TTV analysis of system λ Tauri

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λ Tauri: Parameters

- compact triple system (Tokovinin, 2021)
- constellation Taurus
- $d = 148\,\mathrm{pc}$ (Gaia DR3, 2020)
  $e_1 = 0.025$ (Fekel & Tomkin, 1982)
  $e_2 = 0.016$ (Fekel & Tomkin, 1982)

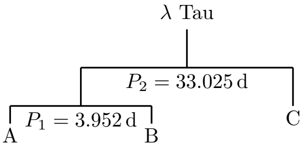


Figure: Hierarchy of system.

Table: Stellar parameters of inner orbit (Fekel & Tomkin, 1982).

star	Sp. type	M ($M_\odot$)	R ($R_\odot$)
A	B3V	7.18 ± 0.09	6.40
B	mid-A	1.89 ± 0.04	5.30
C	G – K	0.7	?

λ Tauri: Context

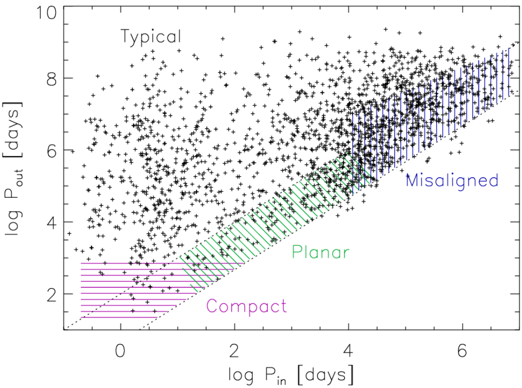


Figure: Periods of inner and outer orbit of hierarchical systems for distance $d < 200\,\mathrm{pc}$. (Tokovinin, 2021).

Measurements

TESS (Transiting Exoplanet Survey Satellite):

- NASA's all-sky space telescope (2018)
- 4 CCD cameras, each having 16 megapixels
- CCDs are wide passband (R to I)
- together covering area of $24^\circ \times 96^\circ$
- each sector is covered for around 27 days

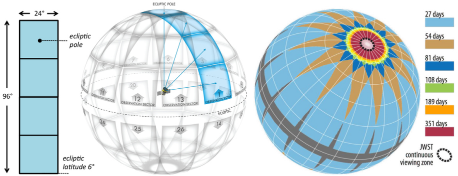


Figure: Sector coverage of TESS with their overlap.

Source: `https://www.eoportal.org/satellite-missions/tess`

Data and Fitting Eclipses

Data:

- 7 sectors with exposure times from 3 to 24 minutes
- 78 eclipses total (40 primary and 38 secondary)
- $\mathcal{F} \sim 5.5 \cdot 10^6\,\mathrm{e^{-}} \cdot \mathrm{s}^{-1}$, $\sigma_{\mathcal{F}} \sim 10^2\,\mathrm{e^{-}} \cdot \mathrm{s}^{-1}$

Mathematical model:

- constructed model with 8 free parameters: A, μ, σ, C_1, B, γ, C_2, d

$$f(t) = \begin{cases} A \cdot \exp\left(-\dfrac{(t-\mu)^2}{2\sigma^2}\right) + C_1 & \text{for } t < d \\ B \cdot \dfrac{\gamma^2}{\gamma^2 + (t-\mu)^2} + C_2 & \text{for } t \geq d \end{cases}$$

MCMC method:

- estimating parameters, their uncertainities and correlations between parameters using Bayes statistics

Fitting Eclipses

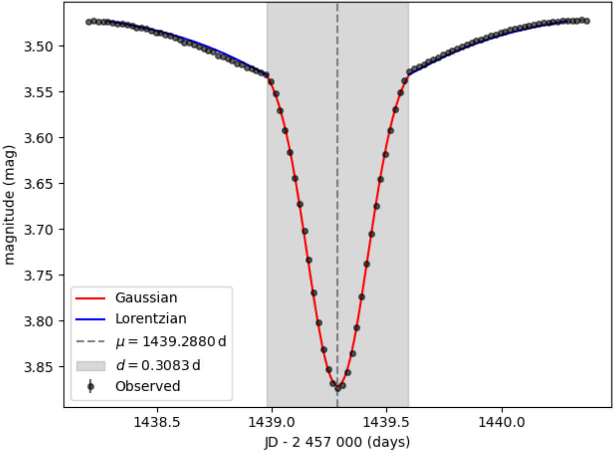


Figure: Example of fitted eclipse.

