ECLIPSING BINARIES: THE ROYAL ROAD

John Southworth (Keele University)

Astrometric binaries: distant friends?

- William Herschel (1802) christened the term "binary star"
- Félix Savary (in 1827) established the equations of an astrometric orbit
- Burnham (1906): catalogue of 13 665 double stars for declinations $> -30°$

Albireo (β Cyg), separated by $35''$.

β Persei and the eclipse hypothesis

- John Goodricke (1783) suggested that β Persei underwent eclipses
- Its 2.87 day orbital period is recorded in the Ancient Egyptian Calendar (Jetsu & Porceddu 2015)

Except of the Cairo Calendar (Jetsu & Porceddu 2015, fig. S1)

β Persei and the eclipse hypothesis

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- Its 2.87 day orbital period is recorded in the Ancient Egyptian Calendar (Jetsu & Porceddu 2015)
- Vogel (1890) proved the binary nature of β Persei: "spectroscopic binary"
- Stebbins (1910): light curve from a selenium photometer

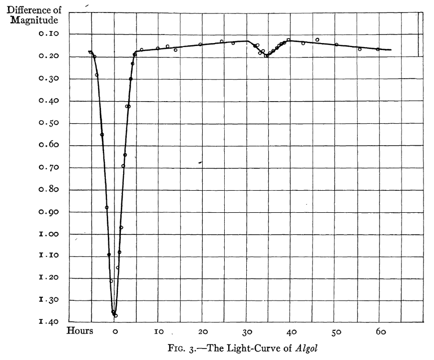

FIG. 3.—The Light-Curve of *Algol*

Light curve of β Per from Stebbins (1910)

β Persei and the eclipse hypothesis

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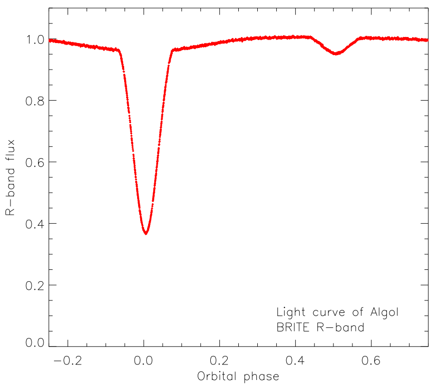
- Stebbins (1910): light curve from a selenium photometer
- BRITE satellite: first modern light curve



Light curve of β Per from UniBRITE and BRITE-Toronto

β Aurigae begins the era of direct measurements

- Rambaut (1891): first double-lined RV curve, for β Aurigae
- Stebbins (1911): light curve from his selenium photometer
  - measured mass and radius of both stars

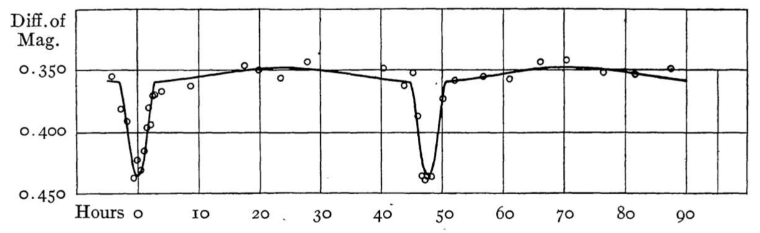
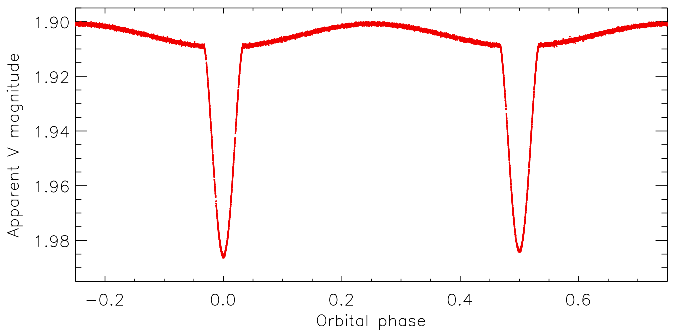


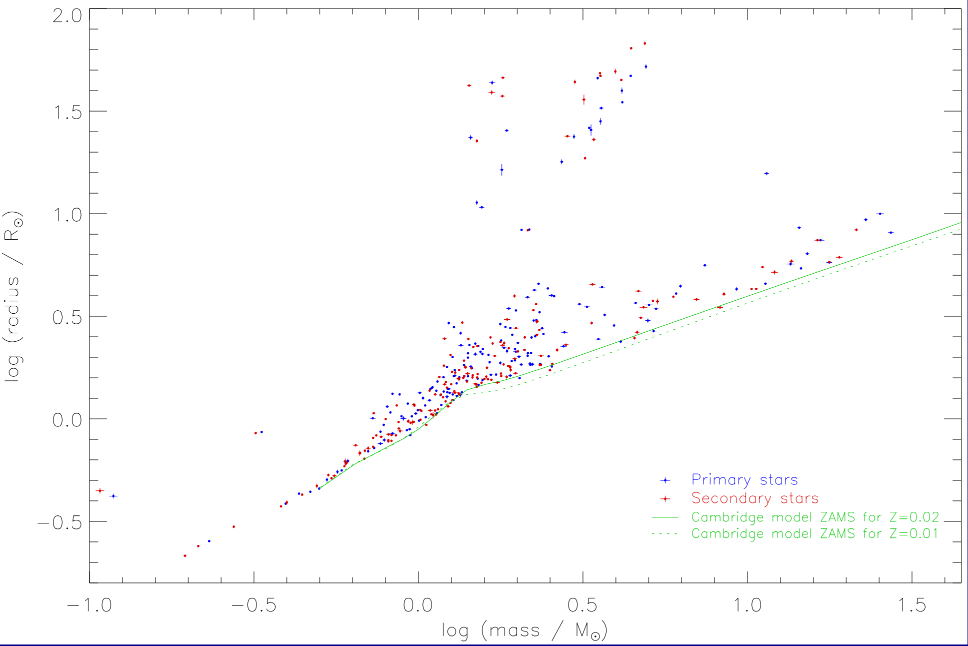
FIG. 1.—The light-curve of β *Aurigae*

Light curve of β Aurigae from Stebbins (1911)

β Aurigae begins the era of direct measurements

- Rambaut (1891): first double-lined RV curve, for β Aurigae
- Stebbins (1911): light curve from his selenium photometer
  - measured mass and radius of both stars
- Southworth et al (2007): light curve from the WIRE satellite
  - masses and radii to $\sim$1%, distance from interferometry

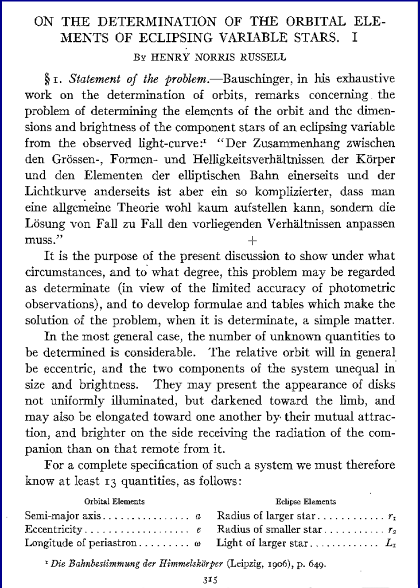




http://www.astro.keele.ac.uk/jkt/debcat/

Light curve models

- Russell (1912): first mathematical treatment of eclipse fitting



ON THE DETERMINATION OF THE ORBITAL ELEMENTS OF ECLIPSING VARIABLE STARS. I

By HENRY NORRIS RUSSELL

§ 1. *Statement of the problem.*—Bauschinger, in his exhaustive work on the determination of orbits, remarks concerning the problem of determining the elements of the orbit and the dimensions and brightness of the component stars of an eclipsing variable from the observed light-curve:[1] "Der Zusammenhang zwischen den Grössen-, Formen- und Helligkeitsverhältnissen der Körper und den Elementen der elliptischen Bahn einerseits und der Lichtkurve anderseits ist aber ein so komplizierter, dass man eine allgemeine Theorie wohl kaum aufstellen kann, sondern die Lösung von Fall zu Fall den vorliegenden Verhältnissen anpassen muss."

It is the purpose of the present discussion to show under what circumstances, and to what degree, this problem may be regarded as determinate (in view of the limited accuracy of photometric observations), and to develop formulae and tables which make the solution of the problem, when it is determinate, a simple matter.

In the most general case, the number of unknown quantities to be determined is considerable. The relative orbit will in general be eccentric, and the two components of the system unequal in size and brightness. They may present the appearance of disks not uniformly illuminated, but darkened toward the limb, and may also be elongated toward one another by their mutual attraction, and brighter on the side receiving the radiation of the companion than on that remote from it.

