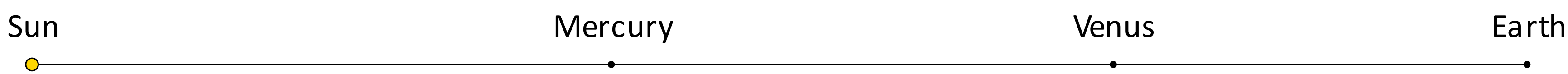
Eclipse Timing Variation and Spots in Close Binaries

ATILA ČEKI

ASTRONOMICAL OBSERVATORY

Introduction

Definition: Binary system is considered **close** when component radii are larger than 10% of the orbit's semi-major axis



Main properties of close binaries:

- Stars are no longer spherical
- Proximity effects (mutual irradiation, tidal interaction…)
- We can't assume that they evolve independently of each other
- Short periods (less than 20 days)
- Many are eclipsing binaries
- …

They are challenging and fun to study!

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Ephemeris

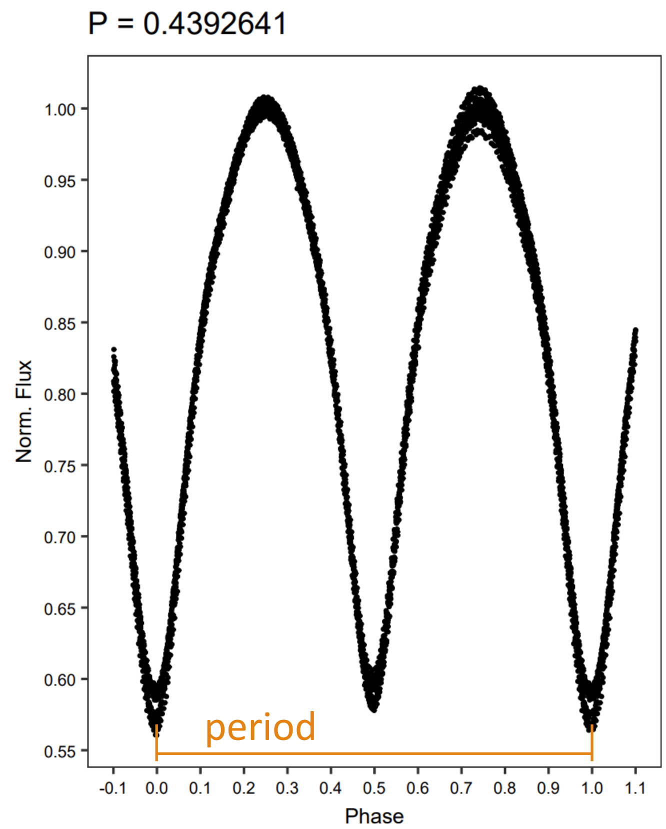
We need the **period P** and the **epoch t_0** to phase-fold light curves

P - interval between two consecutive primary minima

t_0 - time of some referent primary minimum

Then, **phase** is:

$$\phi_i = \left[\!\left[\frac{t_i - t_0}{P}\right]\!\right]$$



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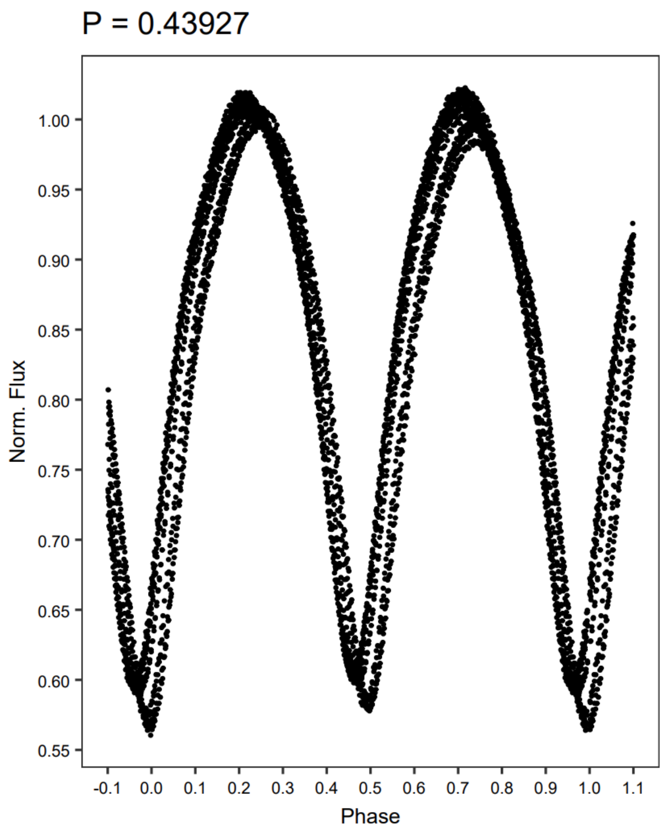
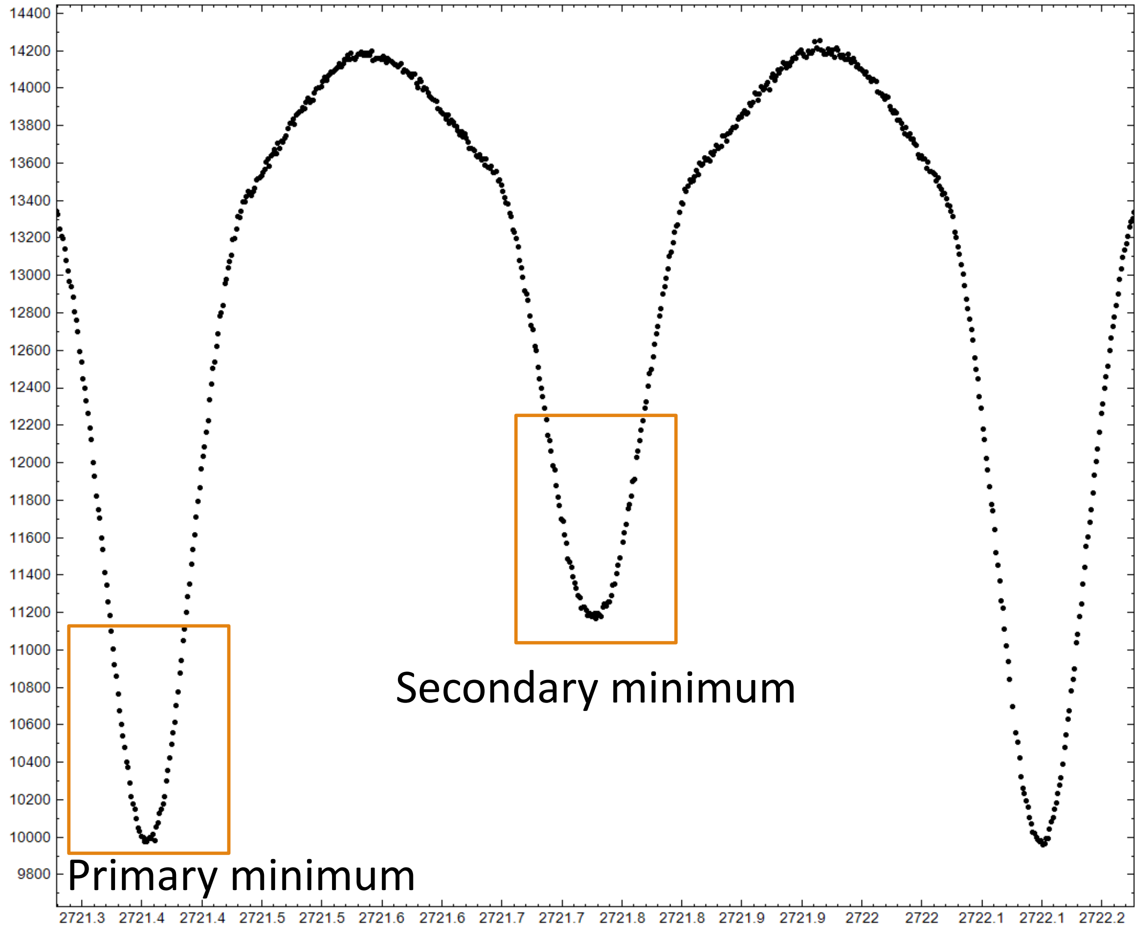


