Invocation

lroche model data noise seed nfile [output] (device)]]

noise	multiplier of the real error bars
seed	Seed integer
nfile	Number of files to store
output	File to save the results in the form of rows each with time, exposure time, flux and uncertainty
device	Plot device to use

Data file

Data file

- can be in any time units or phase
- must be in normalized flux not magnitudes
- combining data from different nights by phasing the data
- for deriving the period use Lomb-Scargle algorithm
- binning improves the S/N

Careful with combining data from different nights

- check normalization
- check for trends due to atmospheric dispersion

Data file

```
#phase   delta_phase  flux  flux_error weight factor
0.000000 0.005000 0.998687 0.000039 1 1
0.005000 0.005000 0.998429 0.000039 1 1
0.010000 0.005000 0.998627 0.000040 1 1
0.015000 0.005000 0.998445 0.000039 1 1
0.020000 0.005000 0.998252 0.000039 1 1
0.025000 0.005000 0.998146 0.000039 1 1
0.030000 0.005000 0.997968 0.000039 1 1
0.035000 0.005000 0.997922 0.000039 1 1
0.040000 0.005000 0.997763 0.000039 1 1
0.045000 0.005000 0.997587 0.000040 1 1
0.050000 0.005000 0.997578 0.000039 1 1
0.055000 0.005000 0.997595 0.000039 1 1
0.060000 0.005000 0.997497 0.000039 1 1
```

Parameter file – Physical parameters – Binary and stars

x = initial_value param_space steps fitting(True/False) ignore_param(True/False)

q	Mass ratio, q = M2/M1
iangle	Inclination angle, degrees
r1	Radius of star 1, scaled by the binary separation
r2	Radius of star 2, scaled by the binary separation
t1	Temperature of star 1, K, This is a substitute for surface brightness, which is set assuming a black-body given this parameter.
t2	Temperature of star 2, Kelvin.
ldc1_1, etc	Limb darkening for stars is quite hard to specify precisely. Extrapolate from Claret et al.
velocity_scale	sum of unprojected orbital speeds, used for accounting for Doppler beaming and gravitational lensing.
beam_factor	3-alpha factor that multiplies -v_r/c in the standard beaming formula where alpha is related to the spectral shape. Use of this parameter requires the velocity_scale to be set.