For a complete specification of such a system we must therefore know at least 13 quantities, as follows:

Orbital Elements		Eclipse Elements	
Semi-major axis	a	Radius of larger star	r_1
Eccentricity	e	Radius of smaller star	r_2
Longitude of periastron	ω	Light of larger star	L_1

---

[1] *Die Bahnbestimmung der Himmelskörper* (Leipzig, 1906), p. 649.

Light curve models

- Russell (1912): first mathematical treatment of eclipse fitting
- Wilson & Devinney (1971): physically-correct Roche model

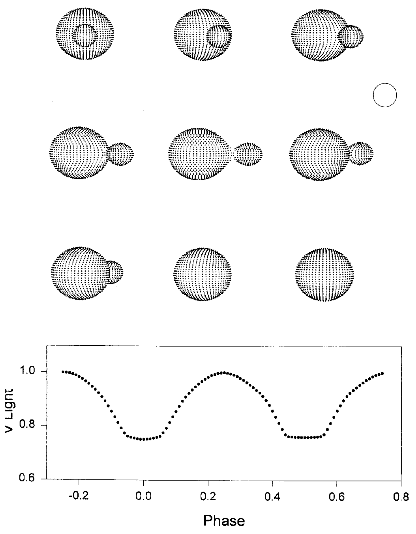
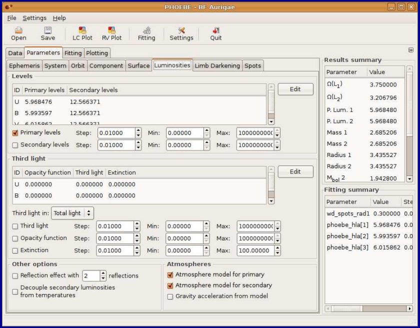


Fig. 3 from Wilson (1994)

Light curve models

- Russell (1912): first mathematical treatment of eclipse fitting
- Wilson & Devinney (1971): physically-correct Roche model
- PHOEBE (Prša & Zwitter 2005):
  - based on WD code
  - graphical user interface



Levels

ID	Primary levels	Secondary levels
U	5.968476	12.566371
B	5.993597	12.566371
V	6.015862	12.566371

☑ Primary levels Step: 0.01000 Min: 0.00000 Max: 100000000
☐ Secondary levels Step: 0.01000 Min: 0.00000 Max: 100000000

Third light

ID	Opacity function	Third light	Extinction
U	0.000000	0.000000	0.000000
B	0.000000	0.000000	0.000000

Third light in: Total light
☐ Third light Step: 0.01000 Min: 0.00000 Max: 100000000
☐ Opacity function Step: 0.01000 Min: 0.00000 Max: 100000000
☐ Extinction Step: 0.01000 Min: 0.00000 Max: 100.00000

Other options

☐ Reflection effect with 2 reflections
☐ Decouple secondary luminosities from temperatures

Atmospheres

☑ Atmosphere model for primary
☑ Atmosphere model for secondary
☐ Gravity acceleration from model

Results summary

Parameter	Value
$\Omega(L_1)$	3.750000
$\Omega(L_2)$	3.206796
P. Lum. 1	5.968480
P. Lum. 2	5.968480
Mass 1	2.685206
Mass 2	2.685206
Radius 1	3.435527
Radius 2	3.435527
M_{bol} 2	1.942800

Fitting summary

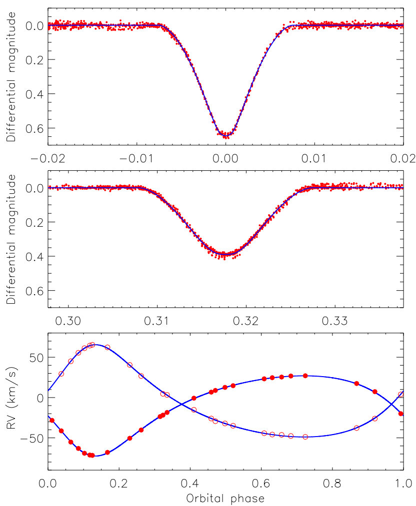
Parameter	Value	Ste
wd_spots_rad1	0.300000	0.0
phoebe_hla[1]	5.968476	0.0
phoebe_hla[2]	5.993597	0.0
phoebe_hla[3]	6.015862	0.0

Screenshot from PHOEBE

(`http://phoebe-project.org/`)

Light curve models

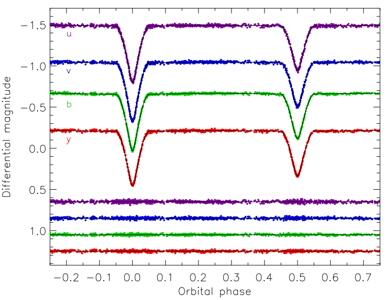
- Russell (1912): first mathematical treatment of eclipse fitting
- Wilson & Devinney (1971): physically-correct Roche model
- PHOEBE (Prša & Zwitter 2005):
  - based on WD code
  - graphical user interface
- Easier alternative: JKTEBOP `http://www.astro.keele.ac.uk/jkt/codes/jktebop.html`



JKTEBOP fit to the light curve and radial velocities of LL Aqr (Southworth 2013)

How do we do it? 1 – Light curves

- Light curve parameters:
  - orbital period: P
  - orbital inclination: i
  - fractional radius of hot star: $r_1 = \frac{R_1}{a}$
  - fractional radius of cool star: $r_2 = \frac{R_2}{a}$



Light curves of WW Aurigae from Etzel (1975)

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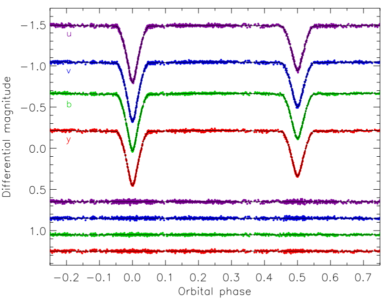
  - fractional radius of cool star: $r_2 = \frac{R_2}{a}$
  - orbital eccentricity: e
  - argument of periastron: ω
  - actually get: $e \cos \omega$



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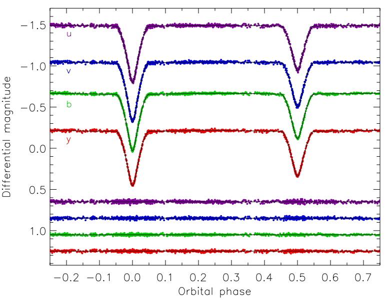
  - *Limb darkening*: not important



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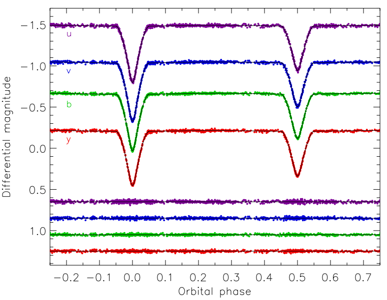
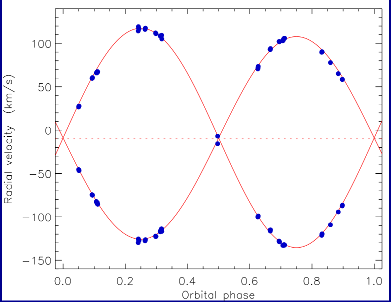
  - argument of periastron: ω
  - actually get: $e \cos \omega$
  - *Limb darkening*: not important
- For WW Aurigae:
  - $P = 2.46113400(34)$ days
  - $r_1 = 0.1586 \pm 0.0009$
  - $r_2 = 0.1515 \pm 0.0009$
  - $i = 87.55 \pm 0.04$ degrees
  - $e = 0$ (circular orbit)



Light curves of WW Aurigae from Etzel (1975)

How do we do it? 2 – RV curves

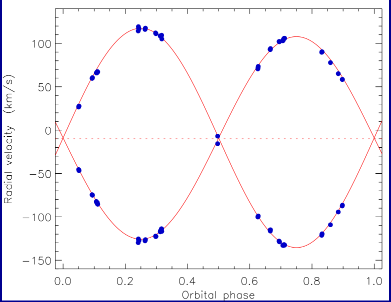
- Radial velocity curve parameters:
  - velocity amplitude of hot star: K_1
  - velocity amplitude of cool star: K_2
  - mass ratio: $q = \frac{K_1}{K_2}$



Radial velocities of WW Aurigae (Southworth et al. 2005)

How do we do it? 2 – RV curves

- Radial velocity curve parameters:
  - velocity amplitude of hot star: K_1
  - velocity amplitude of cool star: K_2
  - mass ratio: $q = \frac{K_1}{K_2}$
  - systemic velocity: V_γ
  - orbital eccentricity: e
  - argument of periastron: ω



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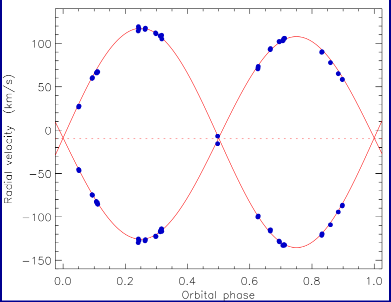
  - mass ratio: $q = \frac{K_1}{K_2}$
  - systemic velocity: V_γ
  - orbital eccentricity: e
  - argument of periastron: ω
- For WW Aurigae:
  - $K_1 = 116.81 \pm 0.23\,\mathrm{km\,s^{-1}}$
  - $K_2 = 126.49 \pm 0.28\,\mathrm{km\,s^{-1}}$
  - $e = 0$ (easy!)



