O-C Diagrams

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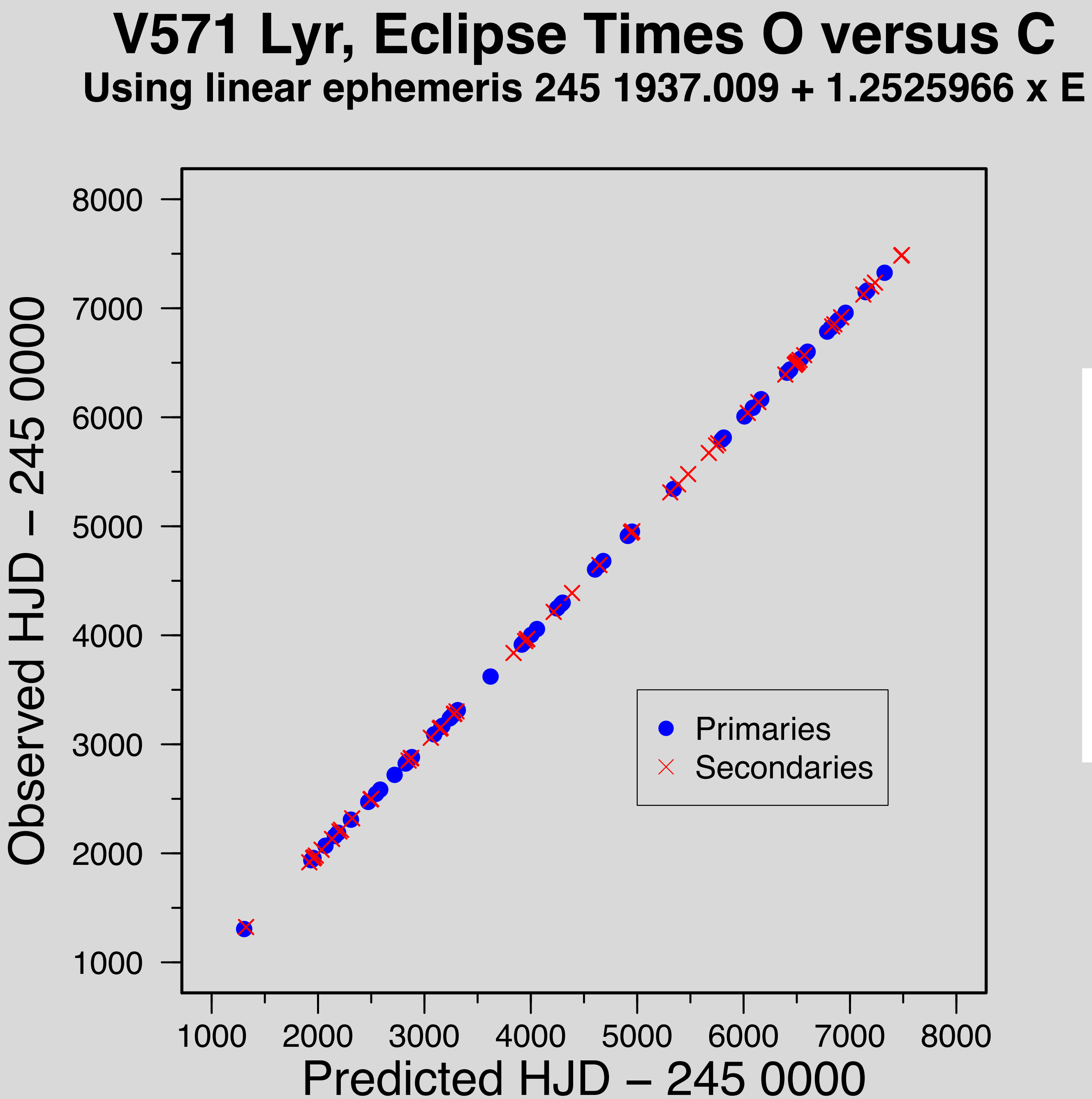
Abstract

The O-C ("observed minus computed") diagram is a simple concept: fit the observational data with a model and examine the quality of the fit. That is, for all the observed datapoints, such as the times of eclipses of an eclipsing binary star, or times of maximum of a pulsator, subtract the times the model would predict, and then plot those "residuals" of the model fit. This allows one to magnify the residuals and study them. Patterns in the residuals may explain how the system has changed, how the model should be adjusted, or whether a different form of model should be used. This discussion presents the concept, describes the mathematical procedure and techniques to calculate this term, and provides specific examples to explain what certain patterns mean in the study of eclipsing binary systems.

Outline:

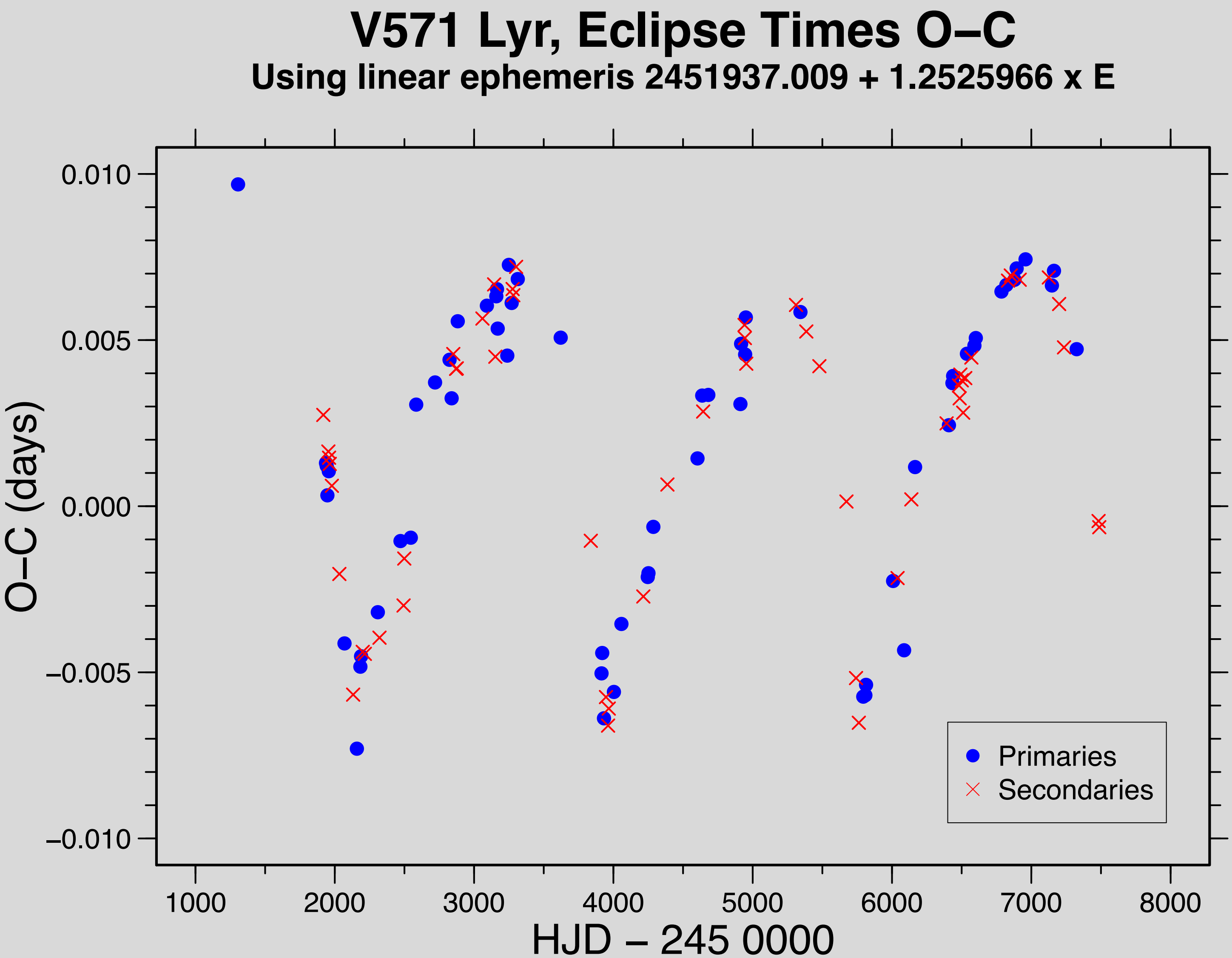
- Introduction
- Data pre-requisites
- Basics of periodic phenomena
- The O-C Zoo: phenomena you will see, and their meaning
- Summary, and resources

Introduction – a naïve attempt:



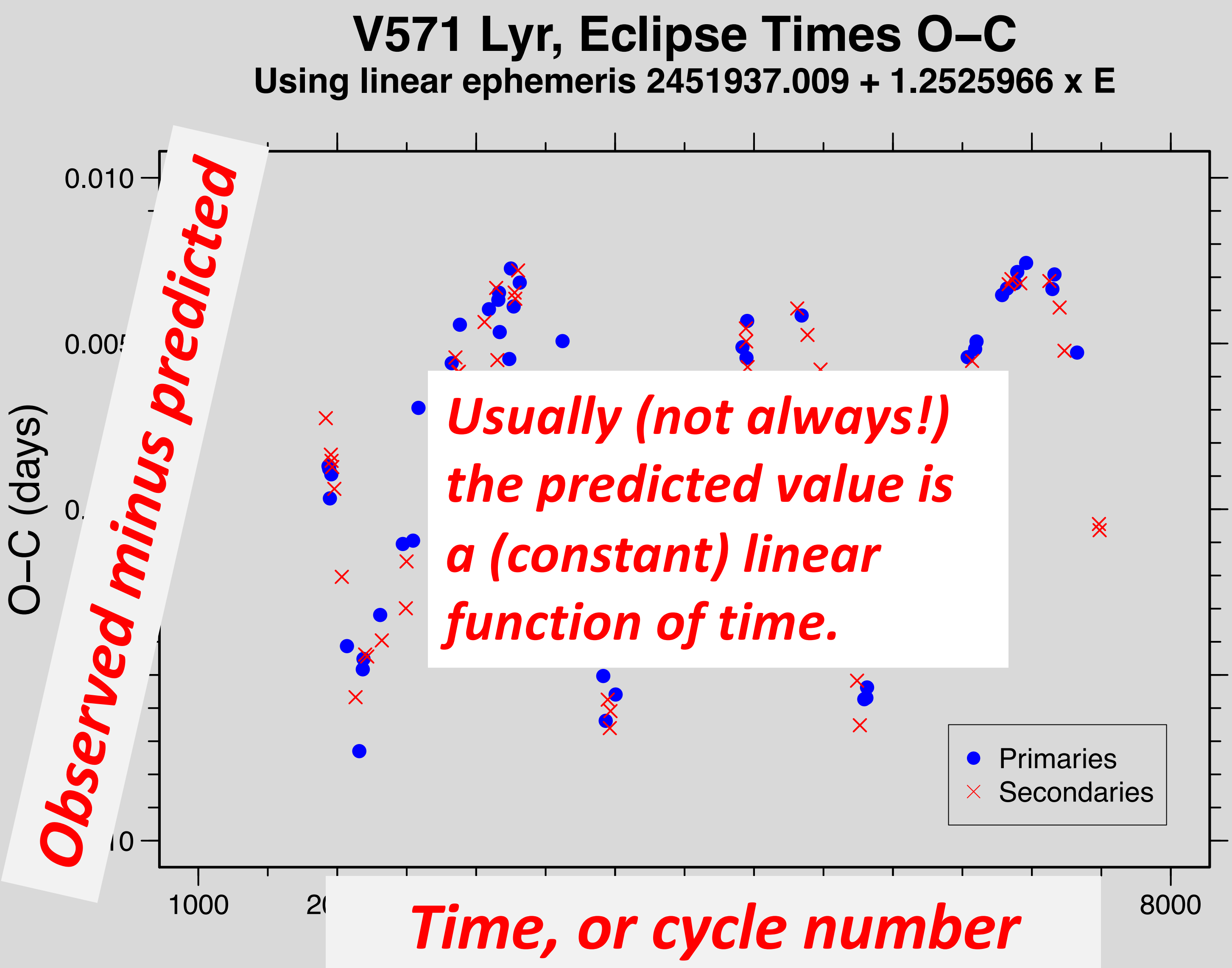
- A naïve test of observations (O) vs. predictions (C).
- Not very sensitive

Introduction – O-C is much more sensitive:



- Same data as previous slide!
- O-C versus C
- Much more sensitive
- Shows there is something else going on with this star

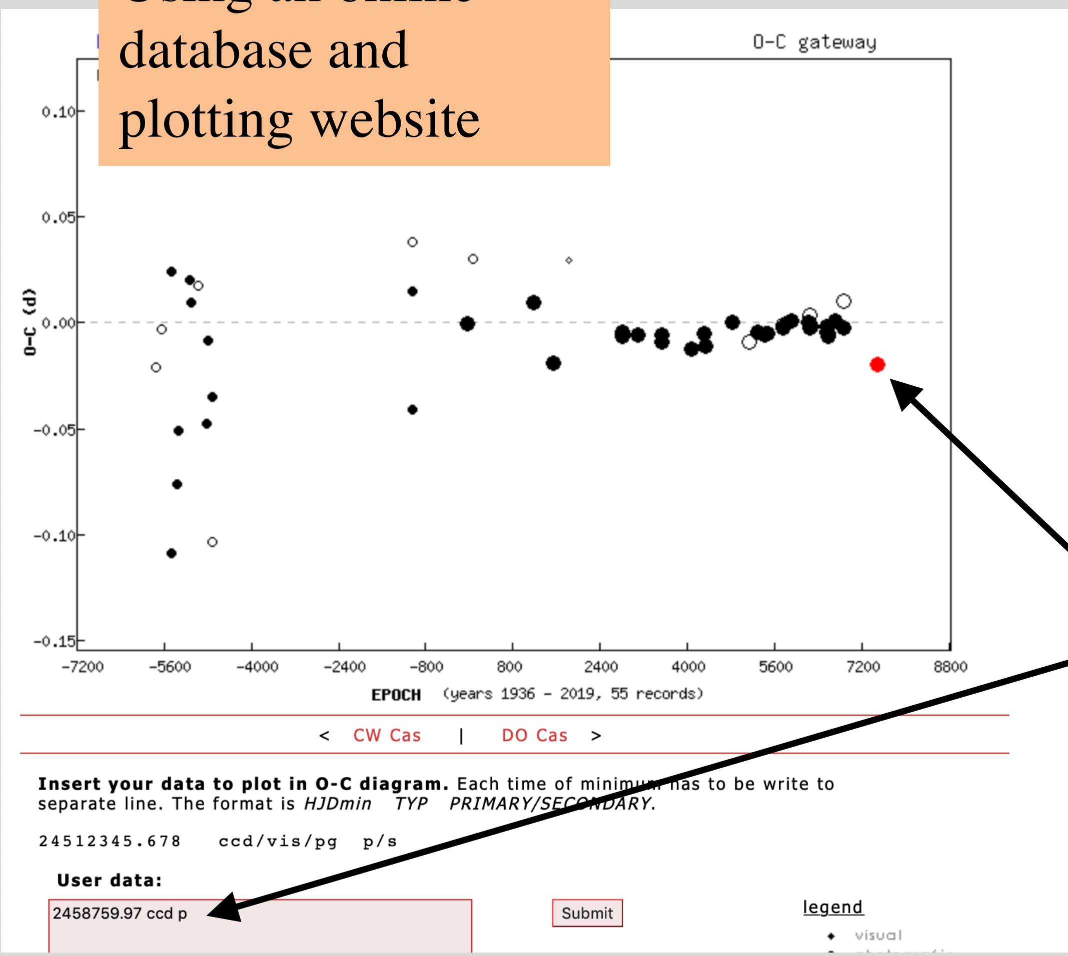
Introduction – definition of the O-C diagram:



Introduction – a simple use:

You've just measured a Time of Minimum (ToM) of an eclipsing binary (EB). What does it say?:

Using an online database and plotting website



- Plot it on an O-C with past ToMs
- is it suggesting more observations are worthwhile?
- In this case, probably!

Your datapoint

Introduction – the core assumption:

- Assumption: there is a mathematical model that can predict the observations.
- That assumption is usually “constant period”.
- The O-C diagram displays the mis-fit: a tool to assess and update the mathematical model.
- Useful for many things…
- *Very useful for studying period changes of variable stars.*
- *Will show in the context of EBs, but good <u>for pulsators too</u>.*

Introduction – diverse uses:

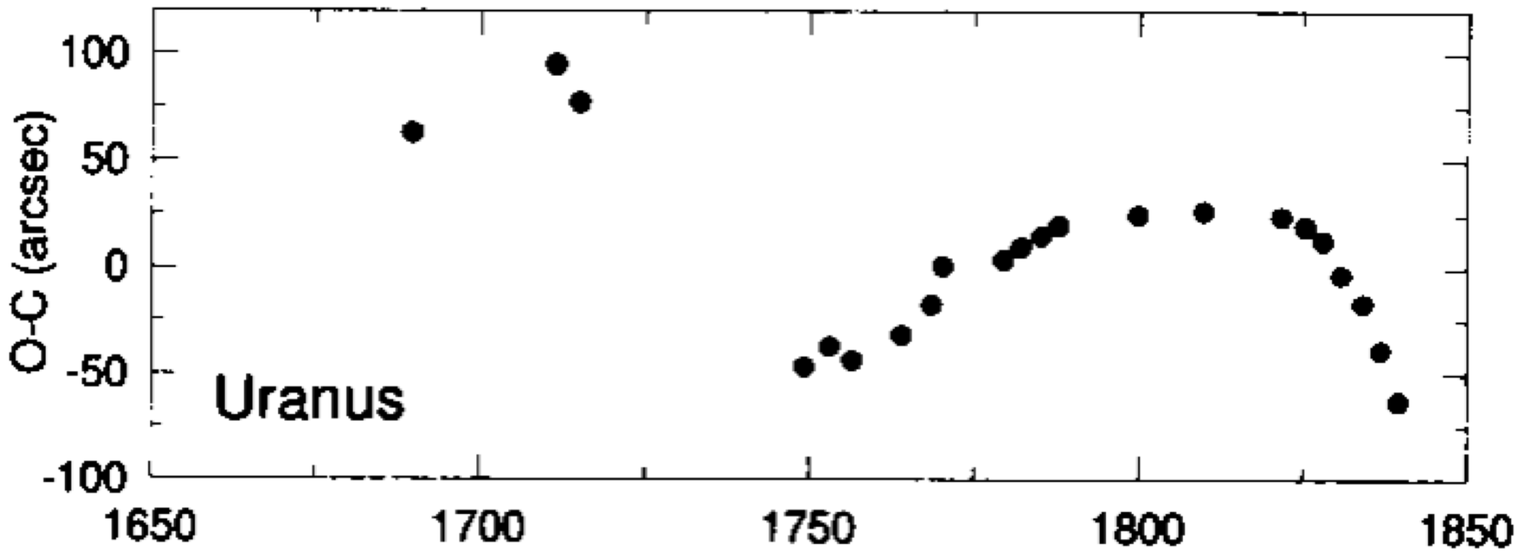


Figure 1. $O - C$ deviations in declination of Uranus.

