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Precession of the orbital planes and rotational axes in transiting exoplanets

Conference of Young Astronomers in Bezovec
16.06.2023

NAME: DMYTRO ORIKHOVSKYI

SUPERVISOR: RNDR. THEODOR PRIBULLA, CSC.

Outline

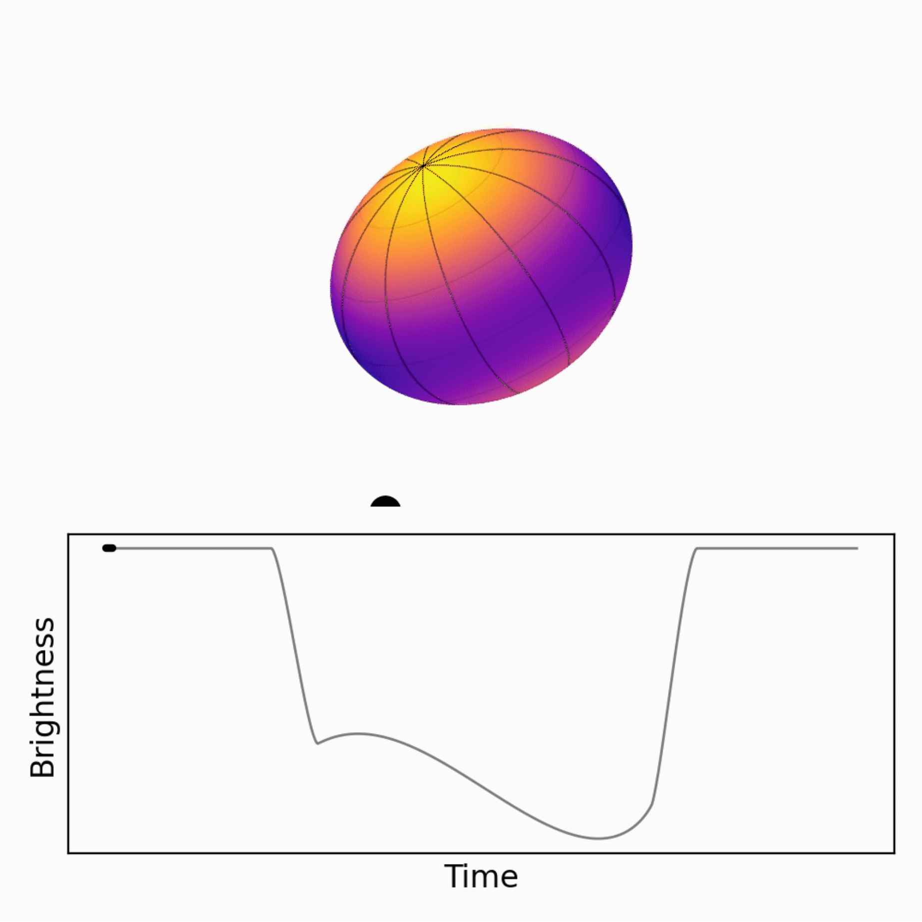
- Goals
- Objects of research
- Methodology
- Results and conclusions

Goals

- To search for exoplanets with spin axis-orbital plane misalignment.
- To quantify asymmetry values for exoplanetary light curves and to detect those which show transit duration variations (TDV) due to the orbital plane precession.

Rapidly rotating parent stars

- Early-type stars from O to mid-F
- ~30 hosts with T_{eff} > 7000 K showing transits
- Systems with hot parent stars show isotropic orientations of rotational axes with respect to the exoplanet orbits, late-type stars are typically aligned
- Fast rotation produces gravitation darkening



Credits: Shashank Dholakia

Data processing

1st sample:

Stellar temperature > 7000 K

TESS magnitude - < 12^m

Transit depth - 5 mmag

Sample size: 84 stars (20 excluded)