Radial velocities of WW Aurigae (Southworth et al. 2005)

How do we do it? 3 – Combine

P
K_1
K_2
e

$$\Longrightarrow$$

$$M_1 \sin^3 i = \tfrac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_2 P$$
$$M_2 \sin^3 i = \tfrac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_1 P$$
$$a \sin i = \tfrac{1}{2\pi}(1-e^2)^{\frac{1}{2}}(K_1+K_2) P$$

How do we do it? 3 – Combine

P
K_1
K_2
e

$\Longrightarrow$

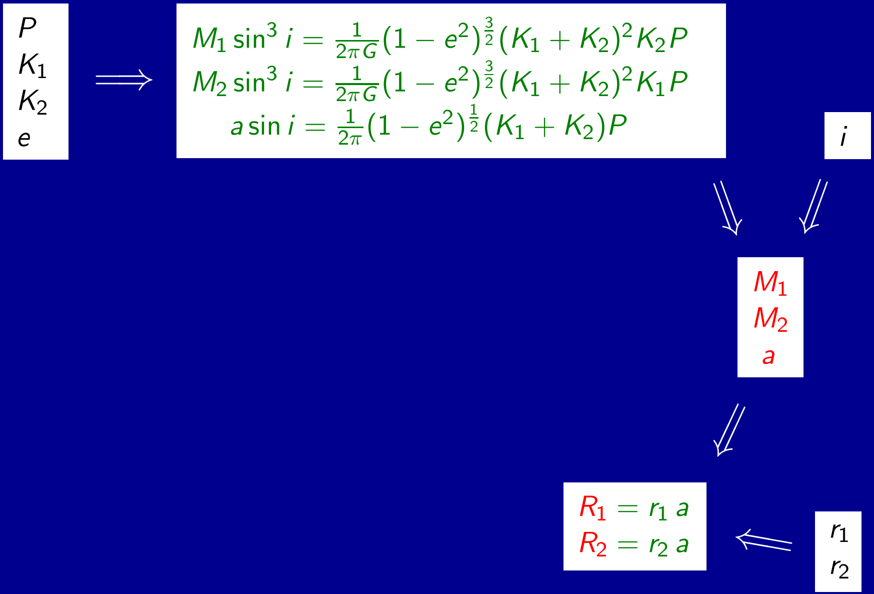
$$
\begin{aligned}
M_1 \sin^3 i &= \frac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_2 P \\
M_2 \sin^3 i &= \frac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_1 P \\
a \sin i &= \frac{1}{2\pi}(1-e^2)^{\frac{1}{2}}(K_1+K_2) P
\end{aligned}
$$

i

$\Downarrow$ $\Downarrow$

M_1
M_2
a

How do we do it? 3 – Combine



P
K_1
K_2
e

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$$a \sin i = \frac{1}{2\pi}(1-e^2)^{\frac{1}{2}}(K_1+K_2) P$$

i

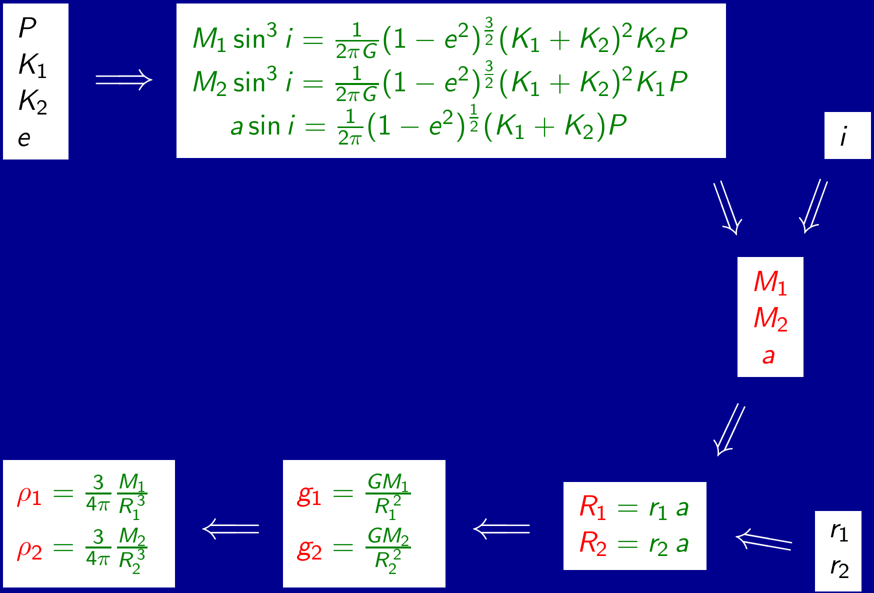
M_1
M_2
a

$$R_1 = r_1\, a$$
$$R_2 = r_2\, a$$

$$\Longleftarrow$$

r_1
r_2

How do we do it? 3 – Combine



P

K_1

K_2

e

$$\Longrightarrow$$

$$M_1 \sin^3 i = \frac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_2 P$$
$$M_2 \sin^3 i = \frac{1}{2\pi G}(1-e^2)^{\frac{3}{2}}(K_1+K_2)^2 K_1 P$$
$$a \sin i = \frac{1}{2\pi}(1-e^2)^{\frac{1}{2}}(K_1+K_2) P$$

i

M_1

M_2

a

r_1

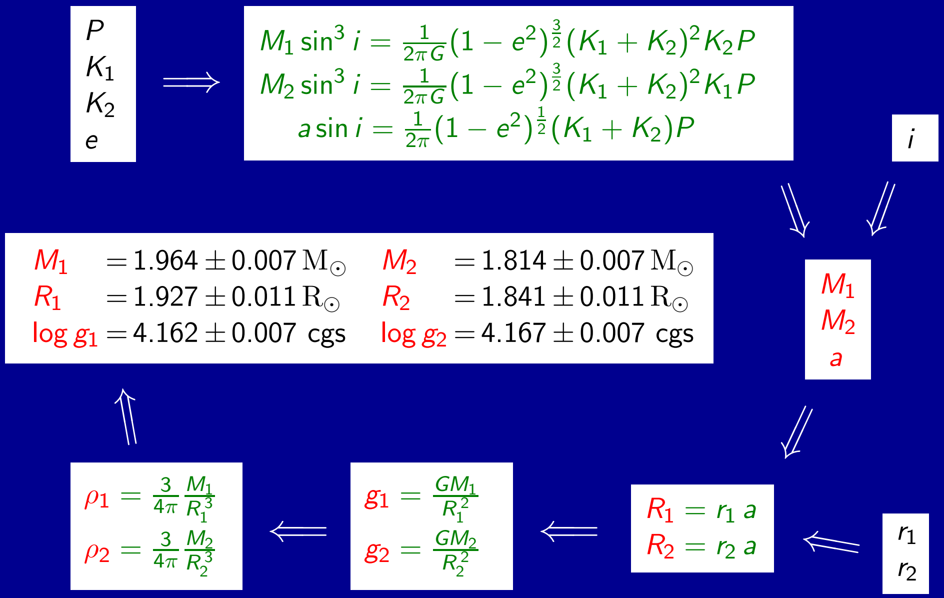
r_2

$$R_1 = r_1\, a$$
$$R_2 = r_2\, a$$

$$g_1 = \frac{GM_1}{R_1^2}$$
$$g_2 = \frac{GM_2}{R_2^2}$$

$$\rho_1 = \frac{3}{4\pi}\frac{M_1}{R_1^3}$$
$$\rho_2 = \frac{3}{4\pi}\frac{M_2}{R_2^3}$$