Sterken, 2005, p 4.

This O-C diagram shows that O-C is a general concept, that has many applications. It can also be called a plot of the “residuals of a fit”, i.e. what is left over when a “fit” is removed from a dataset.

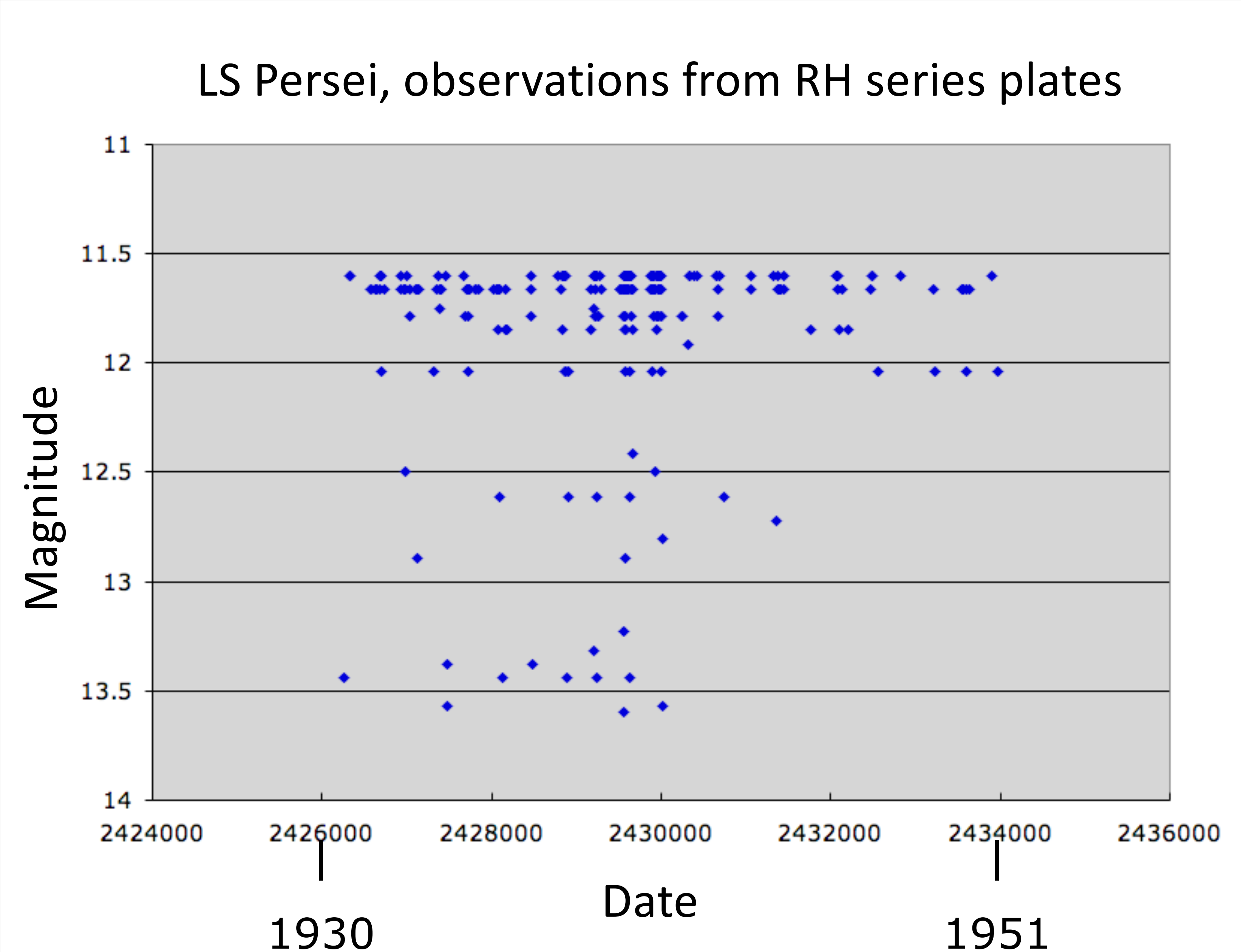
When used in the context of eclipse times, perhaps it would be better called an “eclipse timing diagram”, or an “eclipse time misfit plot”, etc. But the common usage is to call it an O-C diagram.

Data pre-requisites:

- You have observed times of the phenomenon you want to examine on the O-C diagram.
- So you have mastered and done:
  - Data acquisition (maybe an online database)
  - Accurate times of observations (mid-exposure)
  - Correction to HJD
  - Derivation of times of minimum or maximum
- You have a mathematical model (it may be very simple)

Basics of periodic phenomena:

A real data example: randomly timed observations over two decades.



Basics of periodic phenomena:

Based on the equation of a straight line:

$\boldsymbol{y} = \mathrm{m}\boldsymbol{x} + \mathrm{b}$

$\boldsymbol{T_E} = \mathrm{P}\boldsymbol{E} + \mathrm{T}_0$

$\boldsymbol{T_E} = \mathrm{T}_0 + \mathrm{P} \times \boldsymbol{E}$

Index (cycle) number of event

Period

Time of event 0, the <u>“epoch”</u>

Time of event E

Basics of periodic phenomena:

- O-C is done after a (pretty) good period estimate has been made.
- Must determine the cycle number (E):

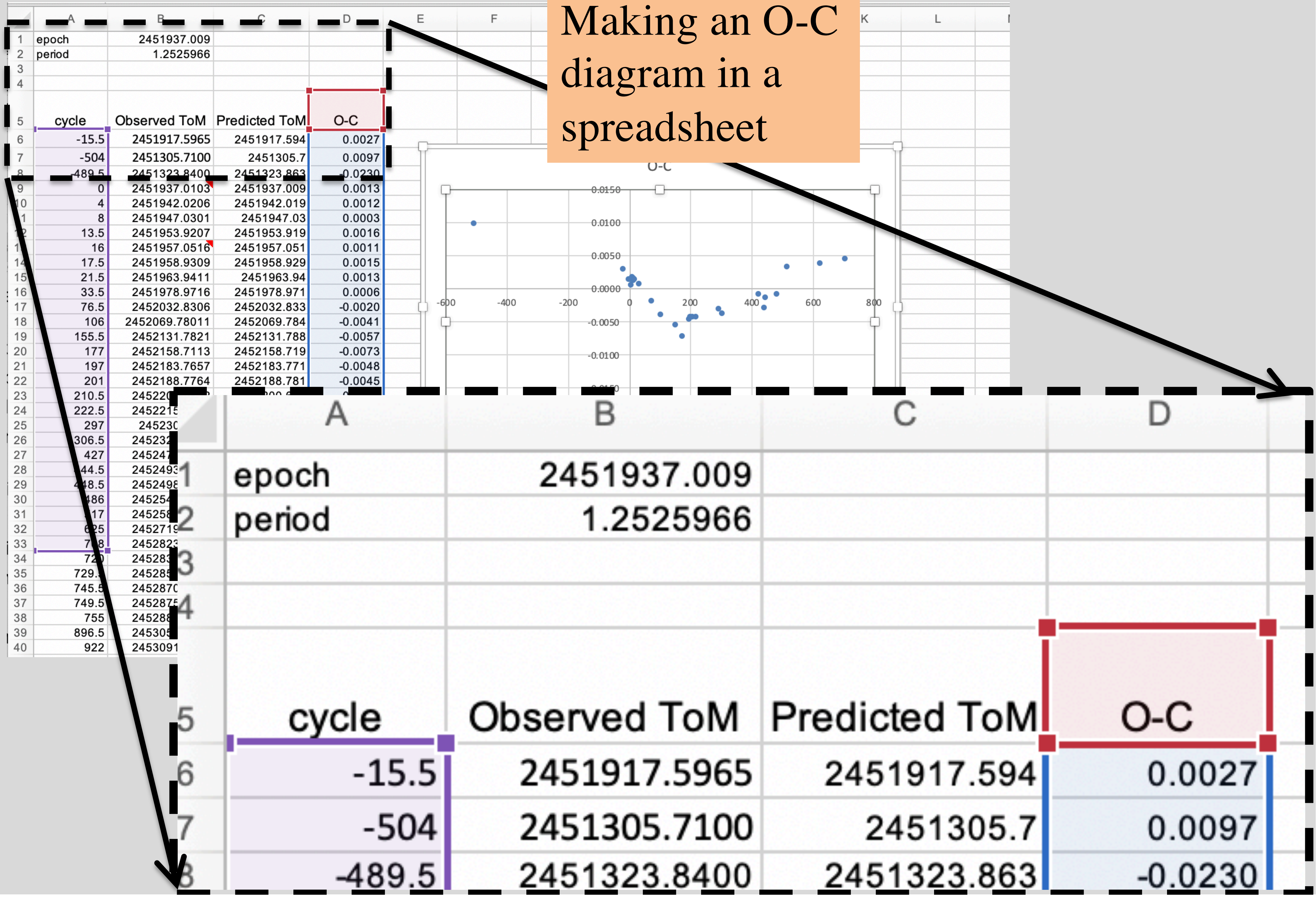
  $\mathbf{T_E} = T_0 + P \times \mathbf{E}$

  $\mathbf{E = (\ T_E\ -}\ T_0\ )\ /\ P$

- E is usually used as a whole number, so must be rounded
  - Can be a bit tricky if T_E-T_0 is large (say, > P/2)
  - Well suited to a simple spreadsheet

Basics of periodic phenomena - spreadsheet:

Making an O-C diagram in a spreadsheet



Basics of periodic phenomena:

The "elements"