Times of minima



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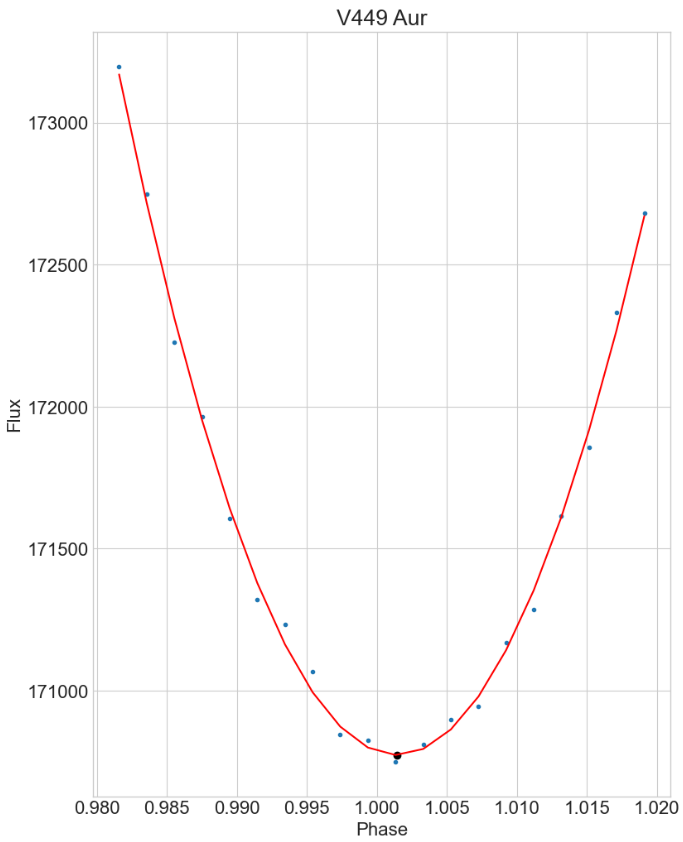

Table 8. The eclipse timings of V527 Dra measured in this study. This table is available in its entirety in the machine-readable format. Only a portion is shown here for guidance regarding its form and content.

Source	BJD	Error	Type
SW	2454607.67753	0.00059	2
SW	2454613.63742	0.00053	2
SW	2454619.59631	0.00039	2
SW	2454622.57518	0.00030	2
–			
TESS	2459961.18868	0.00003	1
TESS	2459961.56117	0.00004	2
TESS	2459961.93350	0.00005	1
TESS	2459962.30596	0.00006	2

*Note.*Source can be: SW (Super-WASP), *TESS*, or TS (this study). Type can be 1 (primary eclipse) and 2 (secondary eclipse).

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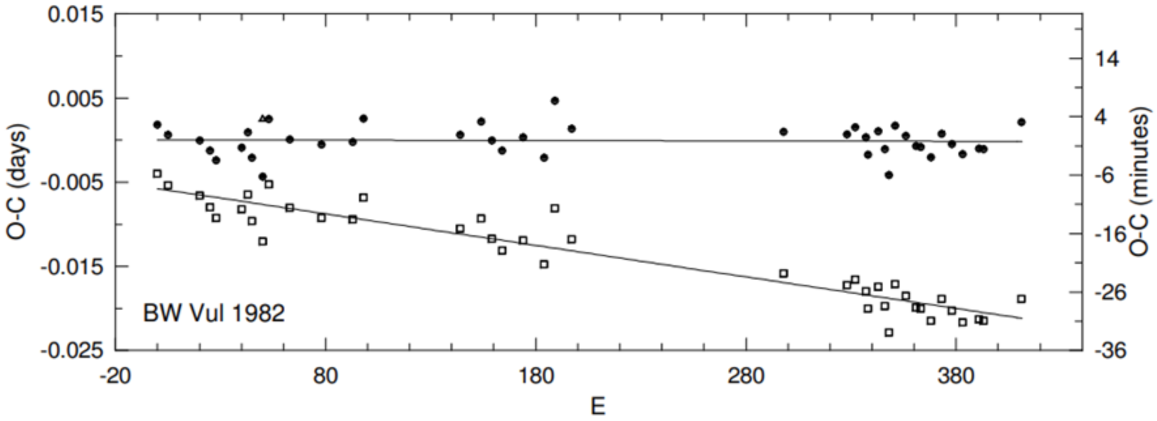
ETV diagram

$$t_{calc} = t_0 + \epsilon P$$

$$\Delta t(\epsilon) = t_{obs} - t_{calc}$$

- t_0 - epoch
- P - period
- ϵ - cycle number



Source: *Sterken C., 2005, ASP Conference Series, 335, 3*

ETV diagram – linear

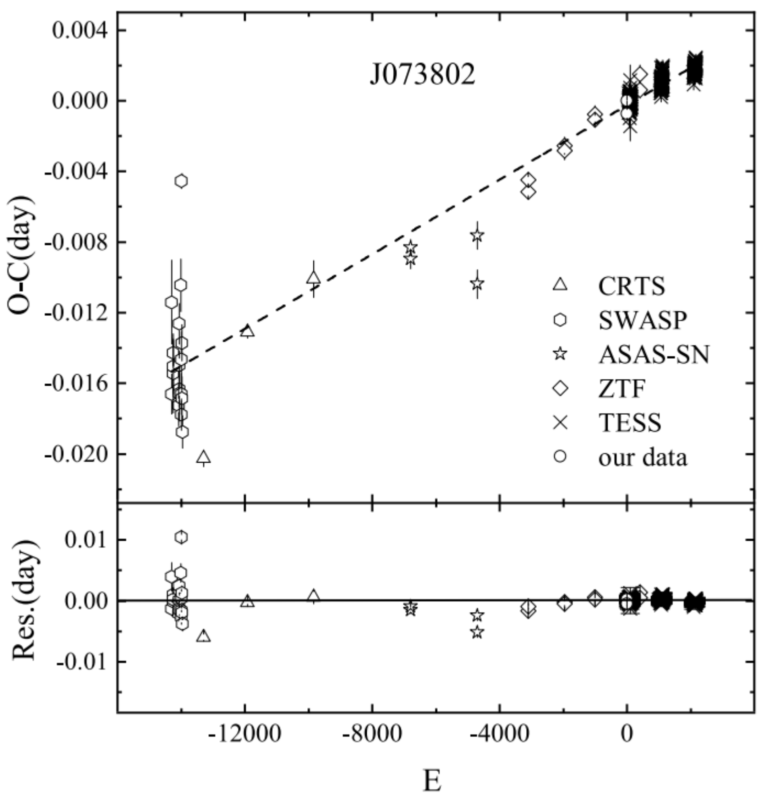
Incorrect, but **constant period** ($P' = P + \Delta P$) will produce a linear ETV diagram:

$$\Delta t(\epsilon) = t_{obs} - t_{calc} = c_1\epsilon + c_0$$

The corrected ephemeris will be:

$$P = P' + c_1$$

$$t_0 = t_0' + c_0$$



Source: *Xin Xu et al, 2025, AJ, 169, 85*

ETV diagram - quadratic

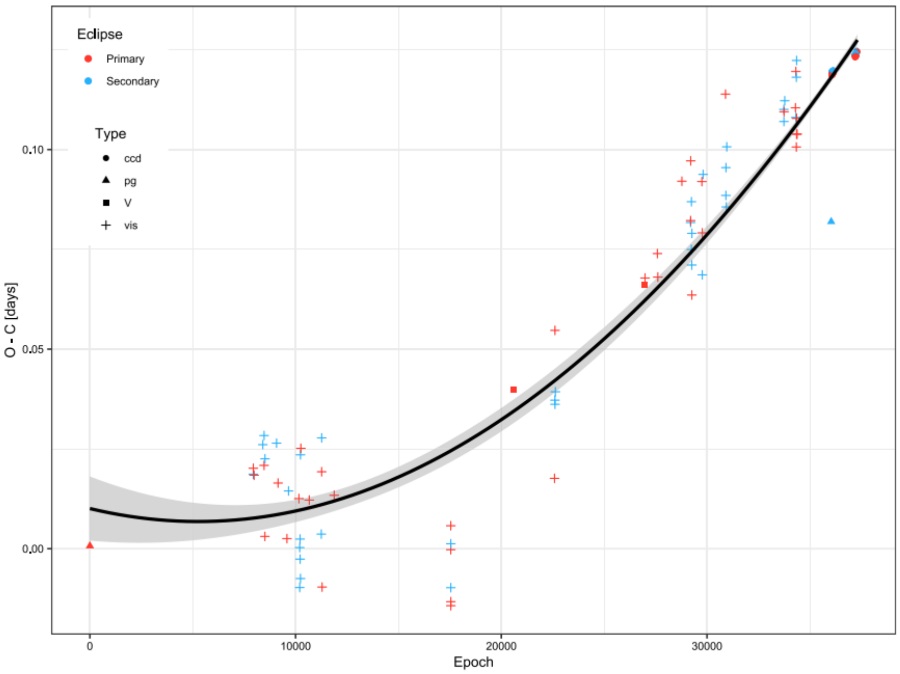
Variable period with constant period change will produce a quadratic ETV diagram:

$$\Delta t(\epsilon) = c_2\epsilon^2 + c_1\epsilon + c_0$$

$$c_2 = \frac{P\dot{P}}{2}, \dot{P} = \frac{dP}{dt} = const$$

Causes of period variability:

- conservative mass transfer
- mass loss (stellar winds, Roche lobe overflow, …)
- angular momentum loss due to magnetic braking



$$\frac{dP}{dt} = 9.55 \times 10^{-8}\,\frac{days}{year} \approx 8\,\frac{ms}{year}$$

Source: *Latković & Čeki, 2024, New Astronomy, 113, 102291*

ETV diagram - cyclic

$\Delta t(\epsilon) = c_3 \sin(c_2 t + c_1) + c_0$

Causes of cyclic variability:

- presence of the third body (light-time effect)
- magnetic activity (Applegate mechanism)

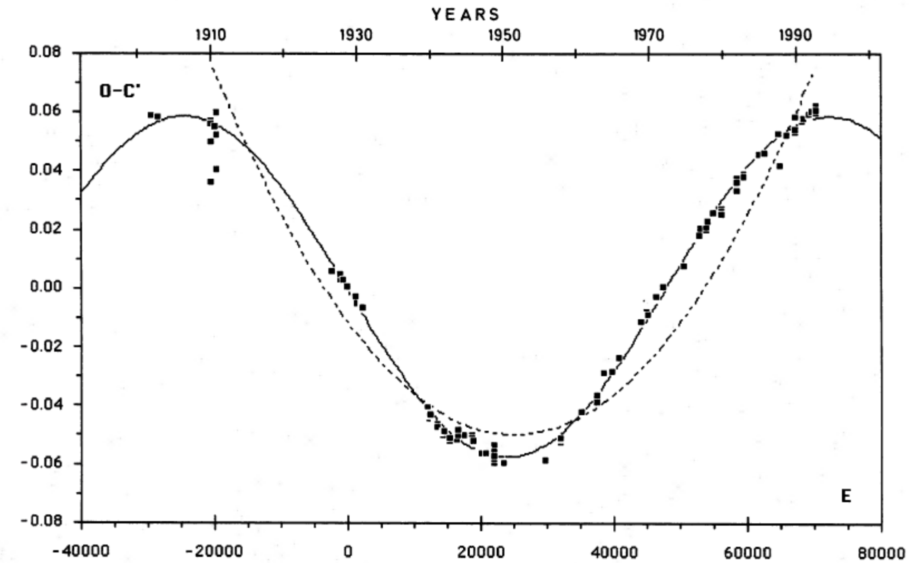


Figure 3. The best-fitting parabolic and sinusoidal curves superimposed on the O – C diagram.

Source: Demircan et al., 1994, MNRAS, 267, 19-25

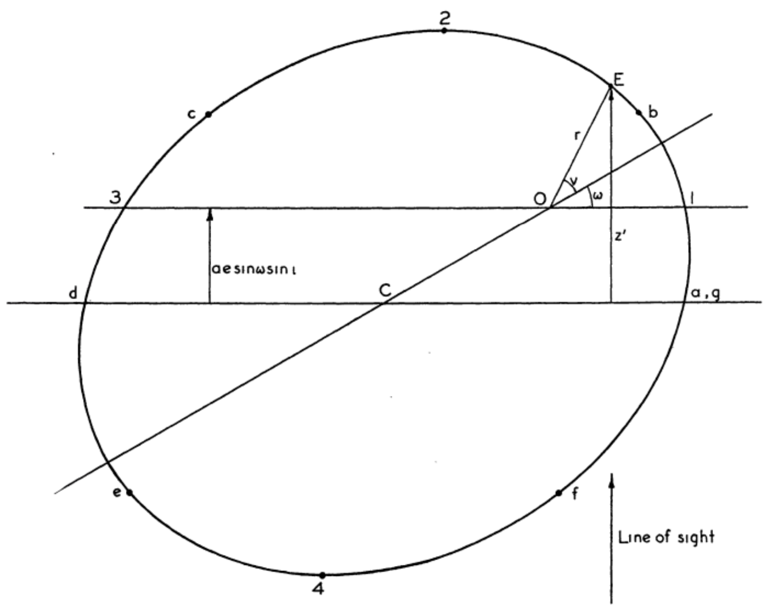
ETV – light-time effect (LiTE)

$$\Delta t(\epsilon) = \frac{A}{1-e^2\cos^2\omega} \times \left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right]$$

$$A = \frac{a_{12}\sin i\sqrt{1-e^2\cos^2\omega}}{2.590\times10^{10}}$$

$$f(M_3) = \frac{1}{P_3}\left[\frac{173.15A}{\sqrt{\sqrt{1-e^2\cos^2\omega}}}\right]$$

- ν, e, ω, i - orbital parameters of the third body
- a_{12} - semi-major axis of the binary



Source: Irwin, 1952, ApJ, 116, 211

ETV – Applegate mechanism

During the magnetic cycle, the active component **changes its shape** and luminosity