How do we do it? 3 – Combine



P
K_1
K_2
e

$$\Longrightarrow$$

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$$a \sin i = \frac{1}{2\pi}(1-e^2)^{\frac{1}{2}}(K_1+K_2) P$$

i

$$\Downarrow$$

M_1
M_2
a

$$\Downarrow$$

r_1
r_2

$$\Longleftarrow$$

$$R_1 = r_1\, a$$
$$R_2 = r_2\, a$$

$$\Longleftarrow$$

$$g_1 = \frac{GM_1}{R_1^2}$$
$$g_2 = \frac{GM_2}{R_2^2}$$

$$\Longleftarrow$$

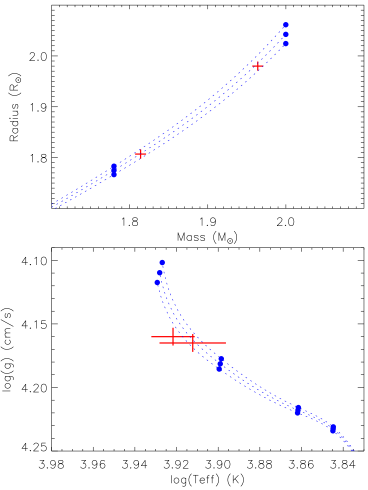
$$\rho_1 = \frac{3}{4\pi}\frac{M_1}{R_1^3}$$
$$\rho_2 = \frac{3}{4\pi}\frac{M_2}{R_2^3}$$

$$\Uparrow$$

$$M_1 = 1.964 \pm 0.007\,\mathrm{M}_\odot \qquad M_2 = 1.814 \pm 0.007\,\mathrm{M}_\odot$$
$$R_1 = 1.927 \pm 0.011\,\mathrm{R}_\odot \qquad R_2 = 1.841 \pm 0.011\,\mathrm{R}_\odot$$
$$\log g_1 = 4.162 \pm 0.007 \text{ cgs} \qquad \log g_2 = 4.167 \pm 0.007 \text{ cgs}$$

How do we do it? 4 – Temperatures

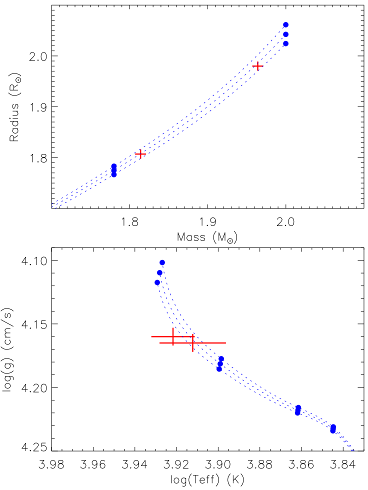
- We now have mass and radius
  - surface gravity and mean density



Comparison of WW Aurigae to theoretical stellar models

How do we do it? 4 – Temperatures

- We now have mass and radius
  - surface gravity and mean density
- Need effective temperatures
  - $T_{\rm eff}$ from photometric colour indices
  - $T_{\rm eff}$ from spectral energy distribution
  - $T_{\rm eff}$ from high-resolution spectra



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How do we do it? 4 – Temperatures

- We now have mass and radius
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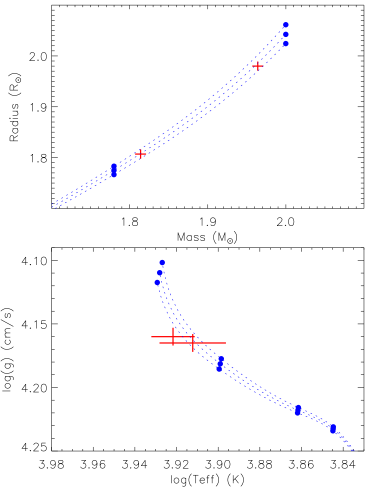
  - T_{eff} from photometric colour indices
  - T_{eff} from spectral energy distribution
  - T_{eff} from high-resolution spectra
- WW Aurigae
  - T_{eff} from *Hipparcos* distance and apparent magnitude
  - $7960 \pm 420\,\mathrm{K}$ and $7670 \pm 410\,\mathrm{K}$
  - theoretical models need $Z = 0.05$



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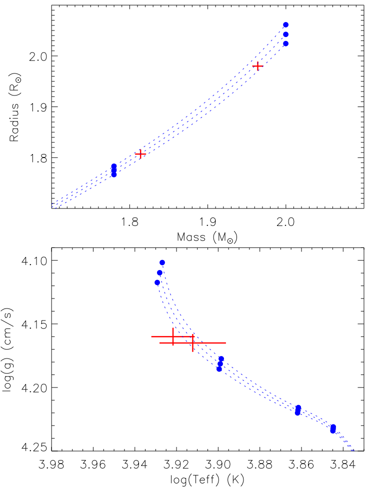
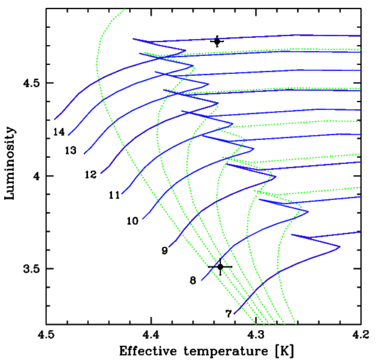
  - $T_{\rm eff}$ from *Hipparcos* distance and apparent magnitude
  - $7960 \pm 420\,\mathrm{K}$ and $7670 \pm 410\,\mathrm{K}$
  - theoretical models need $Z = 0.05$
- Luminosity: $L = 4\pi\sigma R^2 {T_{\rm eff}}^4$
  - WW Aur A: $L = 13.5 \pm 2.9\,\mathrm{L}_\odot$
  - WW Aur B: $L = 10.5 \pm 2.3\,\mathrm{L}_\odot$



Comparison of WW Aurigae to theoretical stellar models

Uses of eclipsing systems

- Test theoretical stellar models
  - models must match M, R, $T_{\rm eff}$ using same age and chemical composition for both stars



Components of V380 Cygni:
$M_1 = 13.13 \pm 0.24\,\mathrm{M}_\odot$
$M_2 = 7.779 \pm 0.095\,\mathrm{M}_\odot$
(Pavlovski et al. 2009).

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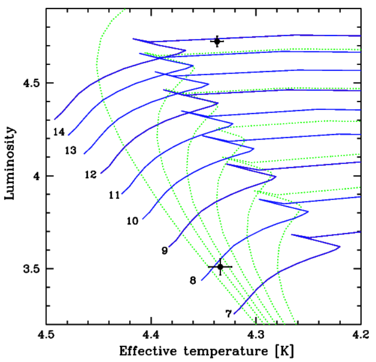
  - tidal effect in eccentric orbits
  - argument of periastron changes
  - depends on internal structure of star



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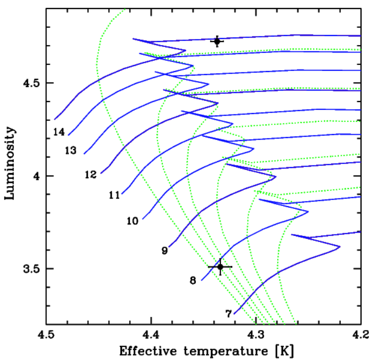
  - depends on internal structure of star
- Direct distance indicators
  - known $T_{\rm eff}$ and radius $\Rightarrow$ luminosity
  - L and bolometric corrections $\Rightarrow$ M_V
  - M_V and V $\Rightarrow$ distance
  - now done for LMC, SMC, M31, M33



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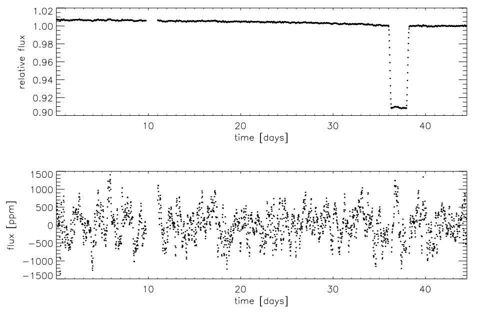
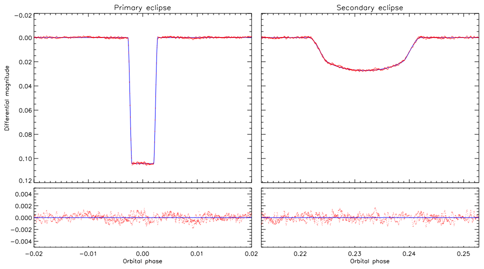
Red giants in eclipsing binaries

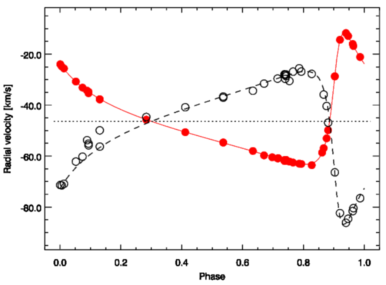
- KIC 8410637 observed by *Kepler* (Hekker et al. 2010)
  - pulsating red giant
  - primary eclipse 2.2 d long
  - secondary eclipse 8.3 d long