- A real example (LS Persei):

$$T_E = T_0 + P \times E$$

(Heliocentric) Julian date of the eclipse that started cycle 0

Length of each cycle – the "period"

- Filling in the numbers, LS Per's eclipses are predicted by the equation:

Cycle number

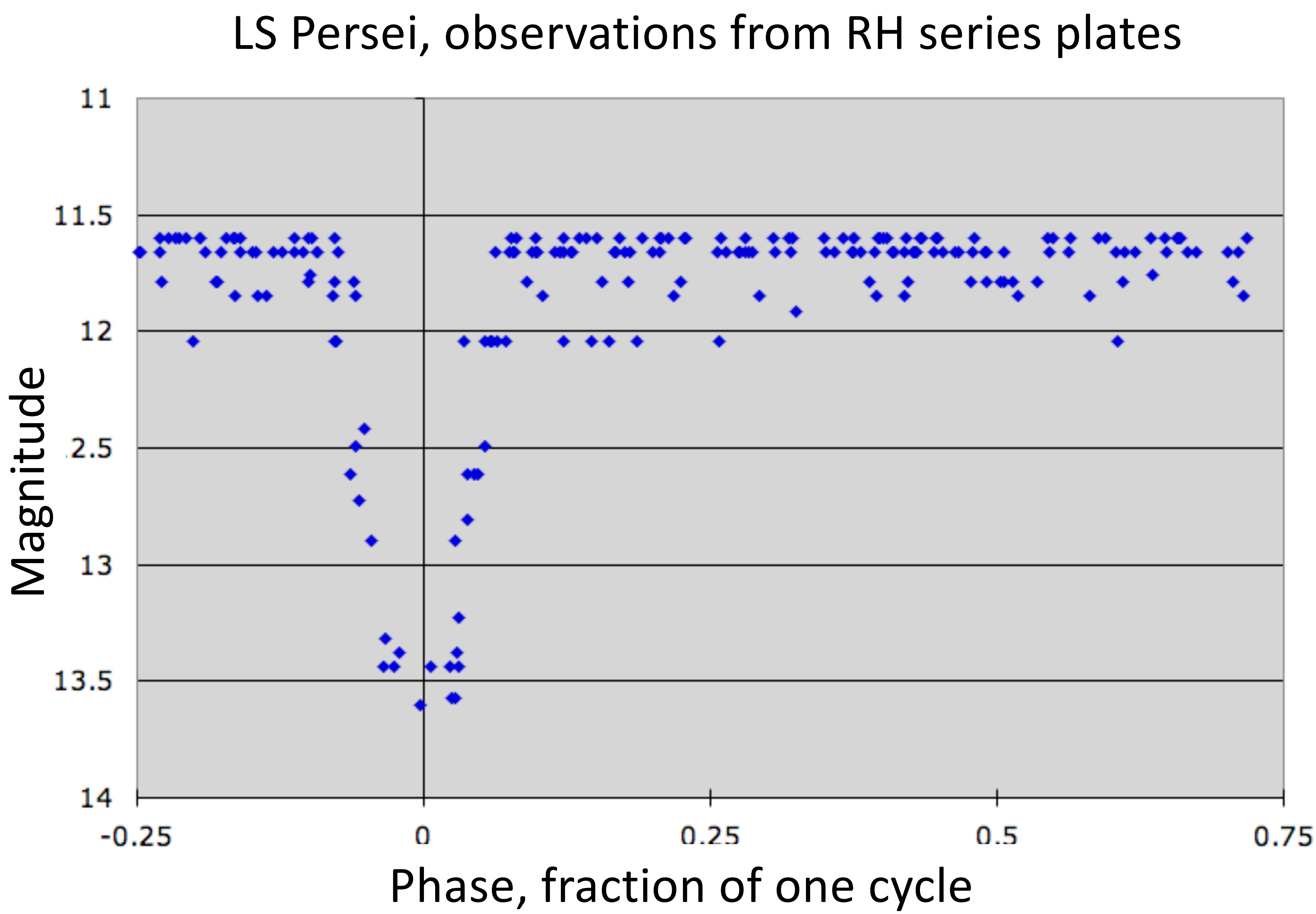
$$T = 243\,9395.52 + 2.915\,693 \times E$$

- This equation predicts the start time of each cycle (for EBs, the middle of the deepest eclipse)

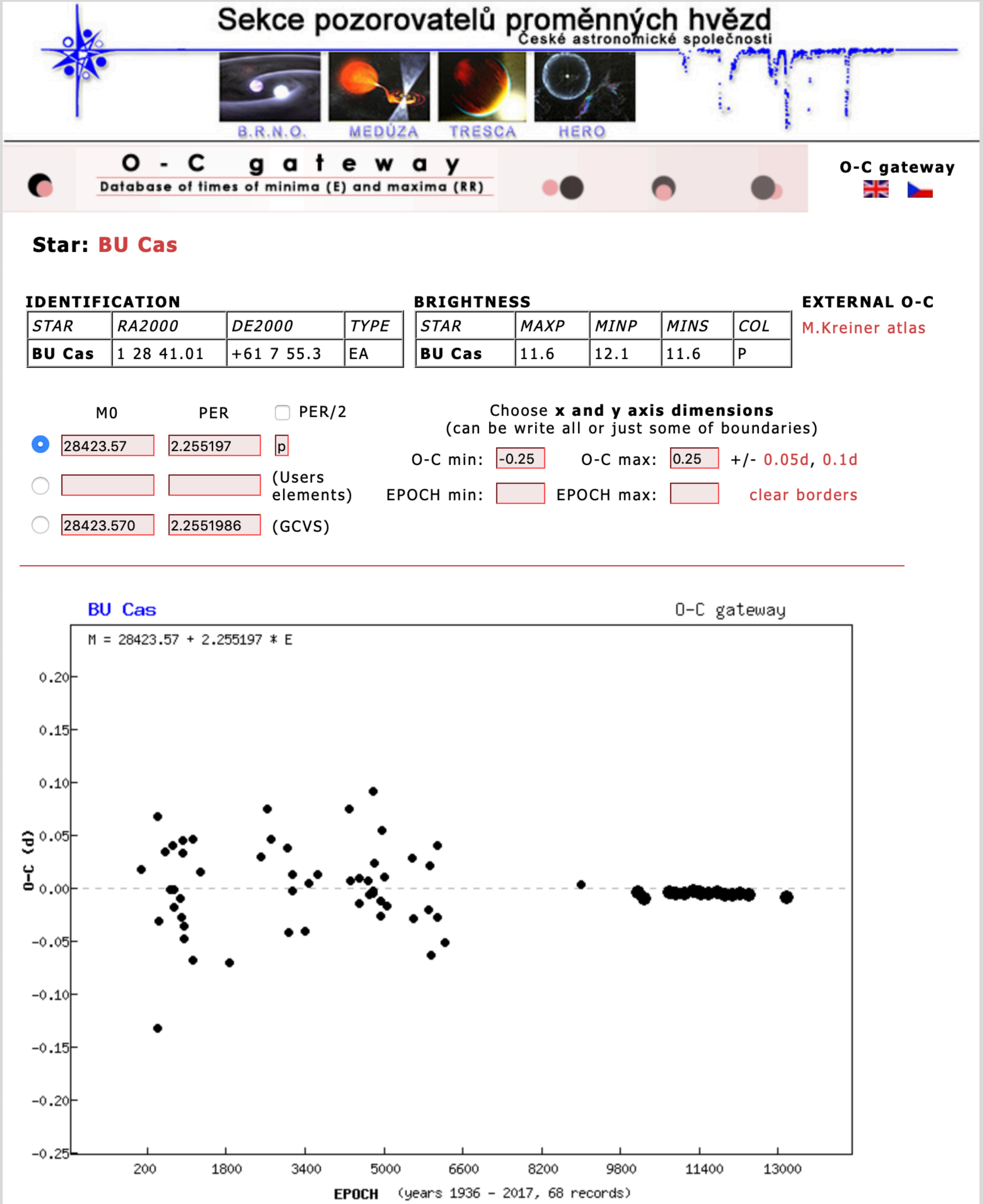
- To make a phased light curve so you can readily compute where, within a cycle, an observation occurred... then plot observations from many cycles as if they were all observed within one cycle.

Basics of periodic phenomena – phased LC:

Two decades of observations folded in to one cycle:

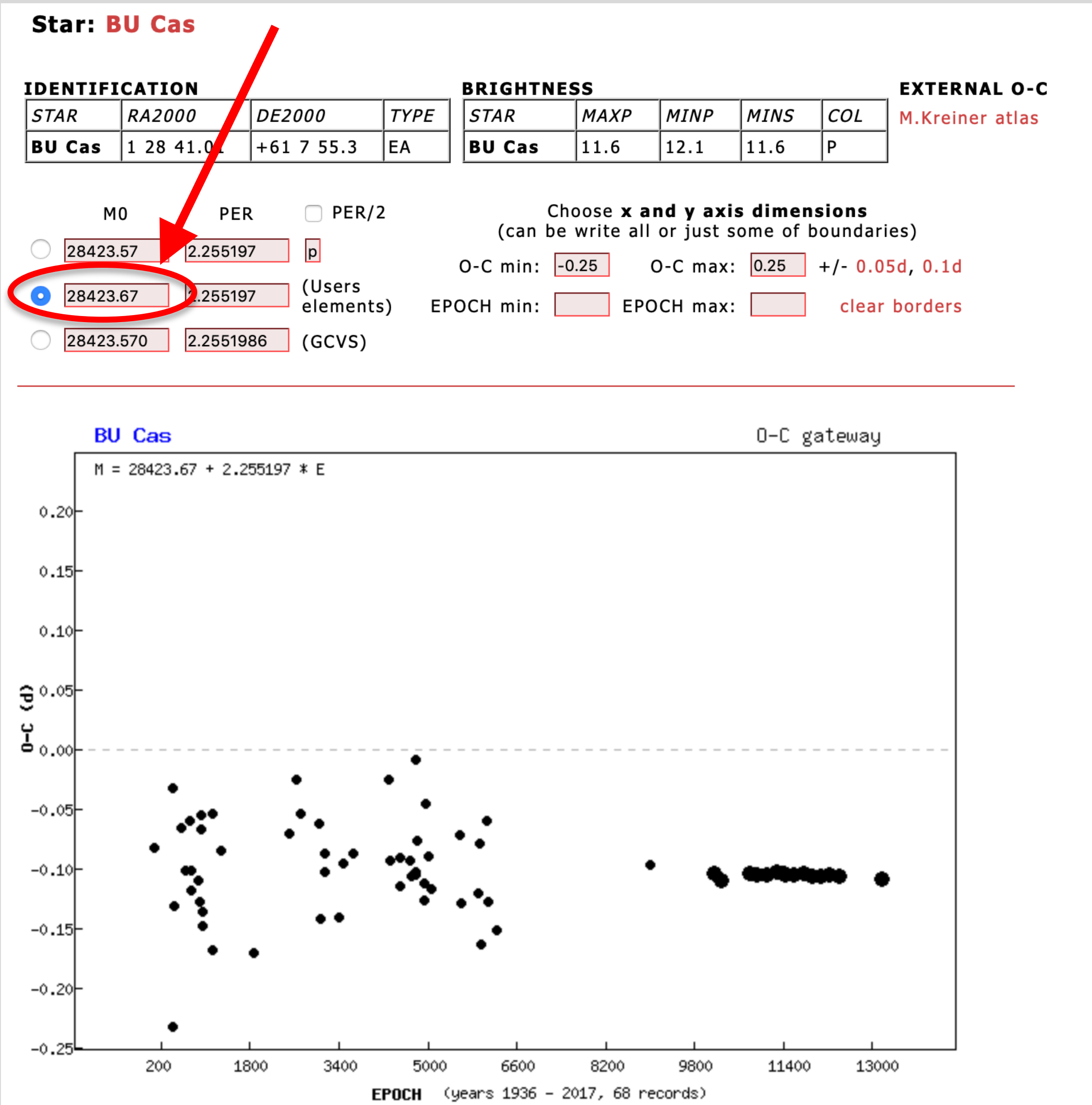


O-C Zoo – with correct elements:



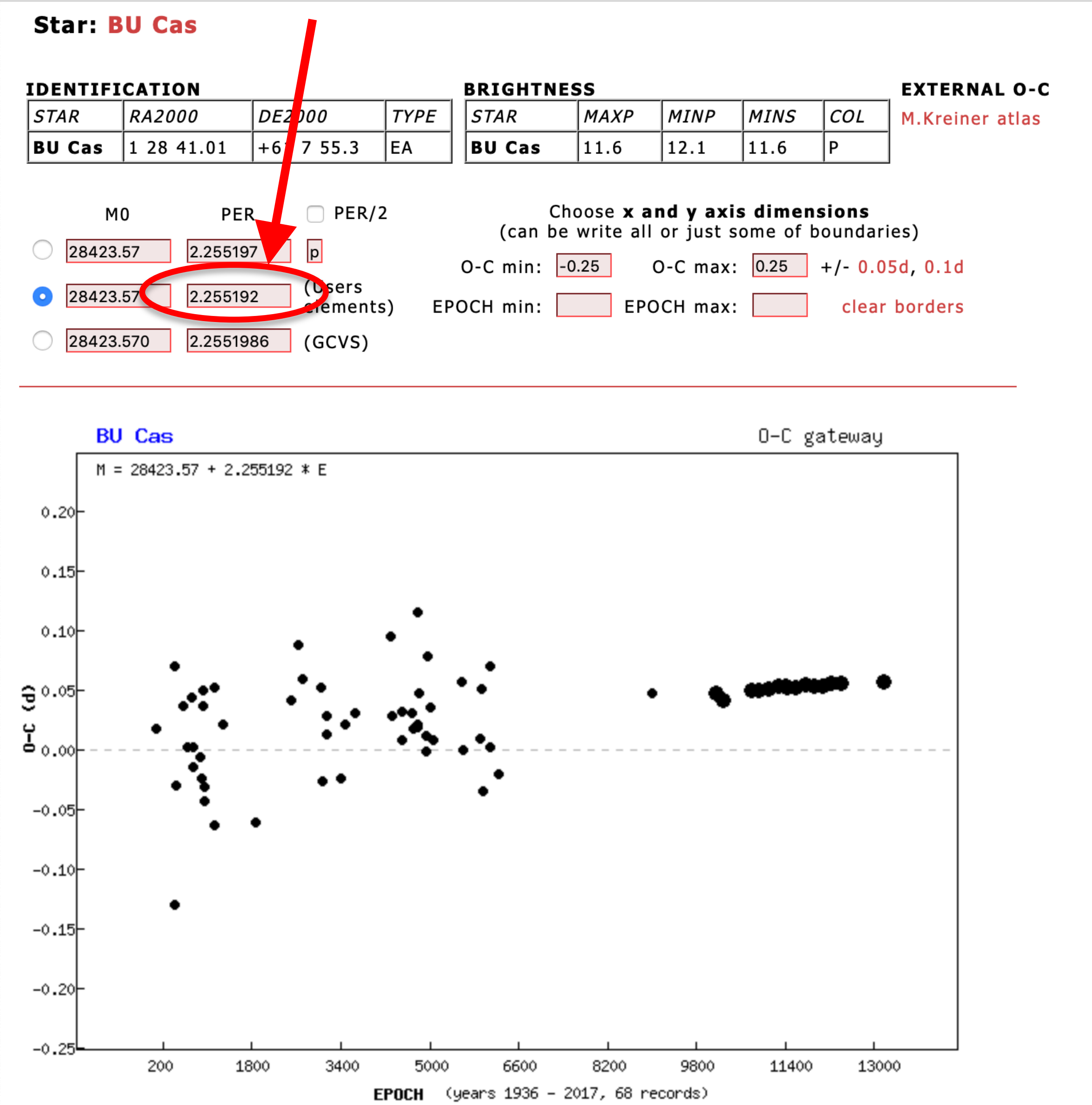
- Using online data and plotter
- A long-known eclipsing binary star with constant period
- Early data is probably from randomly-timed photographic plates
- The O-C is made with pretty good elements (epoch, period)
- So, data will lay horizontally on the line O-C = zero

O-C Zoo – with wrong epoch:



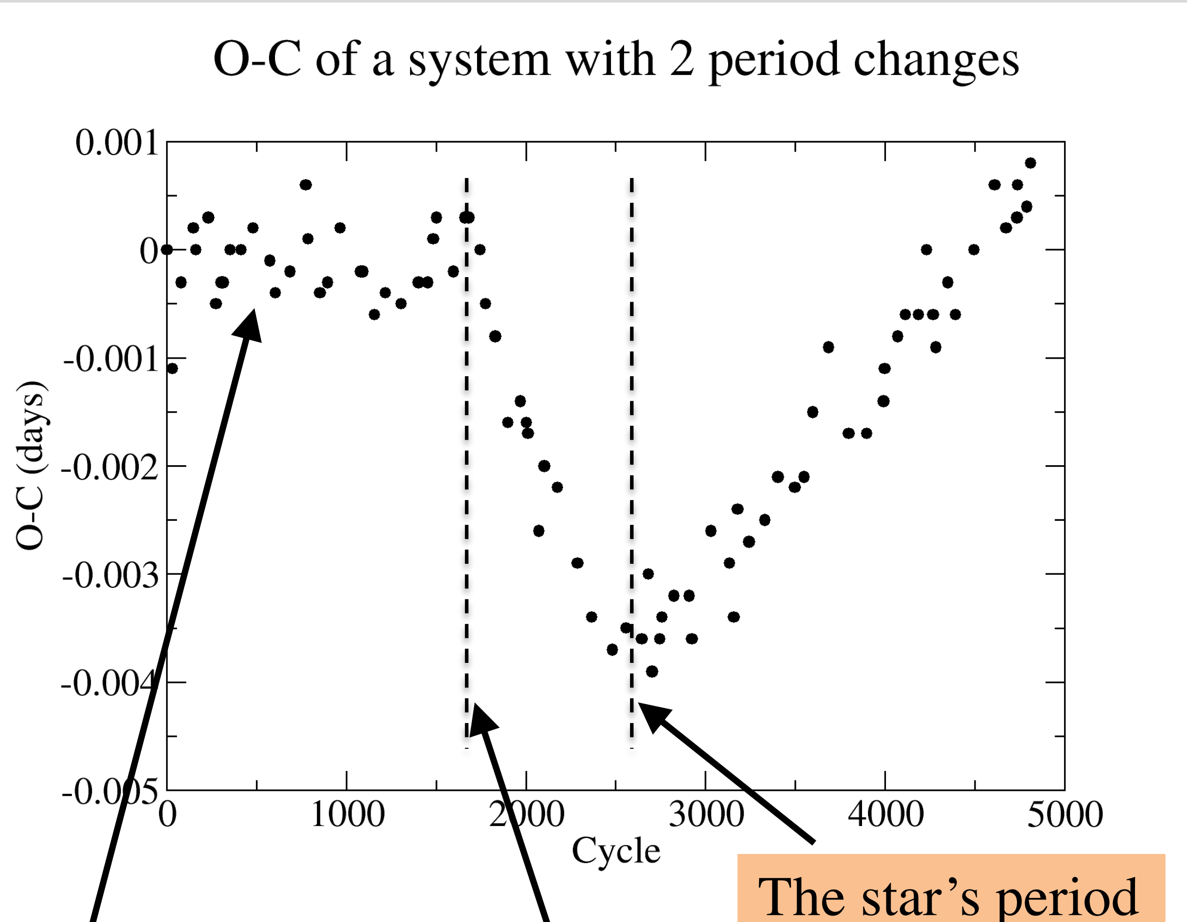
- Constant period star
- O-C made using correct period, <u>but the epoch is 0.1 d late</u>
- All observations line up along O-C = -0.1
- I.e. obs'ns are 0.1 day early to prediction