Physical Model

Software Xitau for constructing physical N-body model (Brož, 2017; Brož et al., 2021, 2022; Nemravova, 2016)

- Xitau evaluates positions and velocities of bodies using numeric integration of motion equations by Bulirsch–Stoer method

$$m_i \frac{\mathrm{d}^2 r_i}{\mathrm{d}t^2} = \sum_{\substack{j=1 \\ i \neq j}}^{N} \frac{G m_i m_j}{|r_j - r_i|^3}(r_j - r_i),$$

- Xitau generates synthetic data and compares them with observation using method χ^2

$$\chi^2 = \chi^2_{\mathrm{ETV}} + \chi^2_{\mathrm{TTV}} + \ \dots \qquad \chi^2 = \sum_{k=1}^{n} \frac{(O_j - C_j)^2}{\sigma^2_{O_j}}$$

Simplified 2-body Model

- 6 free parameters – orbital elements (P, $\log e$, i, Ω, ϖ, λ)
- obtained values:

$$P_{\text{in}} = 3.9527\,\text{d} \qquad \log e_{\text{in}} = -3.51 \qquad i_{\text{in}} = 63.69$$

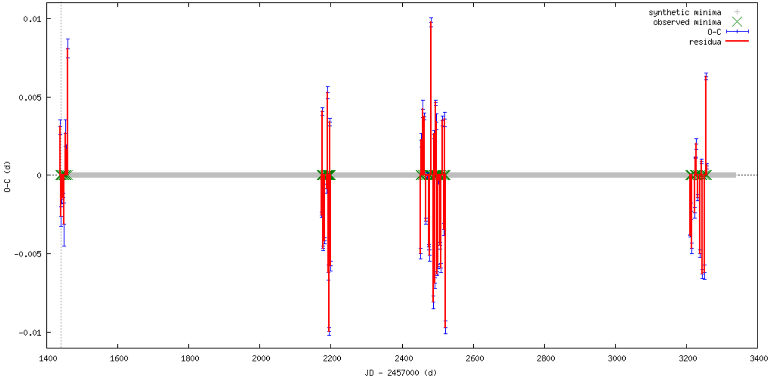
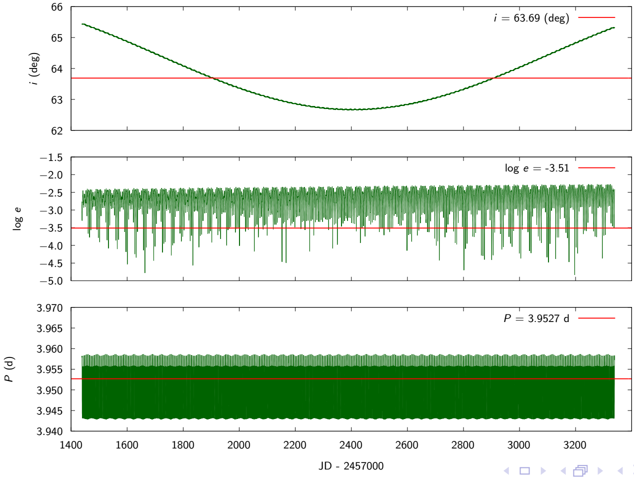


Figure: O–C diagram for simplified 2-body model.

3-body Model

- preliminary model
- 12 free parameters - 2 pairs of orbital elements



Inner Orbit

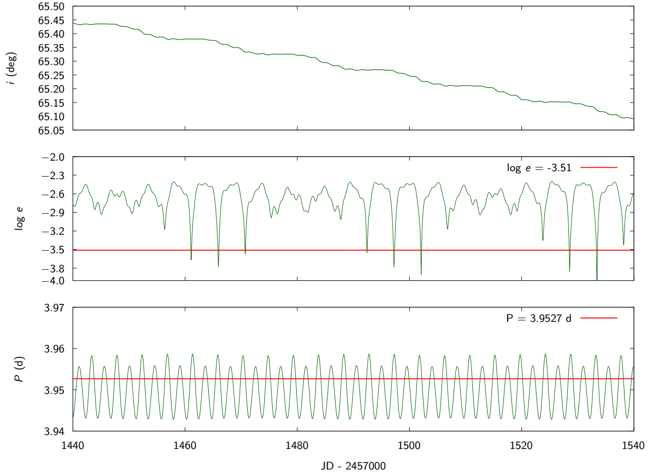


Figure: Short time evolution of i, $\log e$ and P for inner orbit.