Red giants in eclipsing binaries

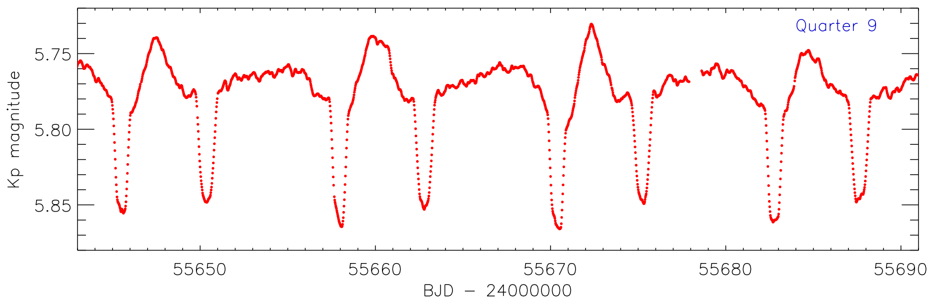
- KIC 8410637 observed by *Kepler* (Hekker et al. 2010)
  - pulsating red giant
  - primary eclipse 2.2 d long
  - secondary eclipse 8.3 d long
- Follow-up radial velocities (Frandsen et al. 2013)
  - orbital period = 408 day
  - $e = 0.686 \pm 0.002$
  - $M_1 = 1.56 \pm 0.03\,\mathrm{M}_\odot$
  - $M_2 = 1.32 \pm 0.02\,\mathrm{M}_\odot$
  - $R_1 = 10.74 \pm 0.11\,\mathrm{R}_\odot$
  - $R_2 = 1.57 \pm 0.03\,\mathrm{R}_\odot$





Stochastic oscillations in eclipsing binaries

- V380 Cygni (Tkachenko et al. 2014)
  - magnitude $V = 5.68$
  - spectral type: B1.5 II-III + B2 V
  - $P = 12.4\,\mathrm{day}$
  - $e = 0.2261$



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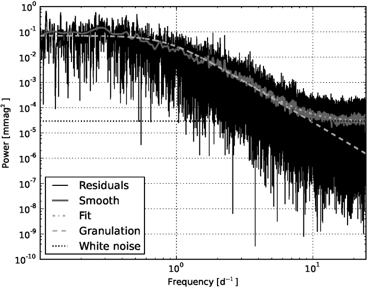
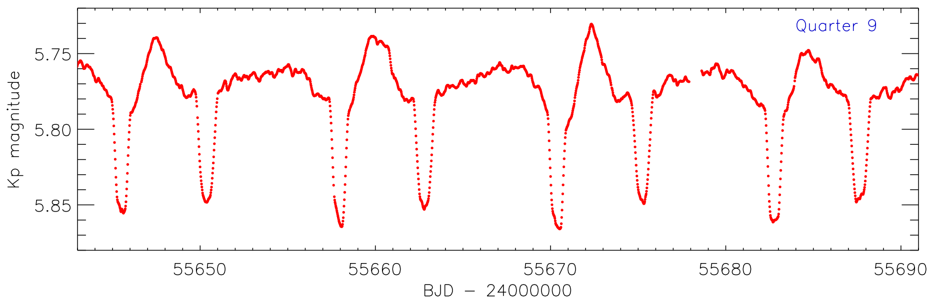
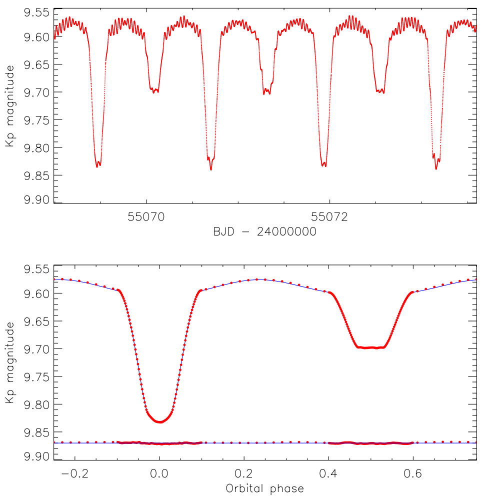
  - granulation signal detected in *Kepler* data after removing binarity effects





δ Scuti stars in eclipsing binaries

- KIC 10661783 (Southworth et al. 2011)
  - semi-detached EB with total eclipses
  - 55 pulsation frequencies, most 20–30 c d^{-1}



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  - spectroscopic orbit for both stars
  - $M_1 = 2.10 \pm 0.03\,\mathrm{M}_\odot$
  - $M_2 = 0.191 \pm 0.003\,\mathrm{M}_\odot$
  - $R_1 = 2.58 \pm 0.02\,\mathrm{R}_\odot$
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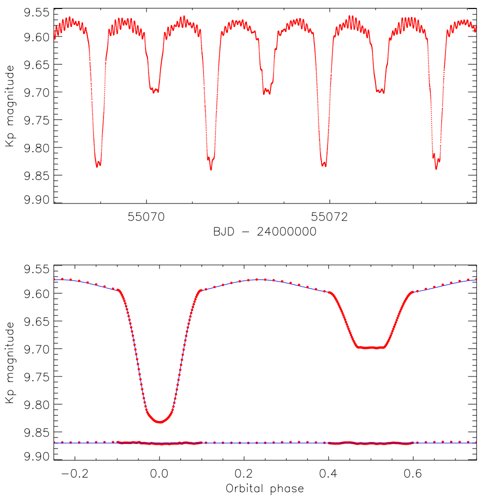

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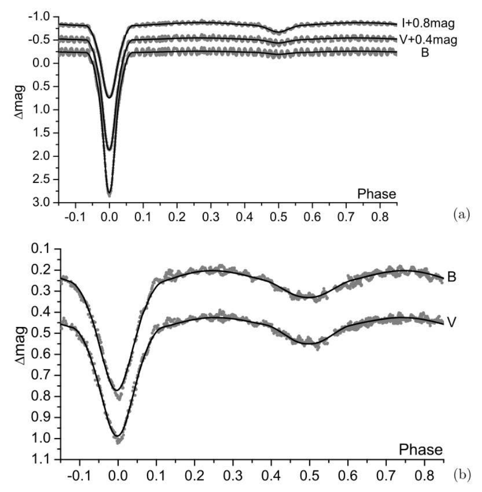
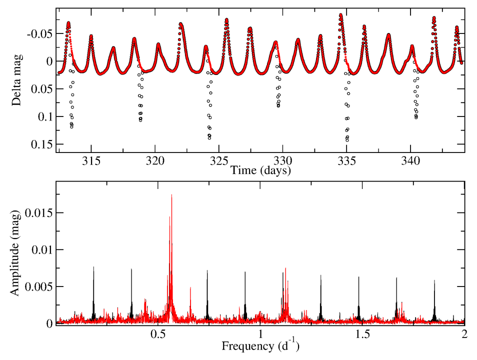
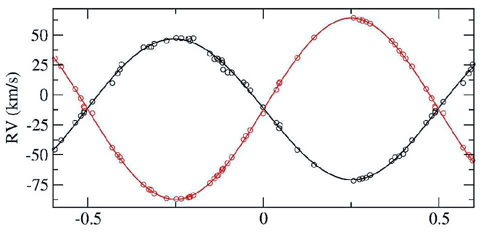


Light curves of BO Her and RR Lep from Liakos & Niarchos (2013)

γ Doradus stars in eclipsing binaries

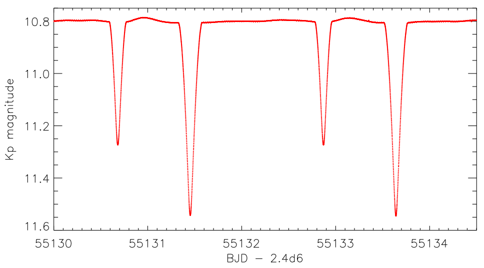
- KIC 11285625 (Debosscher et al. 2013)
  - masses and radii to 1%
  - γ Doradus pulsations