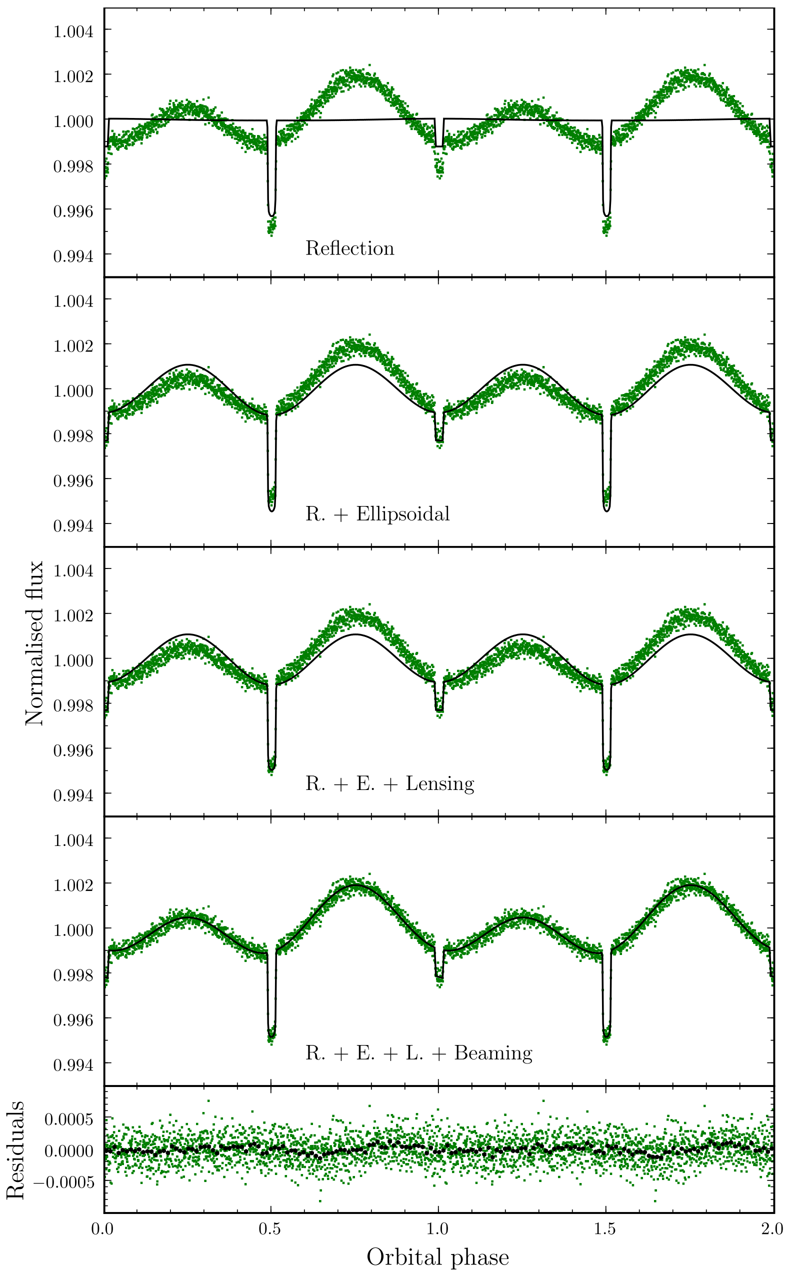
Parameter file – Physical parameters – General

t0	Zero point of ephemeris, marking time of mid-eclipse
period	Orbital period, same units as times.
pdot	Quadratic coefficient of ephemeris, same units as times
deltat	Time shift between the primary and secondary eclipses to allow for small eccentricities and Roemer delays in the orbit. Delay of -deltat/P by the secondary eclipse.
gravity_dark	Gravity darkening coefficient. Only matters for the Roche distorted case. set gdark_bolom (see below) to 0. Use Claret et al.
absorb	The fraction of the irradiating flux from star 1 absorbed by star 2
slope, quad, cube	factors to help cope with any trends in the data as a result of e.g. airmass effects. The fit is multiplied by (1+x*(slope+x*(quad+x*cube)))
third	Third light contribution. Simply adds to whatever flux is calculated and will be subject to auto-scaling like other flux. It only applies if global scaling rather than individual component scaling is used. Third light is assumed strictly constant

Computational parameters

delta_phase	Accuracy in phase of eclipse computations
nlat1/2f	number of latitudes for star 1/2's fine grid. This is used around the phase of primary eclipse
nlat1/2c	number of latitudes for star 1's coarse grid. This is used away from primary eclipse.
phase1	This defines when star 1's fine grid is used abs(phase) < phase1. phase1 = 0.05 will restrict the fine grid use to phase 0.95 to 0.05.
phase2	this defines when star 2's fine grid is used phase2 until 1-phase2. phase2 = 0.45 will restrict the fine grid use to phase 0.45 to 0.55.
wavelength	Wavelength (nm)
tperiod	The true orbital period in days. This is required, with velocity_scale, if gravitational lensing is applied to calculate proper dimensions.
gdark_bolom	True, if gravity darkening coefficient represents the bolometric value
limb1/2	'Poly' or 'Claret' determining the type of limb darkening law. See comments on ldc1_1 above.

Data to model



- find which models are consistent with the data, statistical and computational task
- different methods: Levenberg-Marquardt method, simplex method, Markov Chain Monte Carlo (MCMC)
- much harder to find uncertainties in the parameters, than the best-fitting model itself.