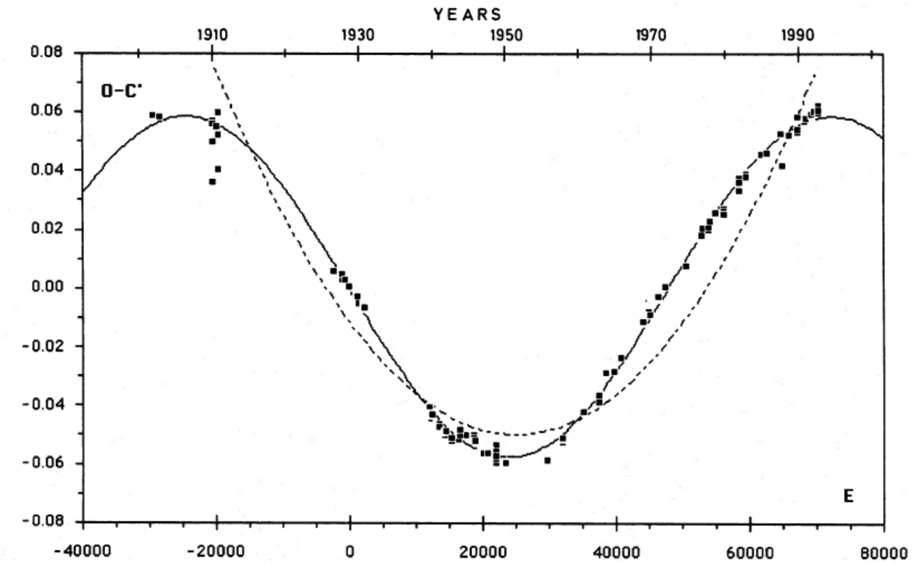
3rd Kepler law for close binaries:

$$P = 2\pi \left(\frac{J}{\mu g^2}\right)^{\frac{1}{3}}, \mu = \frac{M_1 M_2}{M_1 + M_2}$$

$$\frac{\Delta P}{P} \sim -\frac{2}{3}\frac{\Delta g}{g}$$

We can estimate:

- magnetic flux density
- luminosity change during the cycle



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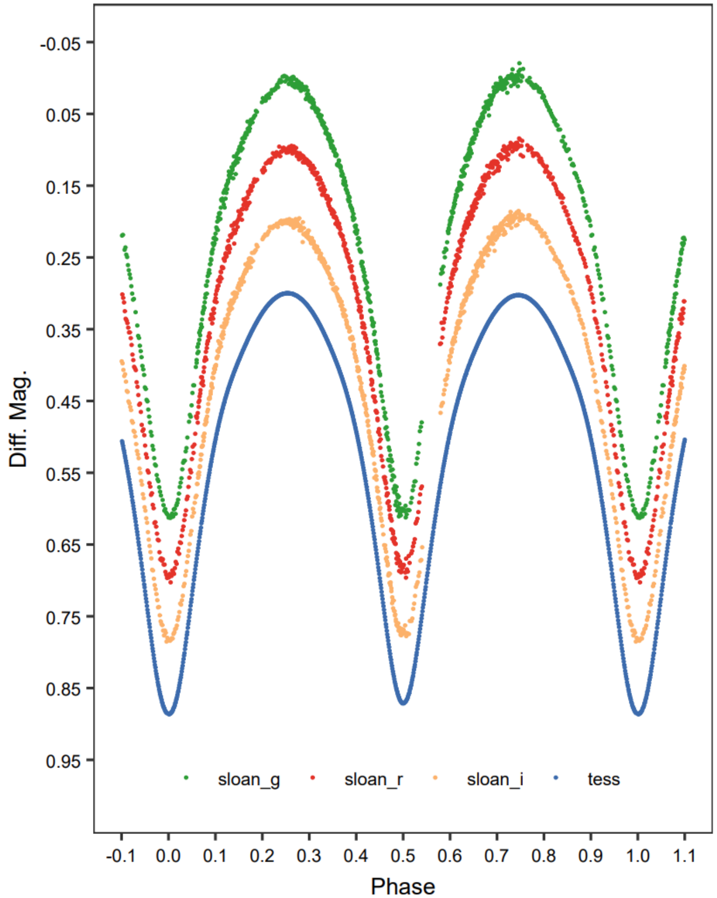
V2846 Cyg

$V_{mag} = 11.23, P \approx 0.45$ days

We collected:

- Spectra from Dominion Astrophysical Observatory (Canada)
  - 8 nights with 1.83m Plaskett Telescope, spectrograph with $R\sim 15000$
- Light curves from Ankara University Kreiken Observatory (Turkey)
  - 3 nights with 0.8m Berahitdin Albayrak Telescope, Apogee Alta U47 CCD camera
- Light curves from TESS
  - 674 complete orbital cycles
- Light curves from SuperWASP



Source: Čeki, A. et al., 2024, MNRAS, 532, 3582

V2846 Cyg – ETV diagram

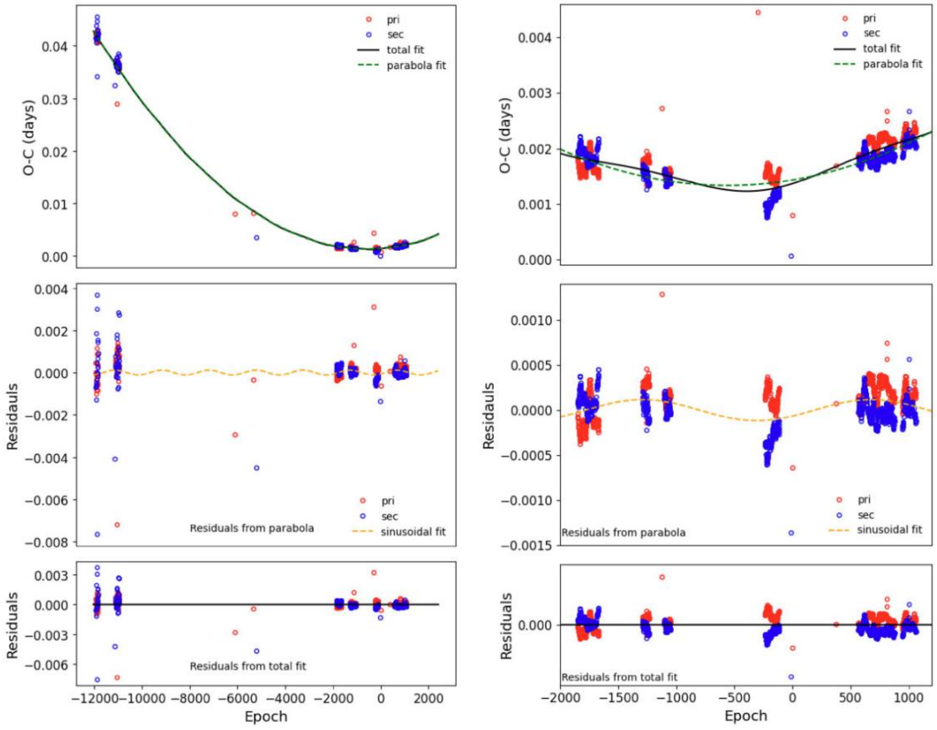
1702 eclipse timings

- 852 primary
- 850 secondary

Quadratic component ⇒ mass transfer rate of $4.86 \times 10^{-7} M_o$

Cyclic component ⇒

- Third body assumption
  - $M_3 \approx 0.016 M_o$
  - $a \sin i \approx 2.56\ AU$
  - $P_3 \approx 2.714\ y$
- Applegate mechanism
  - $B \approx 11.7\ kG, \Delta L \approx 0.02 L_0$