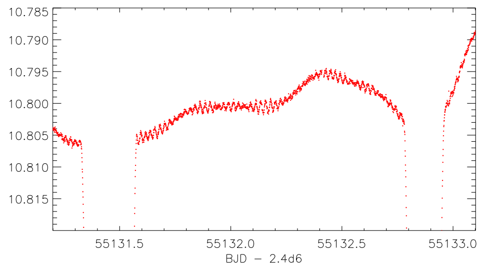




γ Doradus stars in eclipsing binaries

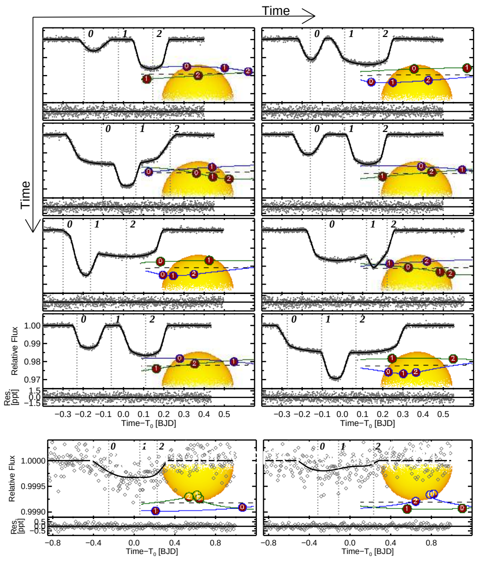
- KIC 11285625
  (Debosscher et al. 2013)
  - masses and radii to 1%
  - γ Doradus pulsations
- KIC 4544587
  (Hambleton et al. 2013)
  - masses to 4%
  - radii to 2%
  - 14 *g*-mode pulsations
  - 17 *p*-mode pulsations
  - pulsations are from the secondary star





Very low mass stars in eclipsing binaries

- KOI-126 (Carter et al. 2011)
  - triply eclipsing G star with two $0.2\,\mathrm{M}_\odot$ stars
  - short period: 1.8 days long period: 33.9 days
  - Masses to 1%, radii to 0.5%



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  - short period: 1.8 days
    long period: 33.9 days
  - Masses to 1%,
    radii to 0.5%
- Model discrepancy: low-mass stars are bigger than theoretical models predict
  - Probable reason: tidal effects cause magnetic activity
  - Solution: study long-period EBs

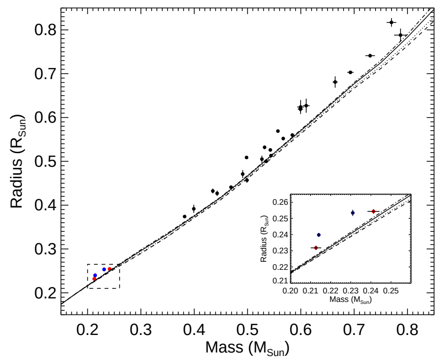
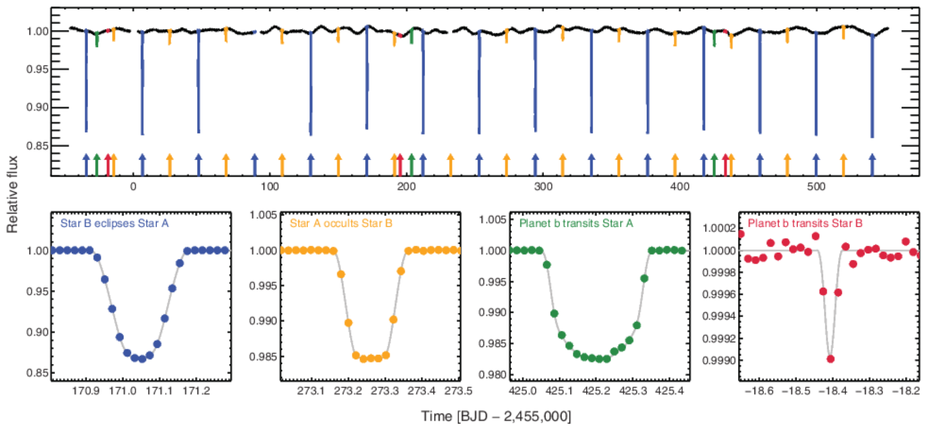


Fig. 2 from Carter et al. (2011)

Circumbinary planets

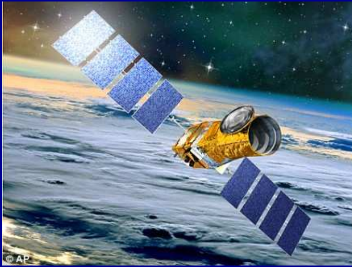
- 10 known transiting circumbinary planets, all orbiting EBs
  - Eclipse timing variations give additional constraints
  - Exquisite measurements of masses and radii of the host stars



Transits in the Kepler-16 system (Welsh et al. 2011)

Near future: photometry

- Continue to exploit *Kepler* data
  - *Kepler* EB catalogue contains 2878 objects (Kirk et al. 2016)



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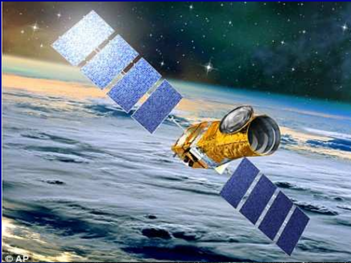

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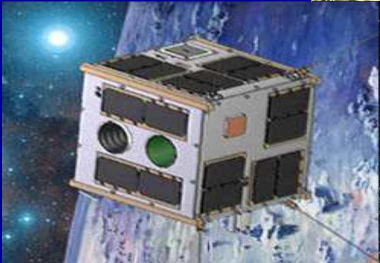

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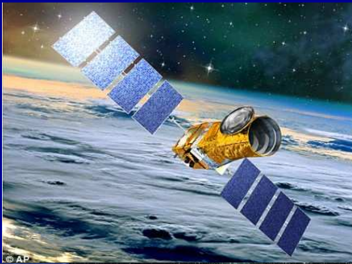
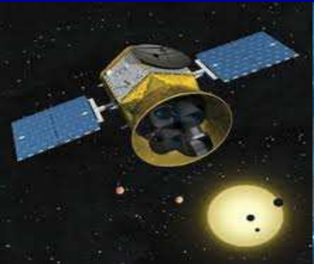
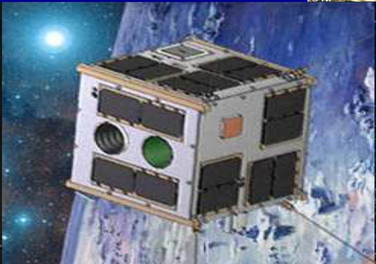
- NASA Transiting Exoplanet Survey Satellite
  - launch 2017, one month per field







Near future: *Gaia*

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  - launched 2013/12/19
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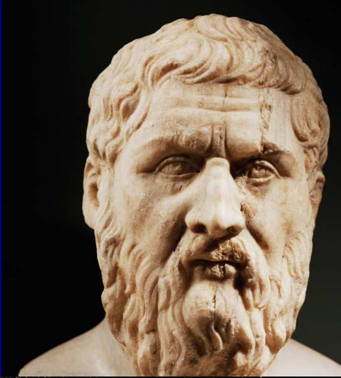
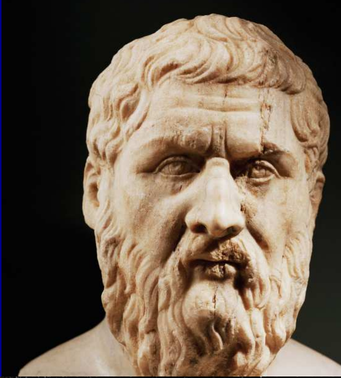
- Eclipsing binary science
  - photometry: 400 000 to 7 000 000 EBs
  - photometry: median 70 epochs – not enough for light curves
  - parallaxes: $T_{\rm eff}$ scale from known distance, brightness, radius
  - spectroscopy: median 70 RVs for late-type stars

P L A T O

- Expect 5000–10000 EBs (depend on strategy)
  - bright stars, long duration, short cadence
  - much better than *Kepler*, CoRoT, TESS, BRITE, or ground-based telescopes
- I am responsible for EBs



PLATO



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    - bright stars, long duration, short cadence
    - much better than *Kepler*, CoRoT, TESS, BRITE, or ground-based telescopes
- I am responsible for EBs
- Likely EB science:
    - giant stars
    - spB stars
    - δ Scuti
    - γ Doradus
    - solar-like oscillations
    - population studies

What amateurs can contribute

- Eclipse timings from light curves
    - apsidal motion measurements

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Astronomy & Astrophysics

Apsidal motion in five eccentric eclipsing binaries

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ABSTRACT

Aims. As part of the long-term Ondřejov and Ostrava observational projects, we aim to measure the precise times of minimum light for eccentric eclipsing binaries, needed for accurate determination of apsidal motion. Over fifty new times of minimum light recorded with CCD photometers were obtained for five early-type and eccentric-orbit eclipsing binaries: V785 Cas ($P = 2\overset{\mathrm{d}}{.}70$, $e = 0.09$), V821 Cas ($1\overset{\mathrm{d}}{.}77$, 0.14), V796 Cyg ($1\overset{\mathrm{d}}{.}48$, 0.07), V398 Lac ($5\overset{\mathrm{d}}{.}41$, 0.23), and V871 Per ($3\overset{\mathrm{d}}{.}02$, 0.24).
Methods. O−C diagrams of binaries were analysed using all reliable timings found in the literature, and new elements of apsidal motion were obtained.
Results. We derived for the first time or improved the relatively short periods of apsidal motion of about 83, 140, 33, 440, and 70 years for V785 Cas, V821 Cas, V796 Cyg, V398 Lac, and V871 Per, respectively. The internal structure constants, log k_2, for V821 Cas and V398 Lac are then found to be –2.70 and –2.35, under the assumption that the component stars rotate pseudosynchronously. The relativistic effects are weak, up to 7% of the total apsidal motion rate.