Degeneracy in the light curve analysis

If a change in one parameter causes a change in the predicted light curve that can be matched by a change in another or several others, then the fit will be degenerate.

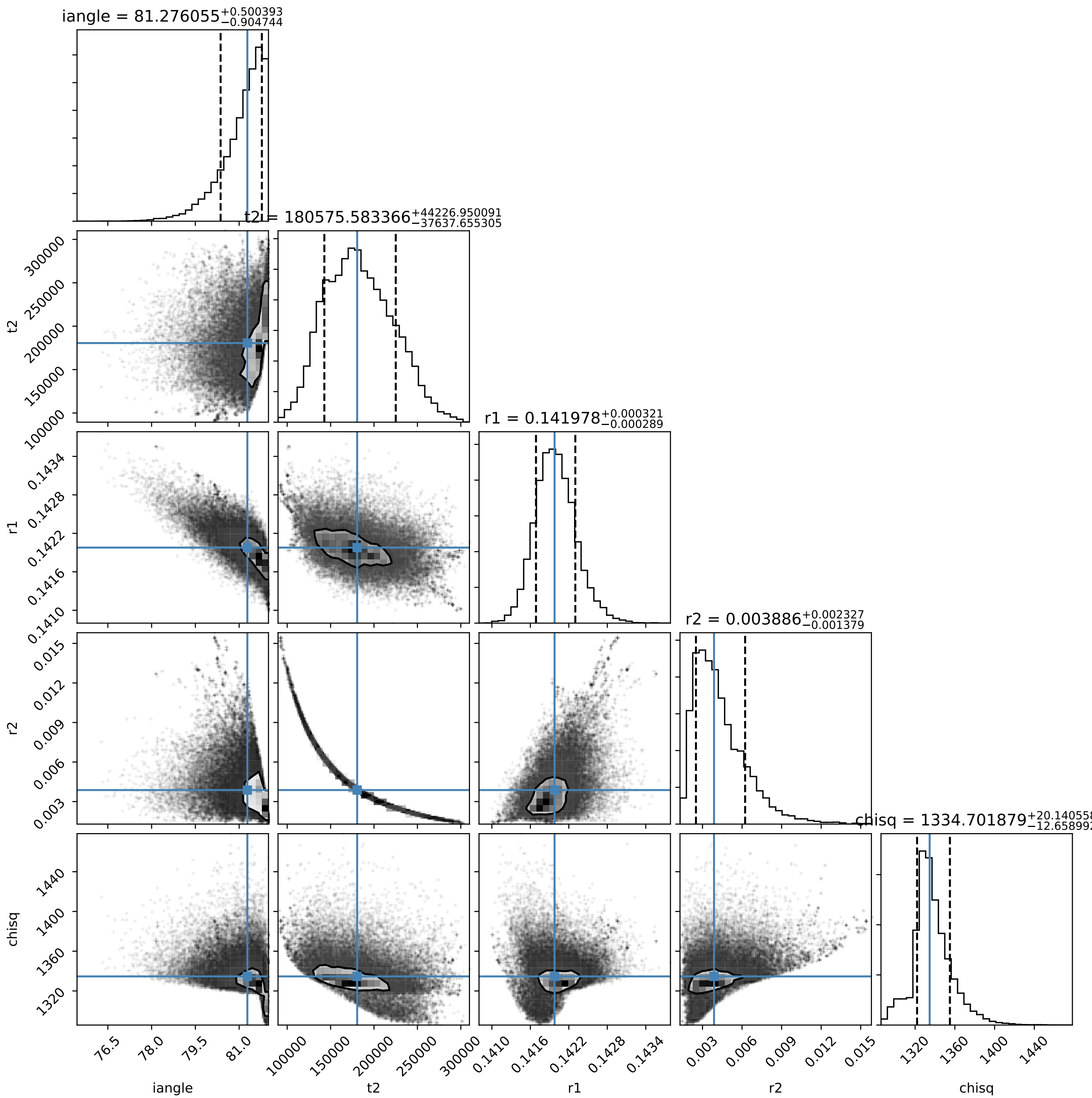
For a parameter to be well-defined, its effect on the light curve must be unique.