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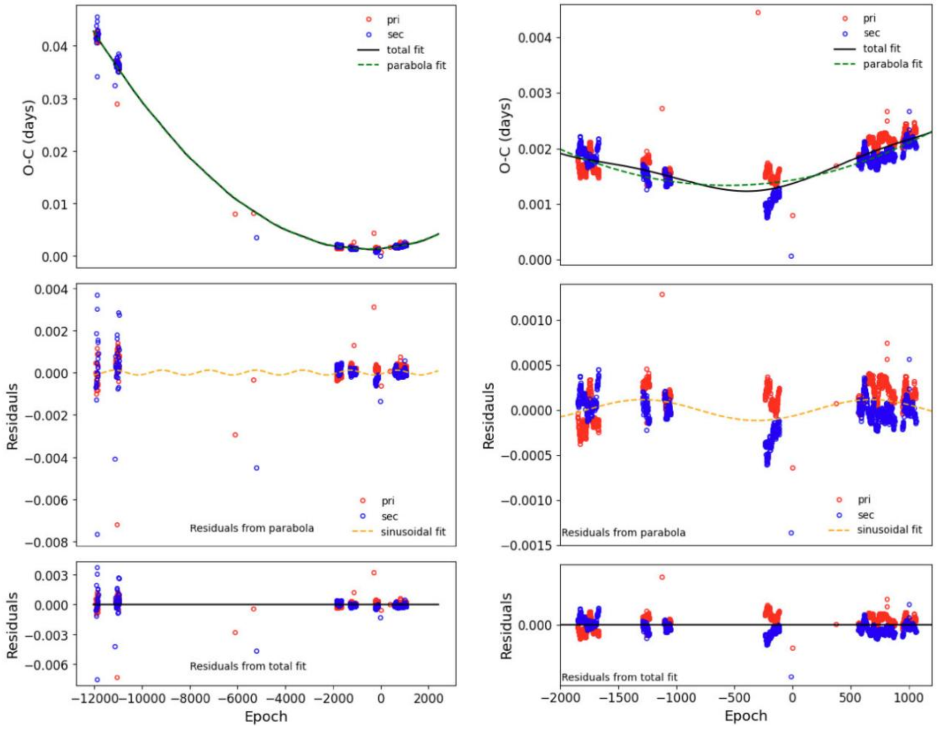

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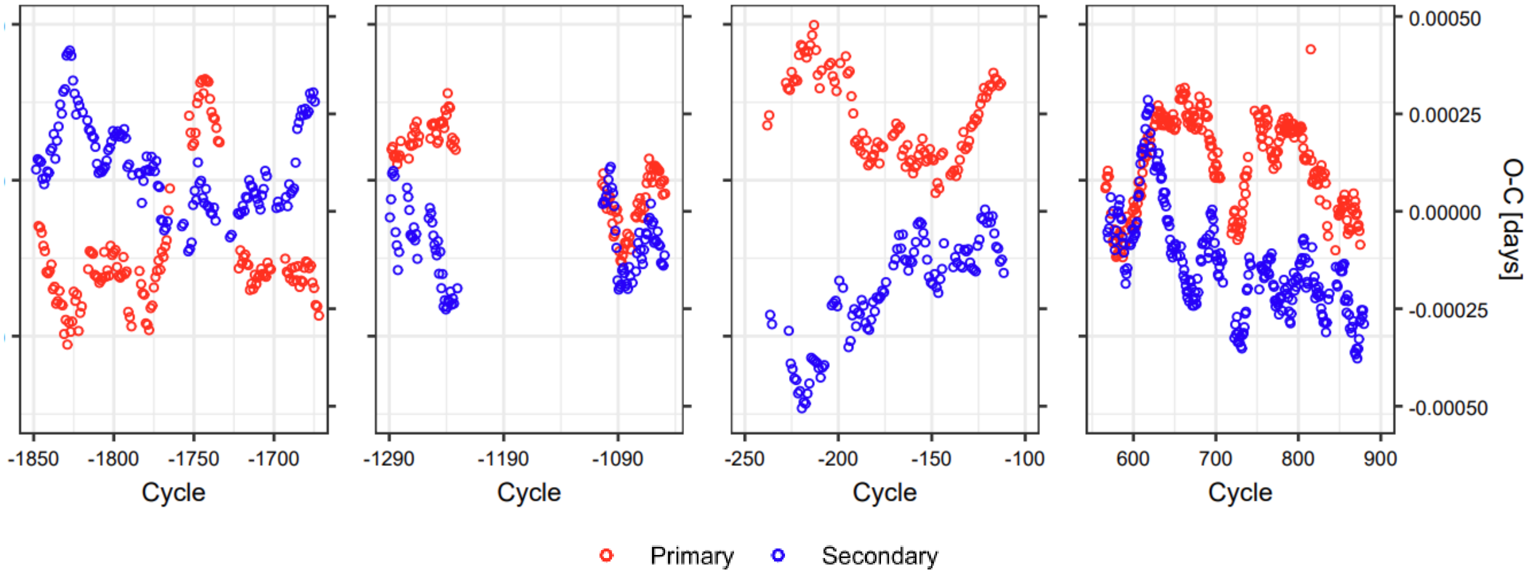


Is this a spot signature?

Possible answer in *Tran et al., 2013, The Astrophysical Journal, 774, 81*.

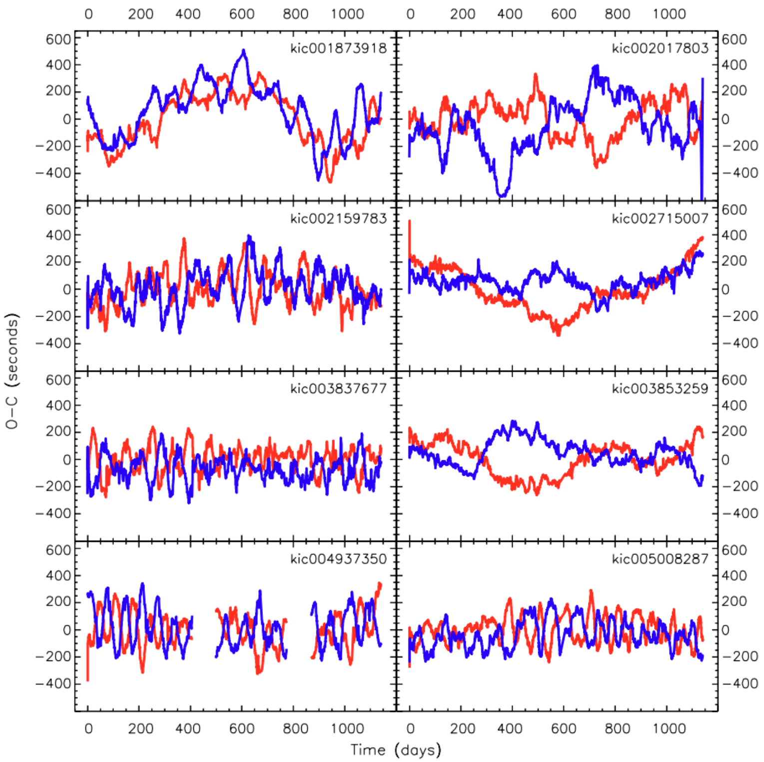
Spot influence on ETV diagram

"Toy" model of a contact binary:

- spherical stars
- circular orbit
- synchronous rotation
- single spot at (λ, θ)
- polar spot

$$\Delta t_n = -(-1)^n \frac{F_{sp} \sin\theta \sin i}{4F_{st}} \sin\lambda$$

$n = 1, 2$ (minimum type)