O-C Zoo – with wrong period:



- Constant period star
- O-C made using correct epoch, but the <u>period 0.000 005 d (0.43 sec) too short.</u>
- The obs'ns lay along a sloping straight line
- By 2017, observations are coming in >1 hour later than predicted.
- Effects are cumulative – kind of like "compound interest"

O-C Zoo – episodic period changes:



The O-C uses the star's initial period (3.14 days)

The star's period decreases by 0.000 005 days

The star's period increases by 0.000 007 days

- Data will lie on connected straight line segments
- Physical causes:
  - Roche lobe overflow as a star evolves, it transfers mass to its companion
  - Alternately, or simultaneously, mass may be lost from the binary system
  - Changes to the masses of the stars change the orbital period

O-C Zoo – continuous, uniform, period change:

Continuous period increase gives a parabolic concave-upwards O-C shape.

Star: WW Cyg

IDENTIFICATION

STAR	RA2000	DE2000	TYPE
WW Cyg	20 4 2.71	+41 35 16.5	EA

BRIGHTNESS

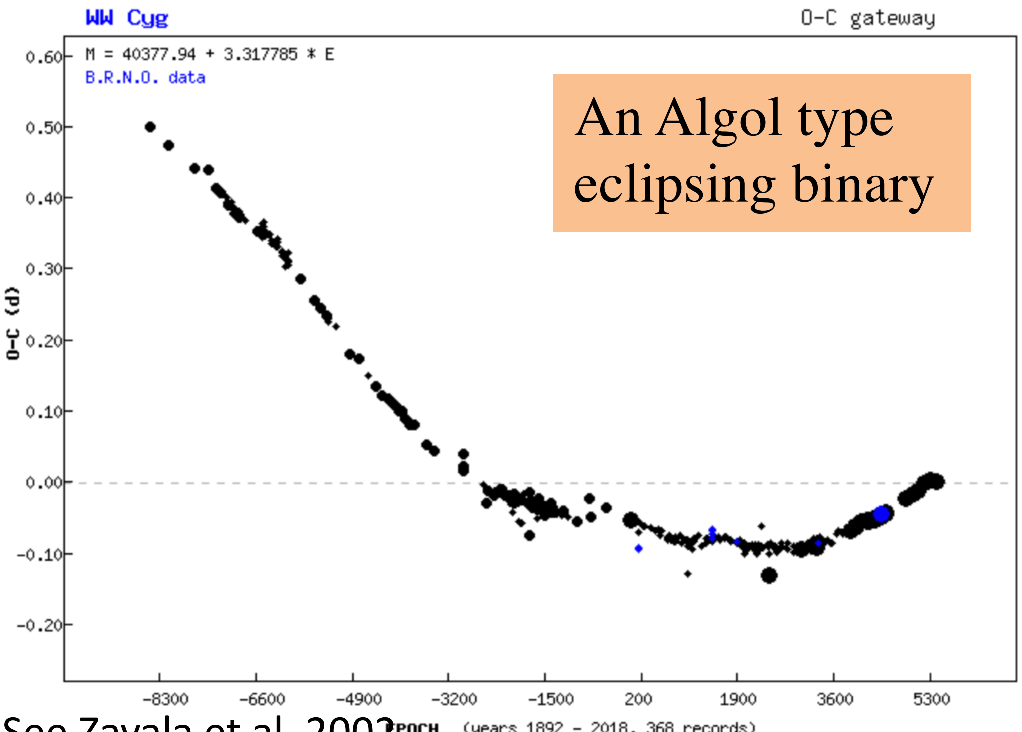
STAR	MAXP	MINP	MINS	COL
WW Cyg	10.02	13.26	10.16	V

EXTERNAL O-C
M.Kreiner atlas

	M0	PER	PER/2
(•)	40377.94	3.317785	p
( )			(Users elements)
( )	40377.886	3.3177690	(GCVS)

Choose **x and y axis dimensions**
(can be write all or just some of boundaries)

O-C min: O-C max: +/- 0.05d, 0.1d
EPOCH min: EPOCH max: clear borders



An Algol type eclipsing binary

See Zavala et al. 2002

A beta Cephei pulsating variable

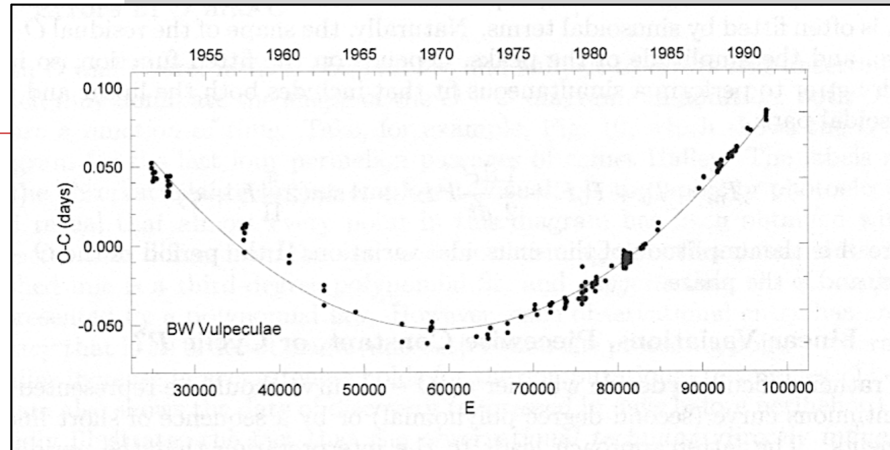


Figure 7. $O - C$ diagram for some $T_{\min}$ of BW Vul with best-fit parabola.

Sterken, 2005, p 7.

Continuous period decrease would give concave downward shape

O-C Zoo – Light time effect:

- Imagine a constant period EB orbiting a 3rd body:
  - The eclipses will alternately come early and late, as the eclipsing pair is alternately nearer and further from us.
  - Variously called the Light Time Effect (LTE), Light Travel Time Effect (LTTE), LiTE
- Historically "over - diagnosed" when a cyclic variation was claimed, but with inadequate observing history.

O-C Zoo – LTE examples:

Fits must make astrophysical sense, e.g.:

- 3rd body orbit fitted using Irwin's (1952, 1959) equations, with reasonable mass of 3rd body
- 3rd body implies 3rd light, does that fit light curve modelling?

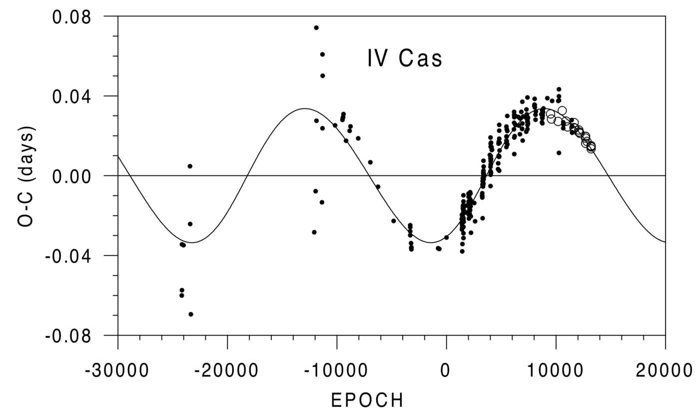
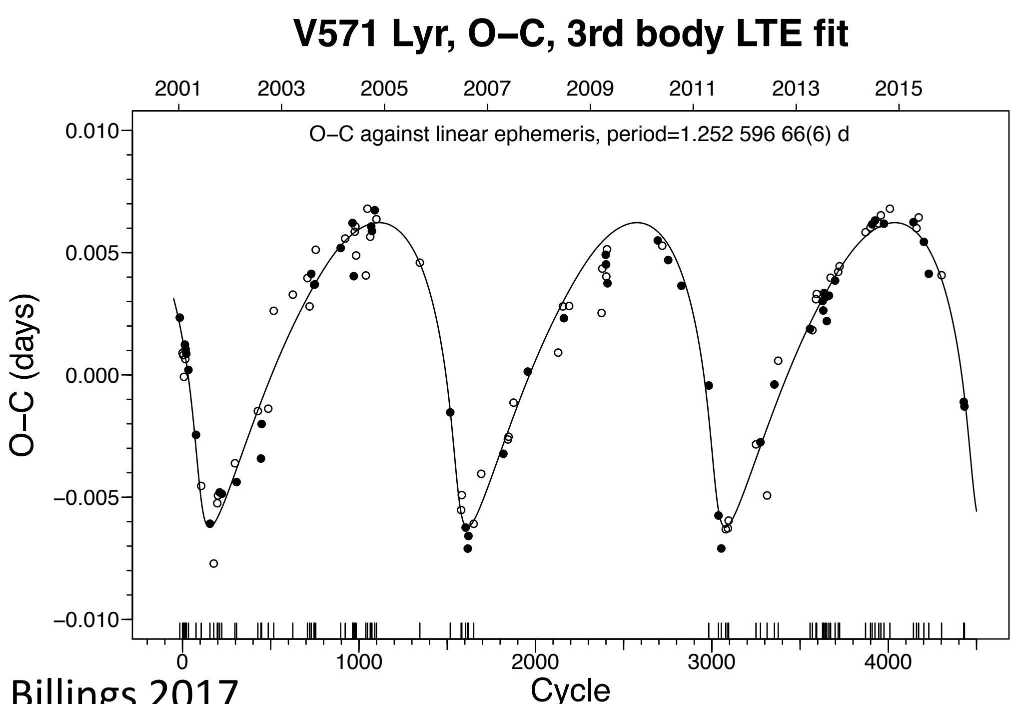