Degeneracy can

- make it impossible to uniquely constrain parameters,
- lead to strong correlations between multiple parameters,
- cause minimisation algorithms (e.g. Levenberg-Marquardt) to fail.

Bayesian methodology allows one to include prior information!
Use as many known parameters as possible from theory or spectroscopic observation (T_1, $\log g_1$, y, limb darkening coefficients, ...)

Degeneracy in the light curve analysis



Calculation of fundamental parameters

Spectrum

- Radial velocity curve K_1 and ideally $K_2 \Rightarrow q = K1/K2$
- effective temperature T_1
- $\log g_1$

Lightcurve

- orbital period P
- mass ratio q
- inclination i
- effective temperature T_2
- relative radius r_1/a
- relative radius r_2/a
- albedo

Calculation of fundamental parameters

orbital separation

$$a = \frac{P}{2\pi}\frac{K_1}{\sin(i)}(1/q + 1) \tag{5.1}$$

radii

$$R_1/2 = \frac{r1/2}{a} \cdot a \tag{5.2}$$

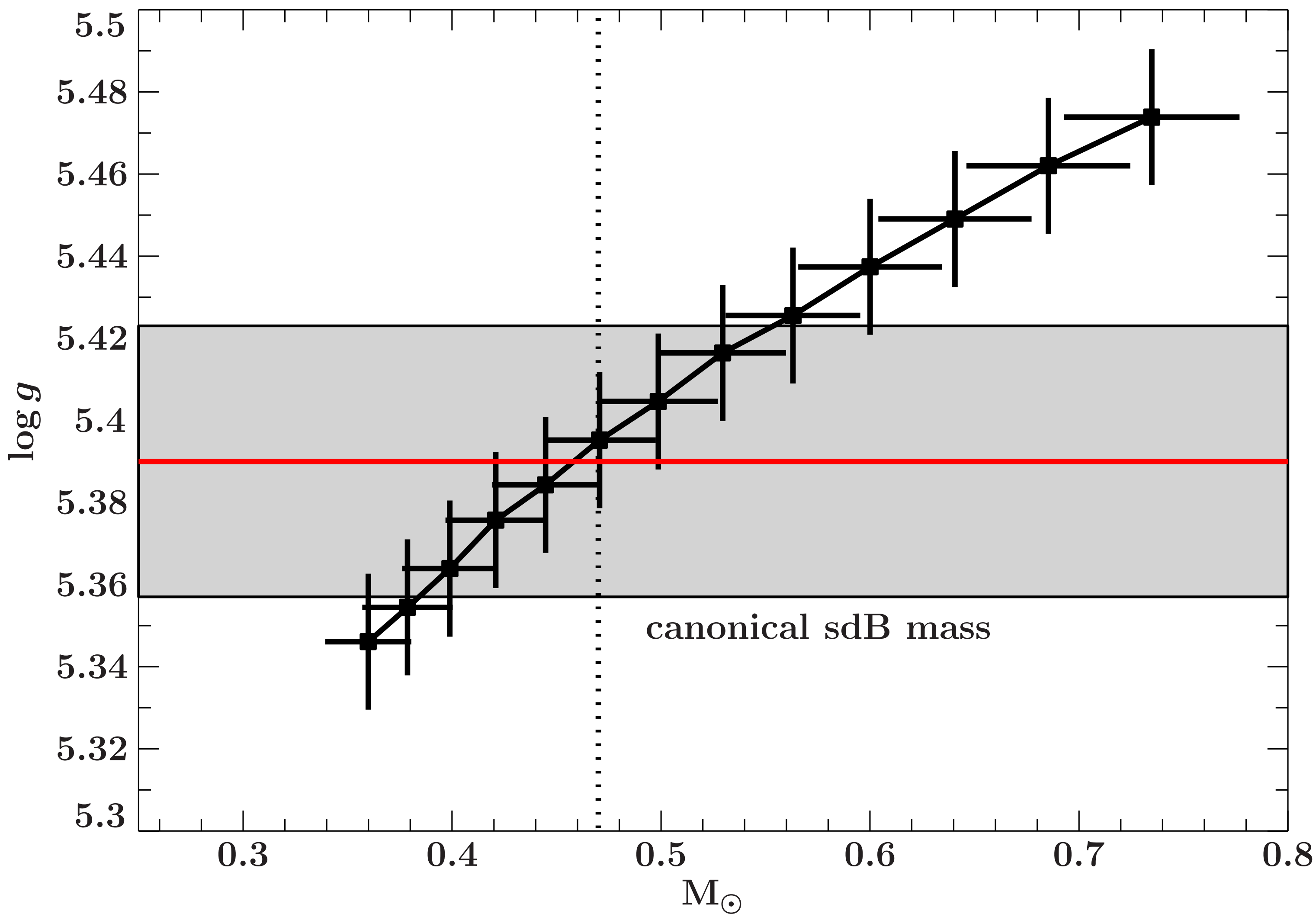
masses

$$M_1 = \frac{P}{2\pi G}\frac{K_1^3(q+1)^2}{(q\sin i)^3} \tag{5.3}$$

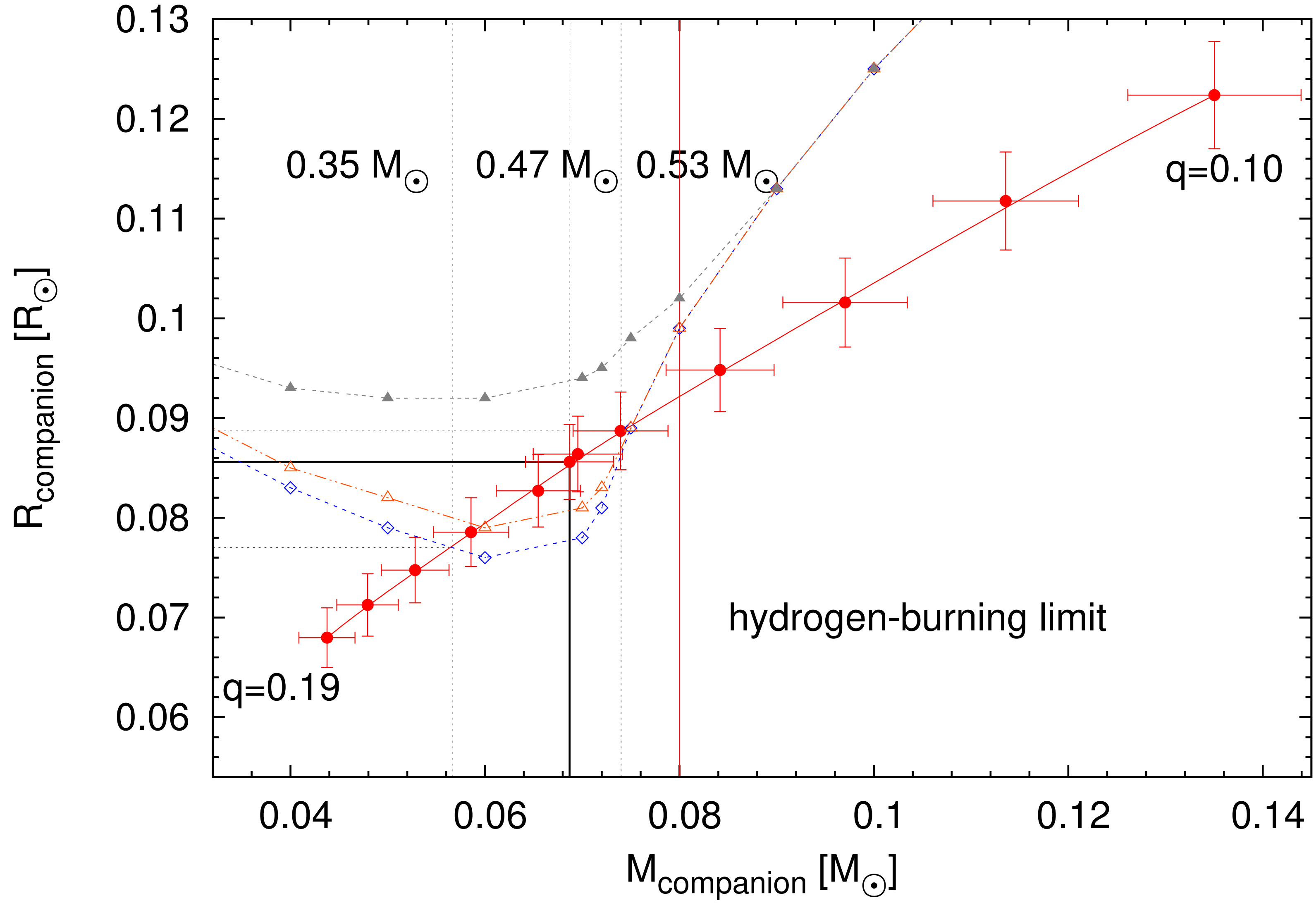
$$M_2 = q \cdot M_1 \tag{5.4}$$

Photometric surface gravity

$$\log g = \log_{10}\left(\frac{GM_1}{(r_1/a)^2 \cdot a^2}\right) \quad (5.5)$$



Mass-radius relation for the companion Baraffe et al. 2003



Schaffenroth et al. 2017

Fit the data