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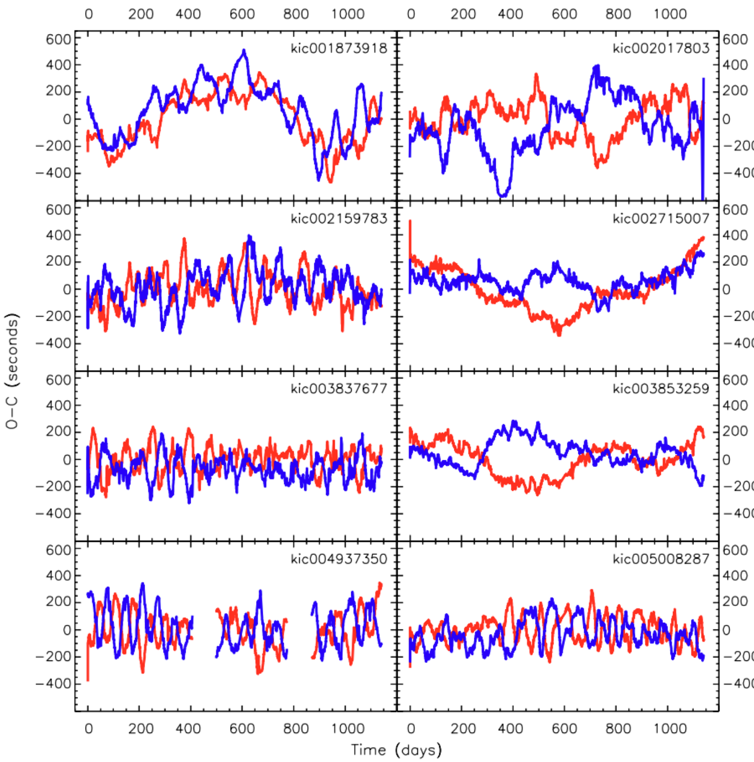

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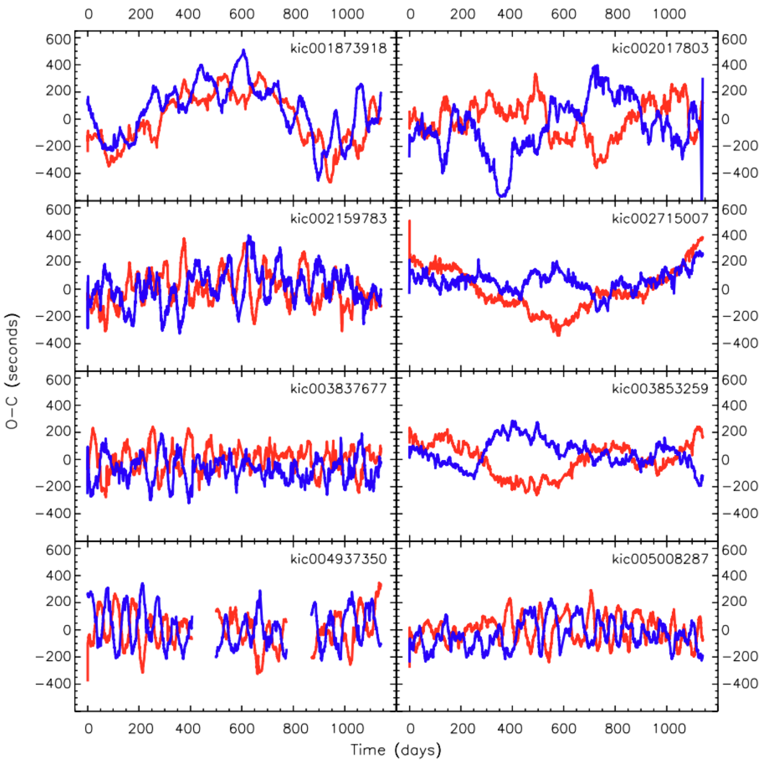
ETV depends on the spot longitude ⇒ **migration** along the longitude will produce **quasi-periodic ETV**



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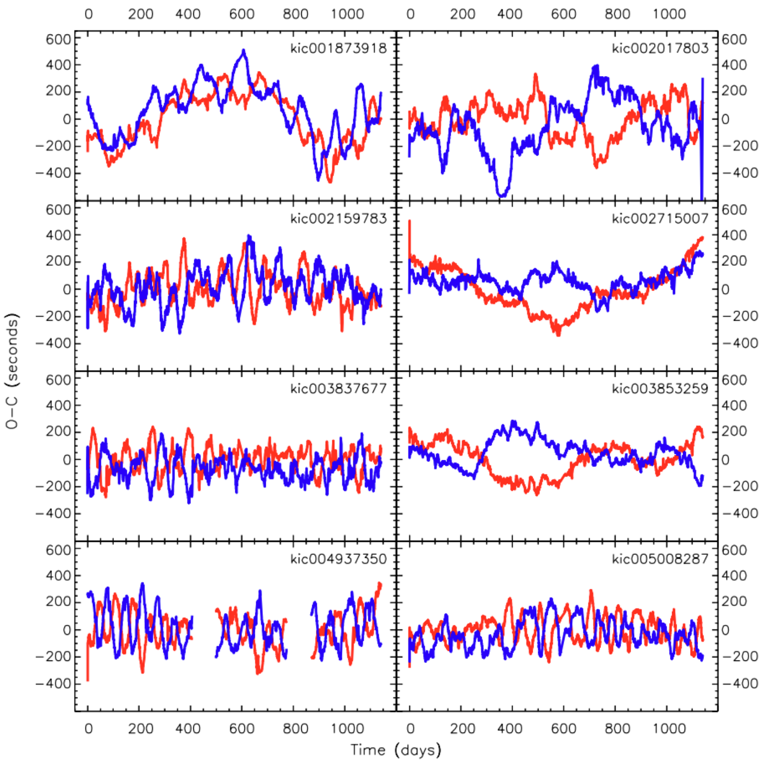
Shifts of the primary and secondary minimum will be **anti-corelated**



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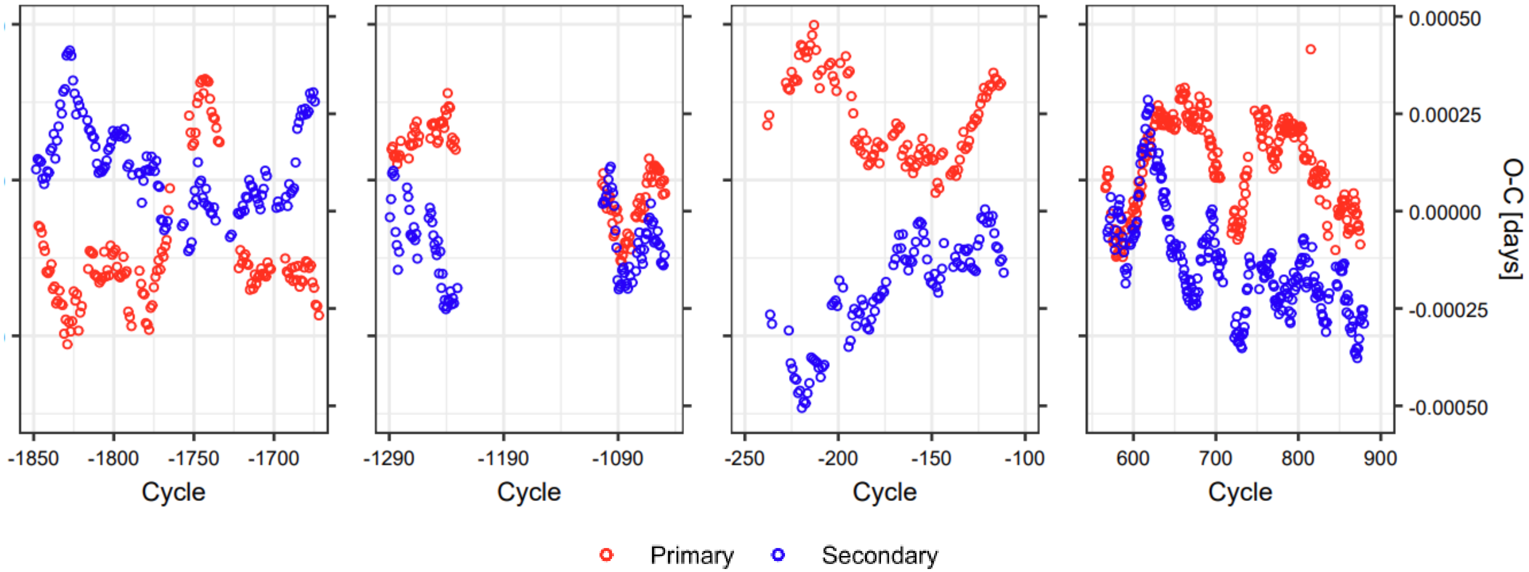


We can see the same effect in the residuals of our ETV diagram

Can we simulate this with “proper”, Roche-based modeling?