Figure 2. $O - C$ diagram for IV Cas. The numerous visual and photographic times are denoted by dots, the photoelectric and CCD times by circles. The sinusoidal curve corresponds to the third body orbit with a period of about 60 years and a semi-amplitude about 48 minutes

Wolf et al. 2006, IBVS 5735

Nearly circular orbit

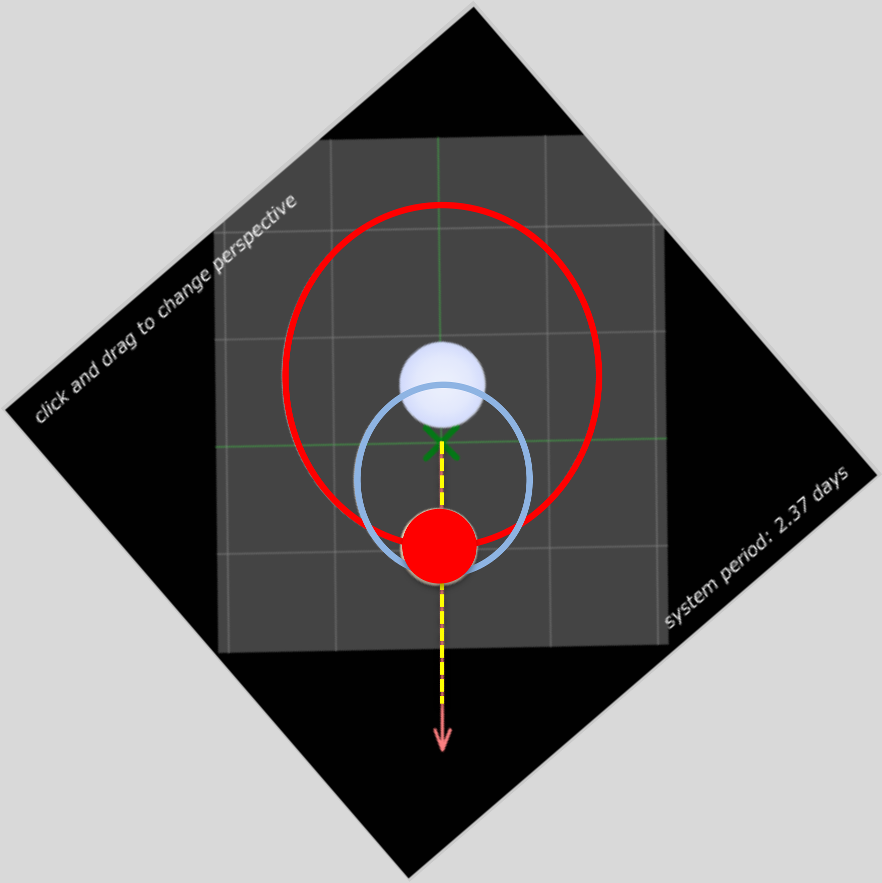


Billings 2017

The line fits an eccentric 3rd body orbit to the O-C

See Frieboes-Conde & Herczeg (1973), Irwin (1952, 1959), Lacy (1992), Mayer (1990).

O-C Zoo – Apsidal rotation:



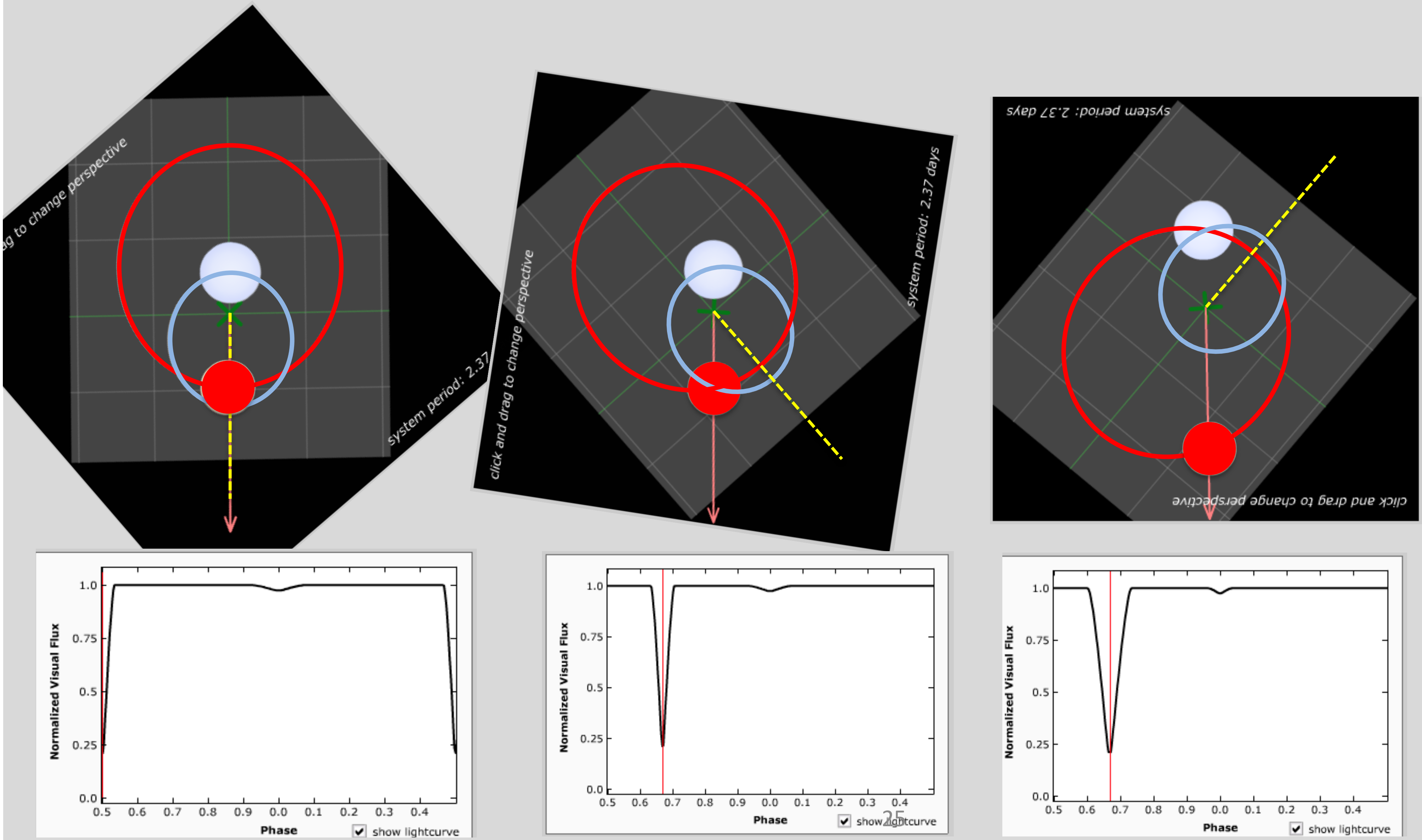
The eclipse observer is towards the bottom of the page.

The viewer of the slide is above the system.

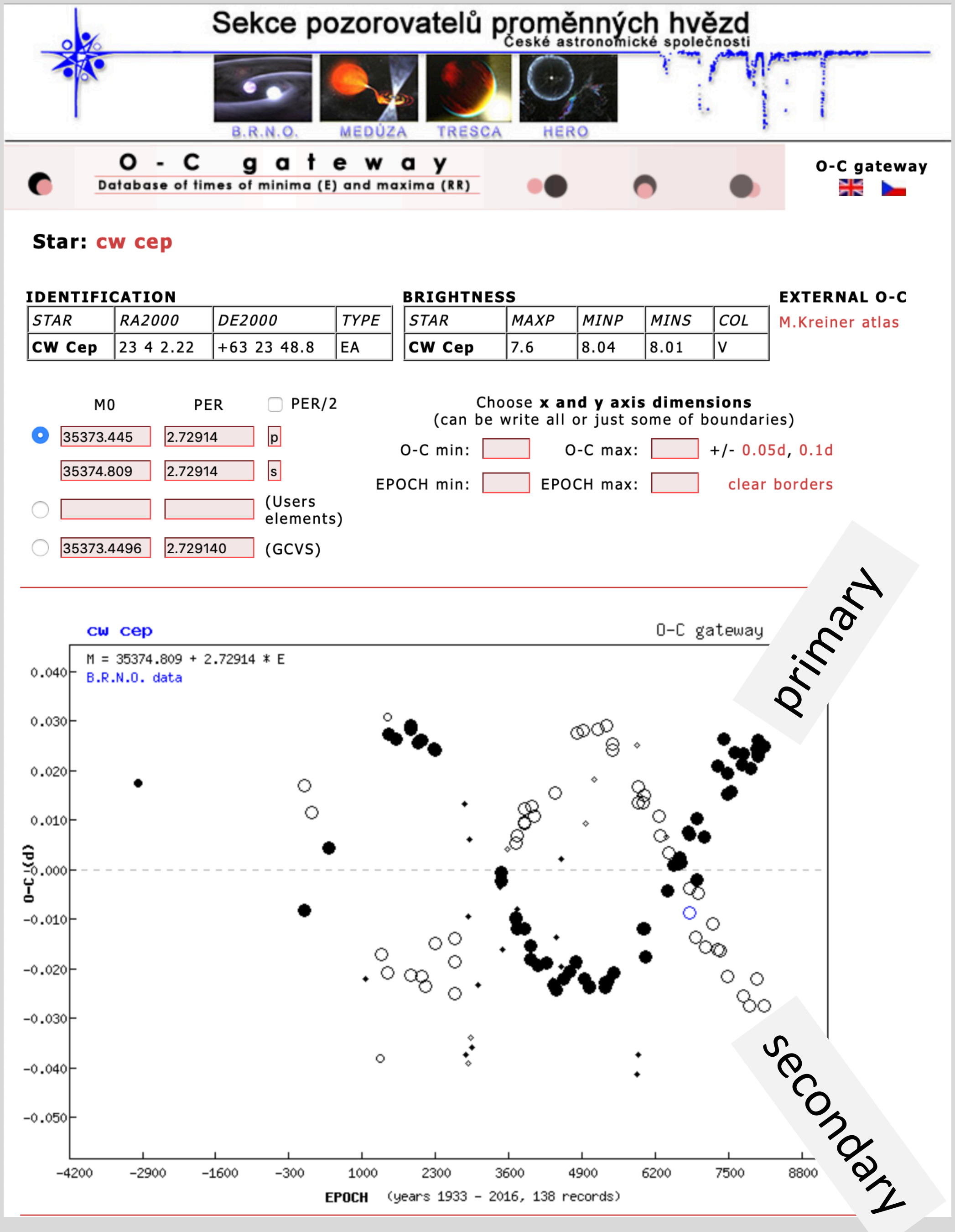
- An eccentric binary (elliptical orbits)
- The semi-major axes of the ellipses can rotate (precess)
- As the orbits precess:
  - The spacing of primary and secondary eclipses will vary.
  - Eclipse widths also vary.