Key words. binaries: eclipsing – stars: fundamental parameters – stars: general – binaries: close

1. Introduction

The study of apsidal motion in eccentric eclipsing binaries (EEB) provides an important observational test of theoretical models of stellar structure and evolution. A detailed analysis of the period variations of EEB can be performed using the times of minimum light observed throughout the apsidal motion cycle, and from this, both the orbital eccentricity and the period of rotation of the periastron can be obtained with high accuracy (Giménez 1994). All eclipsing binaries analysed here have properties that make them important "astrophysical laboratories" for studying the structure and evolution of stars.

Here we analyse the observational data and rates of apsidal motion for five detached eclipsing systems. These systems are all relatively bright northern-hemisphere early-type objects known to have eccentric orbits and to exhibit apsidal motion. With the exception of V821 Cas and V398 Lac, no spectroscopic observations have been published for these binary systems. Our study is part of a series of papers on apsidal motion in eclipsing binaries (Wolf et al. 2008, 2010).

2. Observations of minimum light

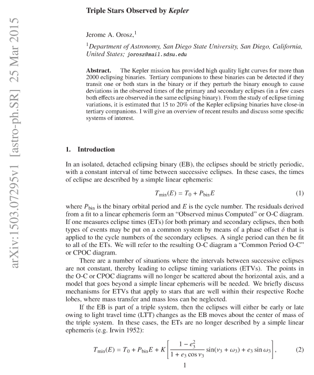
Monitoring of eccentric eclipsing binaries is a long-term observational project, which requires only moderate or small telescopes equipped with a photoelectric photometer or a CCD camera. Moreover, a large amount of observing time is needed, which is unavailable presently at large telescopes but is more practical for small amateur telescopes equipped with modern detectors. During the past ten years, we have accumulated over 8000 photometric observations at selected phases during primary and secondary eclipses and derived over 50 precise times of minimum light for selected eccentric systems. New CCD photometry was obtained at several observatories in the Czech Republic:

- Ondřejov Observatory, Czech Republic: the 0.65-m ($f/3.6$) reflecting telescope with the CCD cameras SBIG ST-8, Apogee AP7p or Moravian Instruments G2-3200 and *BVRI* photometric filters;
- Johann Pallisa Observatory and Planetarium Ostrava, Czech Republic: 0.2-m or 0.3-m telescopes with the CCD camera SBIG ST-8XME and *VRI* filters;
- Observatory and Planetarium Hradec Králové, Czech Republic: 0.4-m ($f/5$) reflector with the CCD camera G2-1600 and *BVRI* filters;
- Observatory Valašské Meziříčí, Czech Republic: the 0.3-m Celestron Ultima telescope with the CCD camera SBIG ST-7 or G2-1600 and *VRI* filters;
- Private observatory of PS at Brno, Czech Republic: 0.2-m Cassegrain telescope with the CCD camera ST-7XME and Johnson-Cousins $BV(RI)_c$ filters;
- Private Observatory of MZ at Brno, Czech Republic: Helios 2/58 lens obscured to 0.035-m with the CCD camera G2-402 and *UBVRI* filters.

CCD measurements at most observatories were dark-subtracted and then flat-fielded using sky exposures taken at either dusk or dawn. Several comparison stars were chosen in the same frame

What amateurs can contribute

- Eclipse timings from light curves
  - apsidal motion measurements
  - light-time effect in triple stars



arXiv:1503.07295v1 [astro-ph.SR] 25 Mar 2015

Triple Stars Observed by *Kepler*

Jerome A. Orosz,[1]

[1]*Department of Astronomy, San Diego State University, San Diego, California, United States;* `jorosz@mail.sdsu.edu`

Abstract. The Kepler mission has provided high quality light curves for more than 2000 eclipsing binaries. Tertiary companions to these binaries can be detected if they transit one or both stars in the binary or if they perturb the binary enough to cause deviations in the observed times of the primary and secondary eclipses (in a few cases both effects are observed in the same eclipsing binary). From the study of eclipse timing variations, it is estimated that 15 to 20% of the Kepler eclipsing binaries have close-in tertiary companions. I will give an overview of recent results and discuss some specific systems of interest.

1. Introduction

In an isolated, detached eclipsing binary (EB), the eclipses should be strictly periodic, with a constant interval of time between successive eclipses. In these cases, the times of eclipse are described by a simple linear ephemeris:

$$T_{\rm min}(E) = T_0 + P_{\rm bin}E \tag{1}$$

where $P_{\rm bin}$ is the binary orbital period and E is the cycle number. The residuals derived from a fit to a linear ephemeris form an "Observed minus Computed" or O-C diagram. If one measures eclipse times (ETs) for both primary and secondary eclipses, then both types of events may be put on a common system by means of a phase offset δ that is applied to the cycle numbers of the secondary eclipses. A single period can then be fit to all of the ETs. We will refer to the resulting O-C diagram a "Common Period O-C" or CPOC diagram.

There are a number of situations where the intervals between successive eclipses are not constant, thereby leading to eclipse timing variations (ETVs). The points in the O-C or CPOC diagrams will no longer be scattered about the horizontal axis, and a model that goes beyond a simple linear ephemeris will be needed. We briefly discuss mechanisms for ETVs that apply to stars that are well within their respective Roche lobes, where mass transfer and mass loss can be neglected.

If the EB is part of a triple system, then the eclipses will either be early or late owing to light travel time (LTT) changes as the EB moves about the center of mass of the triple system. In these cases, the ETs are no longer described by a simple linear ephemeris (e.g. Irwin 1952):

$$T_{\rm min}(E) = T_0 + P_{\rm bin}E + K\left[\frac{1-e_3^2}{1+e_3\cos\nu_3}\sin(\nu_3+\omega_3) + e_3\sin\omega_3\right], \tag{2}$$

What amateurs can contribute

- Eclipse timings from light curves
  - apsidal motion measurements
  - light-time effect in triple stars
- Extremely long-period EBs
  - e.g. Tyc-2505-672-1
  - 69.1 year orbital period
  - eclipse lasts 3.45 years
  - monitored by AAVSO

Draft version January 5, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

AN EXTREME ANALOGUE OF ϵ AURIGAE: AN M-GIANT ECLIPSED EVERY 69 YEARS BY A LARGE OPAQUE DISK SURROUNDING A SMALL HOT SOURCE

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[6]Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125
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Draft version January 5, 2016

ABSTRACT

We present TYC 2505-672-1 as a newly discovered, remarkable eclipsing system comprising an M-type red giant that undergoes a $\sim$3.45 year long, near-total eclipse (depth of $\sim$4.5 mag) with a very long period of $\sim$69.1 yr. This therefore becomes the longest-period eclipsing binary system yet discovered, more than twice as long as that of the currently longest-period system, ϵ Aurigae. We show from analysis of the light curve including both our own data and historical data spanning more than 120 yr and from modeling of the spectral energy distribution, both before and during eclipse, that the red giant primary is orbited by a moderately hot source ($T_{\rm eff} \approx 8000$ K) that is itself surrounded by an extended, opaque circumstellar disk. From the measured ratio of luminosities, the radius of the hot companion must be in the range 0.1–0.5 $R_\odot$ (depending on the assumed radius of the red giant primary), which is an order of magnitude smaller than that for a main sequence A star and 1–2 orders of magnitude larger than that for a white dwarf. The companion is therefore most likely a "stripped red giant" subdwarf-B type star destined to become a He white dwarf. It is however somewhat cooler than most sdB stars, implying a very low mass for this "pre-He-WD" star. The opaque disk surrounding this hot source may be a remnant of the stripping of its former hydrogen envelope. However, it is puzzling how this object became stripped, given that it is at present so distant (orbital semi-major axis of $\sim$24 AU) from the current red giant primary star. Extrapolating from our calculated ephemeris, the next eclipse should begin in early UT 2080 April and end in mid UT 2083 September (eclipse center UT 2081 December 24). In the meantime, radial velocity observations would establish the masses of the components, and high-cadence UV observations could potentially reveal oscillations of the hot companion that would further constrain its evolutionary status. In any case, this system is poised to become an exemplar of a very rare class of systems, even more extreme in several respects than the well studied archetype ϵ Aurigae.