Base model

Input

- Ground based observations
  - SDSS *g'*, r' and *i'* filters
- TESS light curve
  - phase-binned to 1000 normal points
- Radial velocity curve

\+ Model of the binary

- Binary Automation Toolkit (BAT)

\+ Optimization algorithm

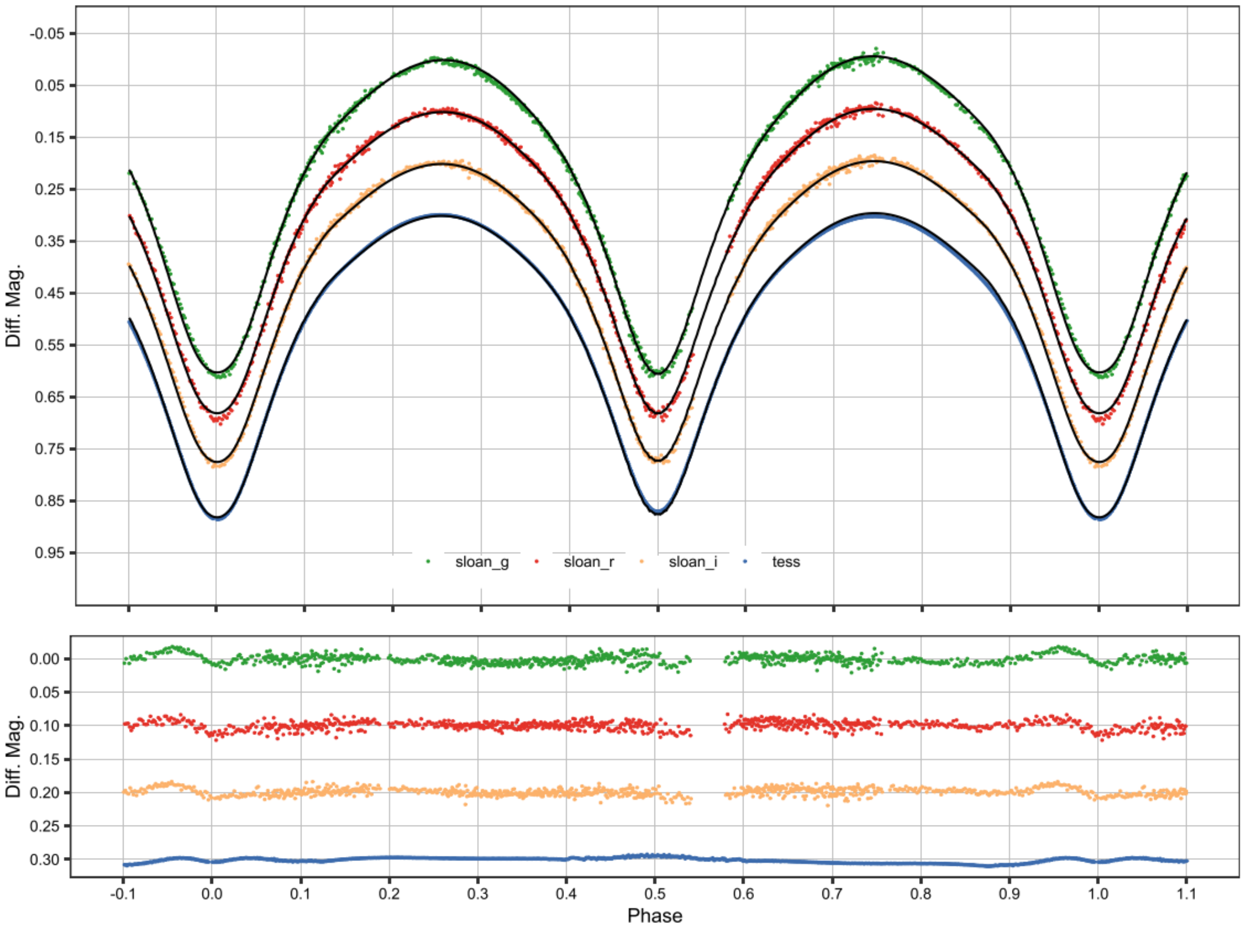
- Constrained Nelder-Mead simplex

= Output

- System parameters

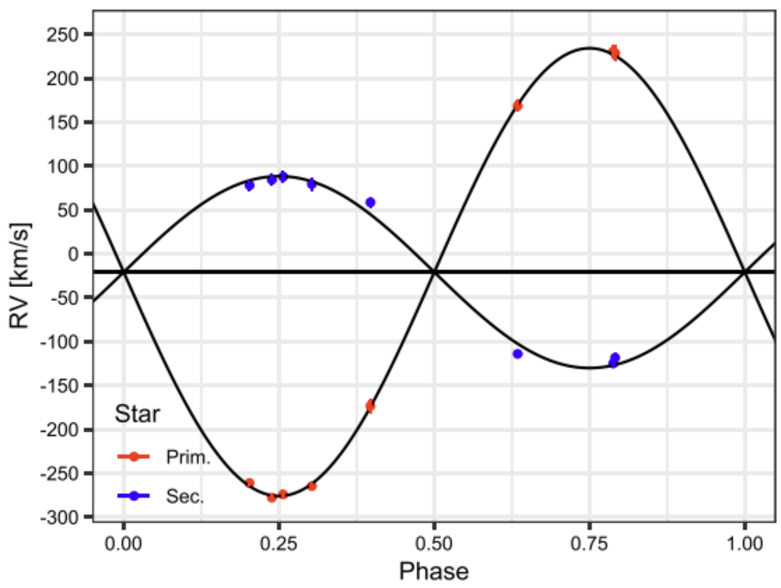
Parameter	Value
period	0.4392644
mass ratio	2.335
semi-major axis	3.209
inclination	80.41
T_1	5350
T_2	5580
potential	2.69746
spot contrast	0.928
spot size	31.8
spot latitude	80.5
…	

Base model

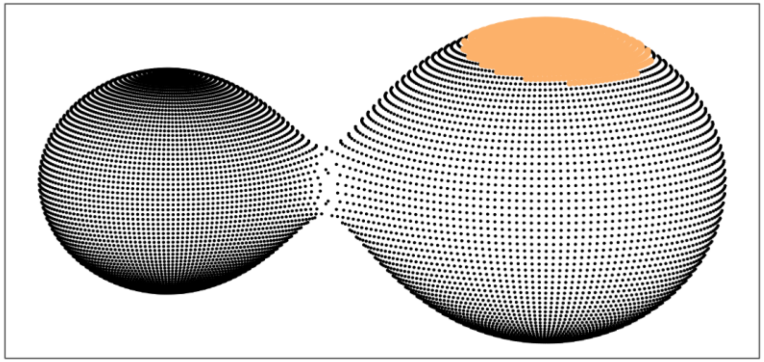


-0.05
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
Diff. Mag.
sloan_g
sloan_r
sloan_i
tess
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Diff. Mag.
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
Phase