Inner Orbit

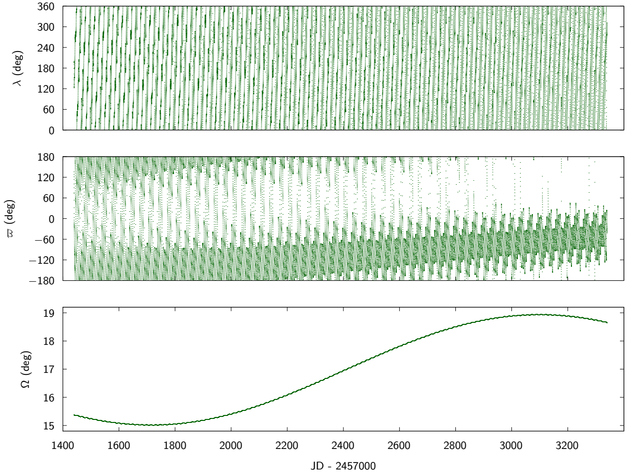
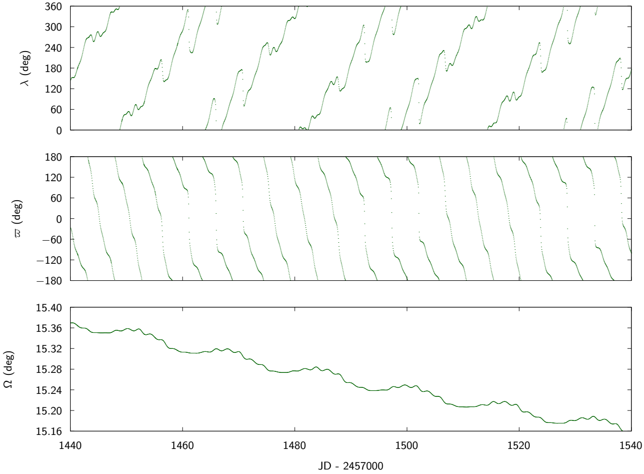


Figure: Long time evolution of λ, ϖ and Ω for inner orbit.

Inner Orbit



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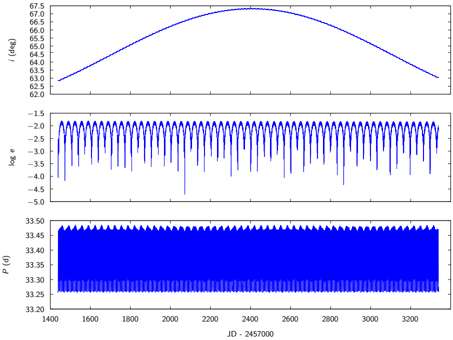
Outer Orbit



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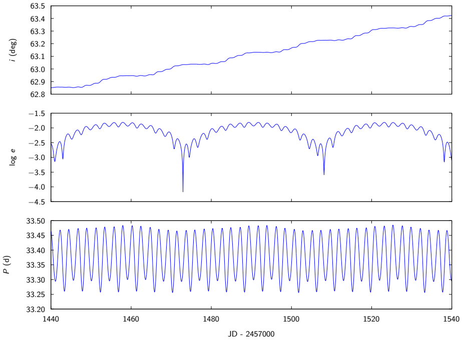

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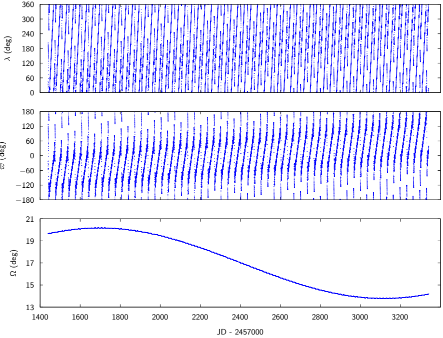

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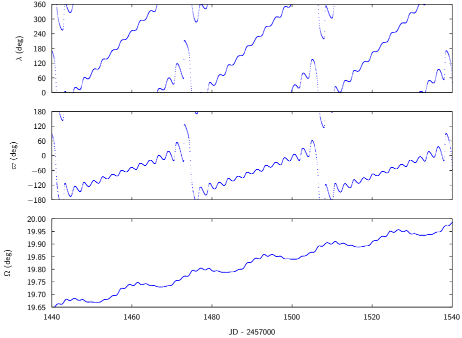

Figure: Short time evolution of λ, ϖ and Ω for outer orbit.