1. INTRODUCTION

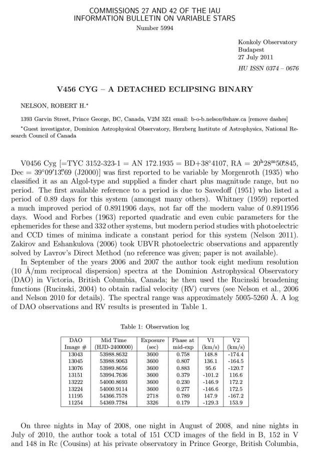
One of the most well studied eclipsing binaries (EB) is ϵ Aurigae (HD 31964). At $V \sim 3$ and having the longest known orbital period for an EB ($\sim$27.1 yr), this unique system has become a prime target for extensive characterization. The primary eclipse has a depth of 0.8–1.0 mag (visual) and lasts for $\sim$2 yr. The primary star is an evolved F0 giant first proposed as being eclipsed by a very large dark companion Carroll et al. (1991). The Spectral Energy Distribution (SED) of ϵ Aur was reproduced using 2 components: a 2.2 $M_\odot$ post-asymptotic giant branch F star, and a 5.9 $M_\odot$ B5V star with a thick semi-transparent disk (Hoard et al. 2010). Using the CHARA array to obtain interferometric images during the 2009-2011 eclipse, Kloppenborg et al. (2010) confirmed the eclipse to be caused by a dark companion with a tilted disk.

In this work, we present the analysis of TYC 2505-672-1, a system similar to ϵ Aur, but with an even longer period of $\sim$69.1 yr, making it now the EB with the longest known period. We use catalog photometry fortuitously obtained both during and prior to eclipse for an analysis of the system spectral energy distribution (SED), and we use extensive photometric observations from the Kilodegree Extremely Little Telescope (KELT) together with archival observations spanning 120 yr. The primary component of the system is an M-type red giant that over the past century has shown two very deep, multi-year-long dimming events, most recently noted in Astronomer Telegrams by the MASTER Global Robotic Net (Lipunov et al. 2010). It has been suggested that the dimmings are caused by either R Coronae Borealis (RCB) events of the M-giant (Denisenko et al. 2013) or by a very long-period eclipse of the M-giant by a dark companion as in ϵ Aur (Tang et al. 2013).

From our SED and light curve analysis, we interpret the dimmings to be caused by a small, hot companion surrounded by a large opaque disk eclipsing the M-giant primary star every $\sim$69 yr. However, as we discuss, the evolutionary status of this hot companion is unclear, but may be a rare example of a low-mass, recently "stripped red giant" destined to become a Helium white dwarf, such as that reported by Maxted et al. (2014).

What amateurs can contribute

- Eclipse timings from light curves
  - apsidal motion measurements
  - light-time effect in triple stars
- Extremely long-period EBs
  - e.g. Tyc-2505-672-1
  - 69.1 year orbital period
  - eclipse lasts 3.45 years
  - monitored by AAVSO
- Physical properties of EBs
  - e.g. V456 Cyg (Nelson 2011)
  - mass and radius measurements



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V456 CYG – A DETACHED ECLIPSING BINARY

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V0456 Cyg [=TYC 3152-323-1 = AN 172.1935 = BD+38°4107, RA = $20^{\mathrm{h}}28^{\mathrm{m}}50\overset{\mathrm{s}}{.}845$, Dec = $39^\circ09'13\overset{\prime\prime}{.}69$ (J2000)] was first reported to be variable by Morgenroth (1935) who classified it as an Algol-type and supplied a finder chart plus magnitude range, but no period. The first available reference to a period is due to Savedoff (1951) who listed a period of 0.89 days for this system (amongst many others). Whitney (1959) reported a much improved period of 0.8911906 days, not far off the modern value of 0.8911956 days. Wood and Forbes (1963) reported quadratic and even cubic parameters for the ephemerides for these and 332 other systems, but modern period studies with photoelectric and CCD times of minima indicate a constant period for this system (Nelson 2011). Zakirov and Eshankulova (2006) took UBVR photoelectric observations and apparently solved by Lavrov's Direct Method (no reference was given; paper is not available).

In September of the years 2006 and 2007 the author took eight medium resolution (10 Å/mm reciprocal dispersion) spectra at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada; he then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson et al., 2006 and Nelson 2010 for details). The spectral range was approximately 5005-5260 Å. A log of DAO observations and RV results is presented in Table 1.

Table 1: Observation log

DAO Image #	Mid Time (HJD-2400000)	Exposure (sec)	Phase at mid-exp	V1 (km/s)	V2 (km/s)
13043	53988.8632	3600	0.758	148.8	-174.4
13045	53988.9063	3600	0.807	136.1	-164.5
13076	53989.8656	3600	0.883	95.6	-120.7
13151	53994.7636	3600	0.379	-101.2	116.6
13222	54000.8693	3600	0.230	-146.9	172.2
13224	54000.9114	3600	0.277	-146.6	172.5
11195	54366.7578	2718	0.789	147.9	-167.2
11254	54369.7784	3326	0.179	-129.3	153.9

On three nights in May of 2008, one night in August of 2008, and nine nights in July of 2010, the author took a total of 151 CCD images of the field in B, 152 in V and 148 in Rc (Cousins) at his private observatory in Prince George, British Columbia,

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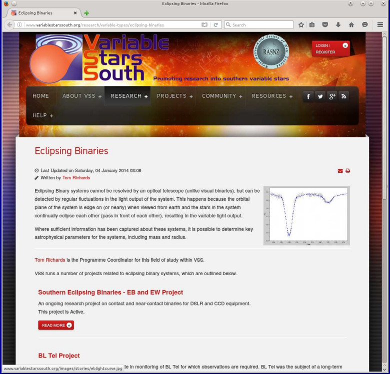
  - mass and radius measurements
- Organised groups



Eclipsing Binaries

Last Updated on Saturday, 04 January 2014 03:08
Written by Tom Richards

Eclipsing Binary systems cannot be resolved by an optical telescope (unlike visual binaries), but can be detected by regular fluctuations in the light output of the system. This happens because the orbital plane of the system is edge on (or nearly) when viewed from earth and the stars in the system continually eclipse each other (pass in front of each other), resulting in the variable light output.

Where sufficient information has been captured about these systems, it is possible to determine key astrophysical parameters for the systems, including mass and radius.

Tom Richards is the Programme Coordinator for this field of study within VSS.

VSS runs a number of projects related to eclipsing binary systems, which are outlined below.

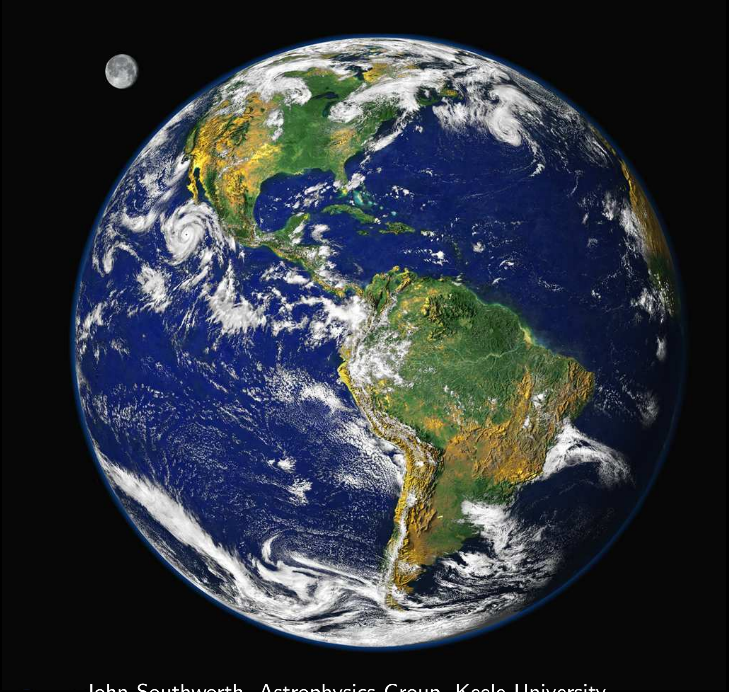
Southern Eclipsing Binaries - EB and EW Project

An ongoing research project on contact and near-contact binaries for DSLR and CCD equipment.
This project is Active.

BL Tel Project

te in monitoring of BL Tel for which observations are required. BL Tel was the subject of a long-term

http://www.variablestarssouth.org/research/variable-types/eclipsing-binaries



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