- you can work remotely: ssh -X blockcourse@carina.astro.physik.uni.potsdam.de; password: late_stellar_evolution
- First play around with lroche to get a feeling which parameters change what
- to invoke simplex algorithm: **simplex** model data
- when you found a good model use the Levenberg-Marquardt algorithm to estimate the error
- **levmarq** model data
- calculate the best model with **lroche** to plot results
- with **visualise** model you get a nice visualization of both stars and their orbit

Logical Order of Topics

- There is a generally accepted form for scientific papers called the IMRaD approach.
- I = Introduction
- M = Methods
- R = Results, and
- D = Discussion

Example: https://iopscience.iop.org/article/10.1088/2041-8205/731/2/L22/pdf

Title and Abstract

- The title and abstract of your article help researchers quickly understand the topics covered in your article.
- They act as a short summary of your article.
- Most researchers do not have time to read complete articles, but rather rely on titles and abstracts when searching scientific literature.

A&A style: `https://www.aanda.org/for-authors`

Introduction of the article

- The introduction is the first part of your article that contains substantial amounts of text.
- Make the main goals of your study clear in the introduction.
- The introduction gives a statement of the problems that you are studying in the article.
- Provide the reasons for conducting this investigation.

Observational or Experimental Work

- In articles about observational or experimental work, the corresponding “Methods” section discusses details of their observations or experiment.
- This section describes aspects of observational or experimental equipment.
- The methods section also highlights how the researchers analyzed their data.

Results section

- The results section details the findings and outcomes of your study.
- This is especially useful in observational, experimental or data analysis studies.
- This section often has tables with numerical data sets.

Discussion for Observational Work

- Do the results agree with the current model of the phenomenon you are studying?
- If not, how do your results change the current understanding?
- Are you surprised by the outcome of your work?
- How does this advance the current state of knowledge of your field?

Conclusion of your article

- The conclusion summarizes the information in your article and restates the major points.
- It attempts to tie all the different parts of the article together into a satisfying end.
- Try to answer all the questions you initially posed in the introduction.
- Conclusions are usually relatively short, around one page of text.

all slides: http://www.raa-journal.org/docs/RAA_Lectures/RAA_Lecture2.pdf