O-C Zoo – Apsidal rotation:

As the orbits rotate… the lightcurve changes dramatically, and eclipse times oscillate

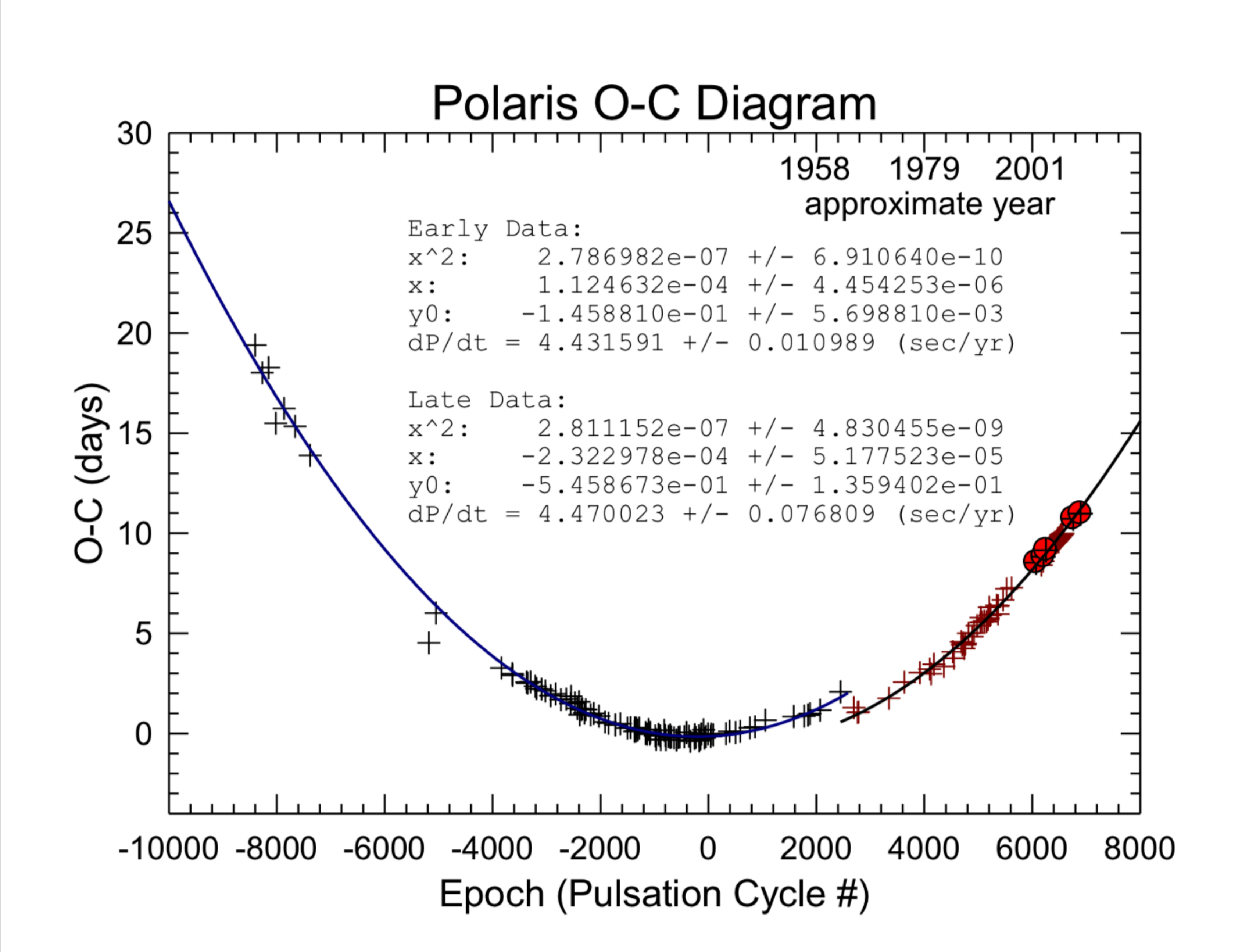


O-C Zoo – Apsidal rotation on the O-C diagram:



- Movement of primary and secondary eclipses are of opposite "polarity"
- Each is quasi-sinusoidal, and not quite mirror images of each other
- Caution: if you only have primary eclipse data, it looks like a 3rd body / LTE system

O-C Zoo – Polaris' "glitch":



Engle, 2015, p 57.

O-C Zoo – some items not discussed:

- Real cases often show multiple phenomena
- Applegate mechanism: a frequently invoked magnetic/convection cycle phenomenon in one star, that can drive periodic orbital period change
- Random period variations are cumulative and can mimic systematic period changes
- Physical sanity checks, e.g.:
  - A “sudden” period change may be explained by a mass transfer: is that reasonable for the type of star. Is the amount/rate reasonable?
  - For 3rd body LTE: is the required mass reasonable? How about its 3rd light?
  - Spectroscopy for radial velocities, confirmation of multiple stars, etc.

Resources:

General information:

- Sterken, C., (editor) (2005). "The light-time effect in astrophysics. Causes and cures of the O-C diagram". ASP Conference Proceedings Volume 335. The first chapter (by Sterken) is a good overview, and is available via ADS as 2005ASPC..335....3S There are many other useful papers in this volume.
- Budding, Edwin, and Osman Demircan (2007). "Introduction to astronomical photometry". Cambridge Univ. Press. This book is much broader than its title suggests. Chapter 8 (28 pages) is titled "Period changes in variable stars" and discusses the phenomena described in this presentation, in more depth. It also includes lists of stars that exhibit these phenomena, and a useful annotated bibliography.
- BRNO O-C Gateway: http://var2.astro.cz/ocgate/?lang=en. Access to an online database of EB ToMs, and plotting an O-C with parameters the user can control. Can also add your own datapoints to the plot, or download their data for plotting yourself. Includes more stars than the Lichtenknecker Database.
- Other online O-C resources:
  - Bob Nelson has compiled ToM data for thousands of EBs and makes it available as spreadsheets for each star, along with plotting and observation planning capability: https://www.aavso.org/bob-nelsons-o-c-files
  - "The Cracow Database" http://www.as.up.krakow.pl/ephem/ Predictions of upcoming eclipses (when the orbits are well enough known; for planning observations), and O-C diagrams for thousands of EBs.

Technical material for modelling complex cases:

- Lacy, C.H.S. (1992), AJ 104(6):221. For modelling systems with apsidal motion
- Irwin, J.B. (1952). ApJ 116:211-217. For computing 3rd body orbits.
- Mayer, P. (1990). Bull. Astron. Inss. Czechosl. 41:231-236. Re computing the mass function using O-C quantities (versus radial velocity data).
- Zavala, R.T. et al. (2002). AJ 123(Jan 2002): 450-457. Regarding multiple effects in the O-C diagram for WW Cyg. A gateway paper to considering the Applegate mechanism of cyclic variations.
- Frieboes-Conde, H., and T. Herczeg (1973). Astron. Astrophys. Suppl. 12:1-78. Re screening criteria for detecting LTE systems.

A few stars with interesting O-C diagrams:

- Algol, beta Per – for its historical interest. Multiple effects.
- CL Aur: 3rd body LTE and long term period increase due to mass transfer.
- SZ Cam: 2.7 d EB, with 51 yr 3rd body LTE (eccentric orbit)
- DR Vul: apsidal motion.

Summary:

- Simple concept, but powerful.
- Used to look for systematic phenomena that are not properly modelled.
- Certain patterns have physical meaning, suggesting what physics needs to be added to your model, or that parameters need adjusting.
- Also useful for observation planning.

Acknowledgment:

This session wouldn’t be taking place but for the vision of Ken Menzies. He suggested this topic, and his feedback *greatly* improved my paper.