Base model



V2846 Cyg, phase 0.25, cycle -220

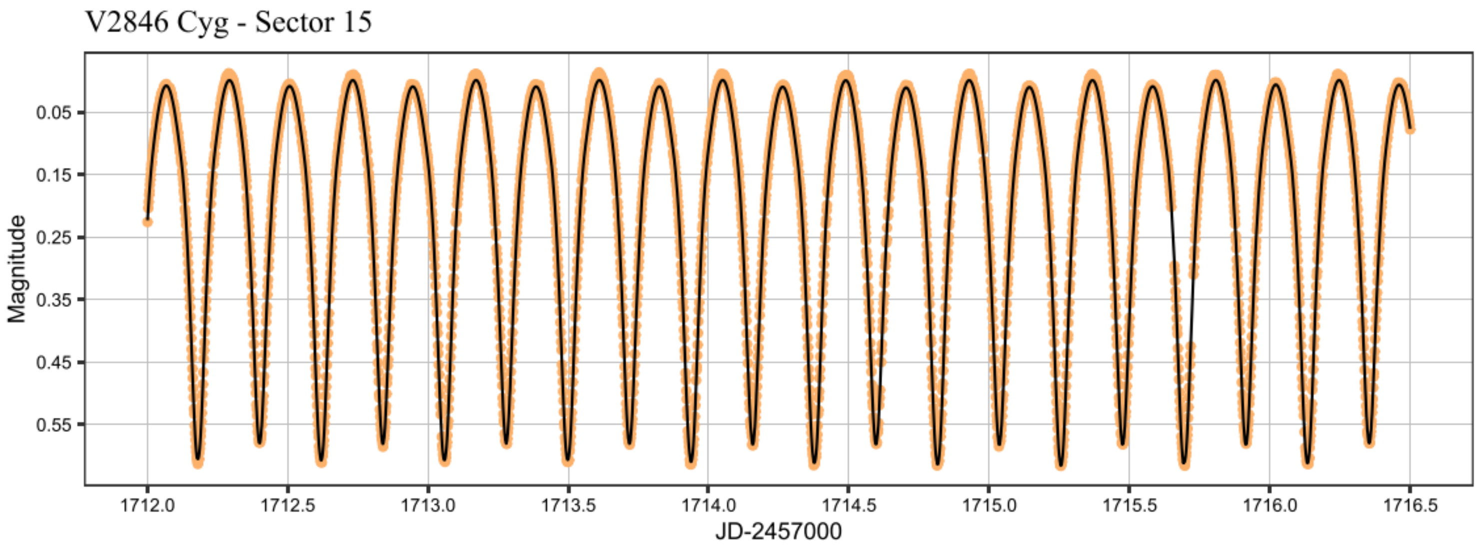


Seasonal modeling

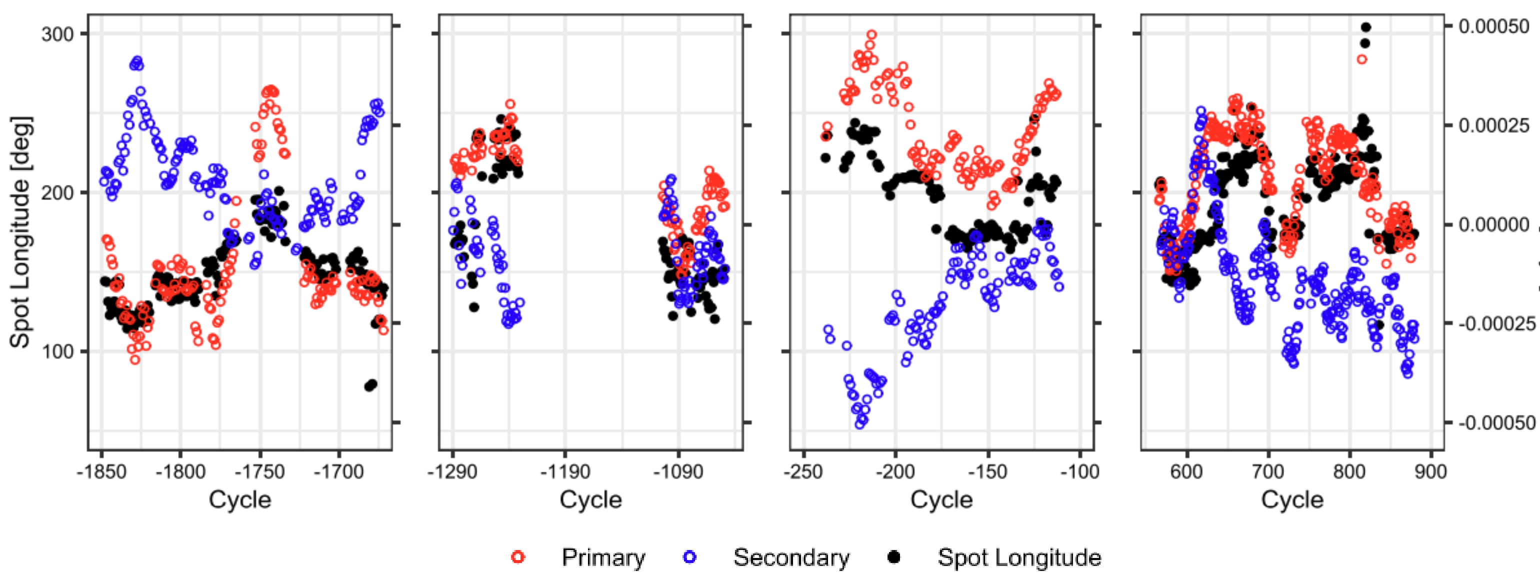
We modelled each of the 674 individual cycles from TESS.

Initial values taken from the base model, except for the spot longitude.

For the longitude, we used a small grid of 8 random initial values per quadrant for a total of 32 trial models per cycle.



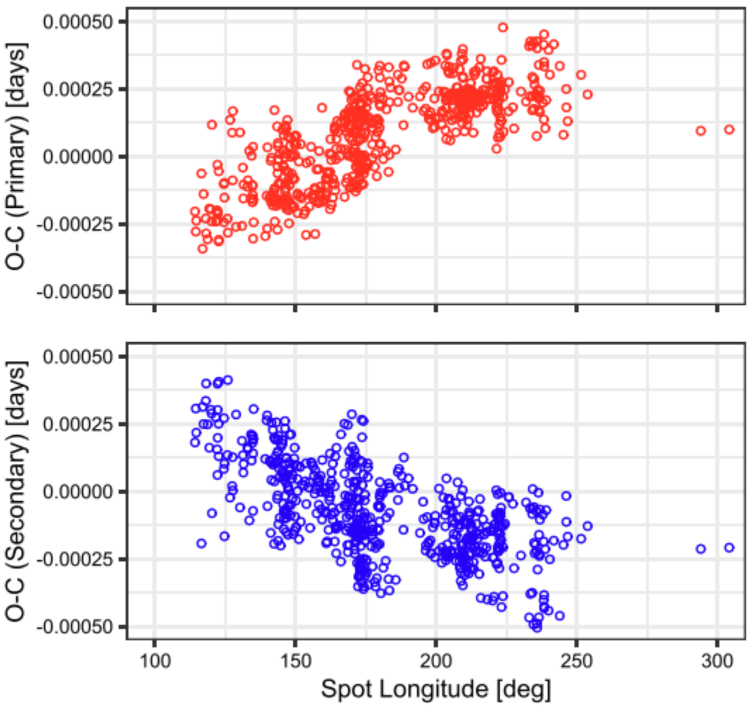
Seasonal modeling



Seasonal modeling

Spot longitude is correlated with the ETV of the primary minimum and anticorrelated with the ETV of the secondary minimum

We confirmed the result by Tran et al. that **ETV residuals can be used as indicators of spot migration**



Summary

ETV diagram analysis is a simple but powerful technique that can provide insight into various processes in close binaries:

- mass transfer and/or loss
- membership in a multiple system
  - orbital parameters of the third body
  - minimal mass of the third body
- magnetic activity
  - magnetic flux density
  - length of the magnetic cycle
  - Luminosity variation over the magnetic cycle
- spot migration

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Thank you for your attention!