6 transits considered asymmetric out of 64

2nd sample

Stellar temperature > 5500 K

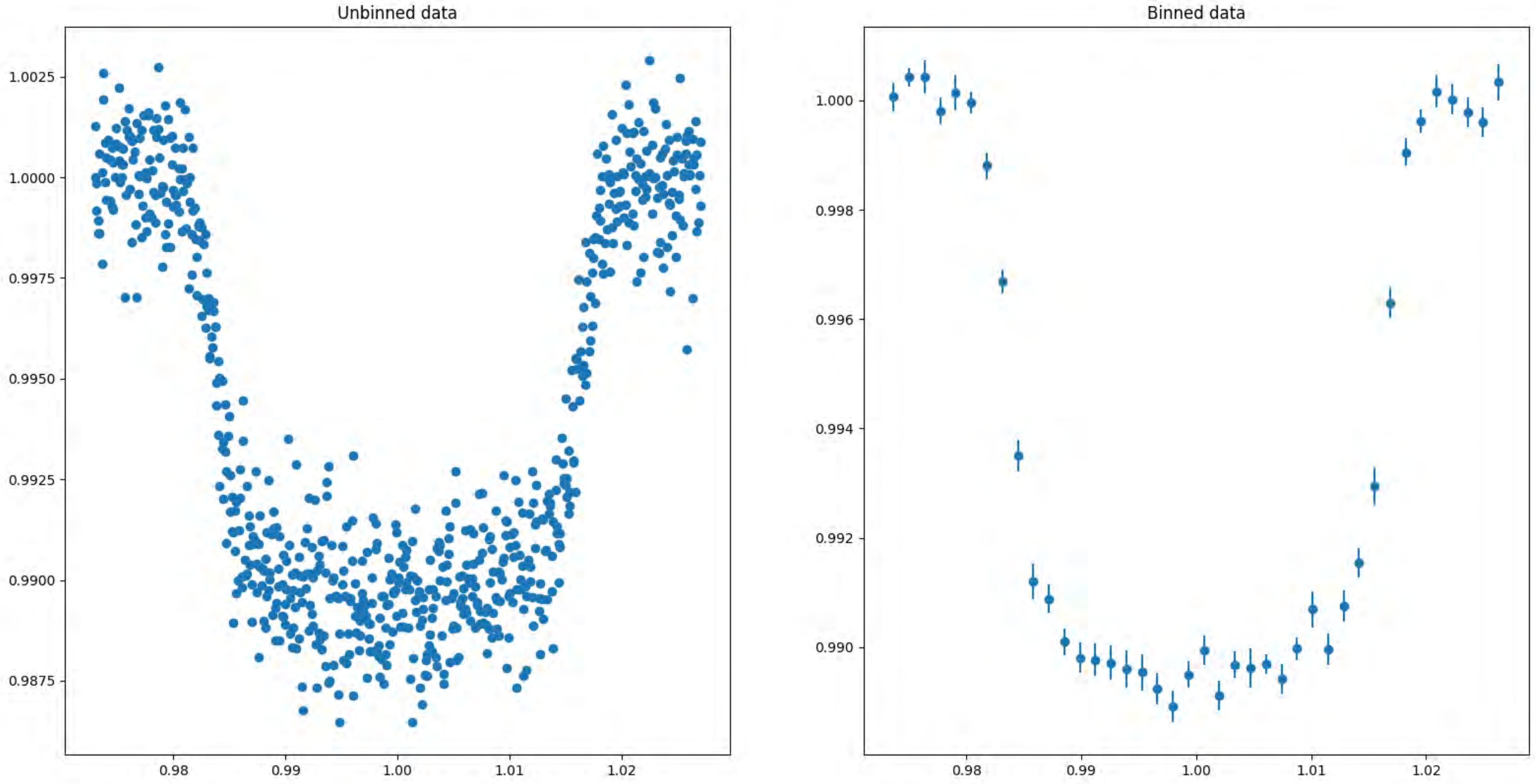
TESS magnitude - < 12.5^m

Transit depth - 3 mmag

Sample size: 96 stars (29 excluded)

1 object close to being asymmetric out of 67 (probably because of spots)

Example light curve



Asymmetry evaluation

1. Divide the phase light curve into even number of bins
2. Asymmetry parameter:

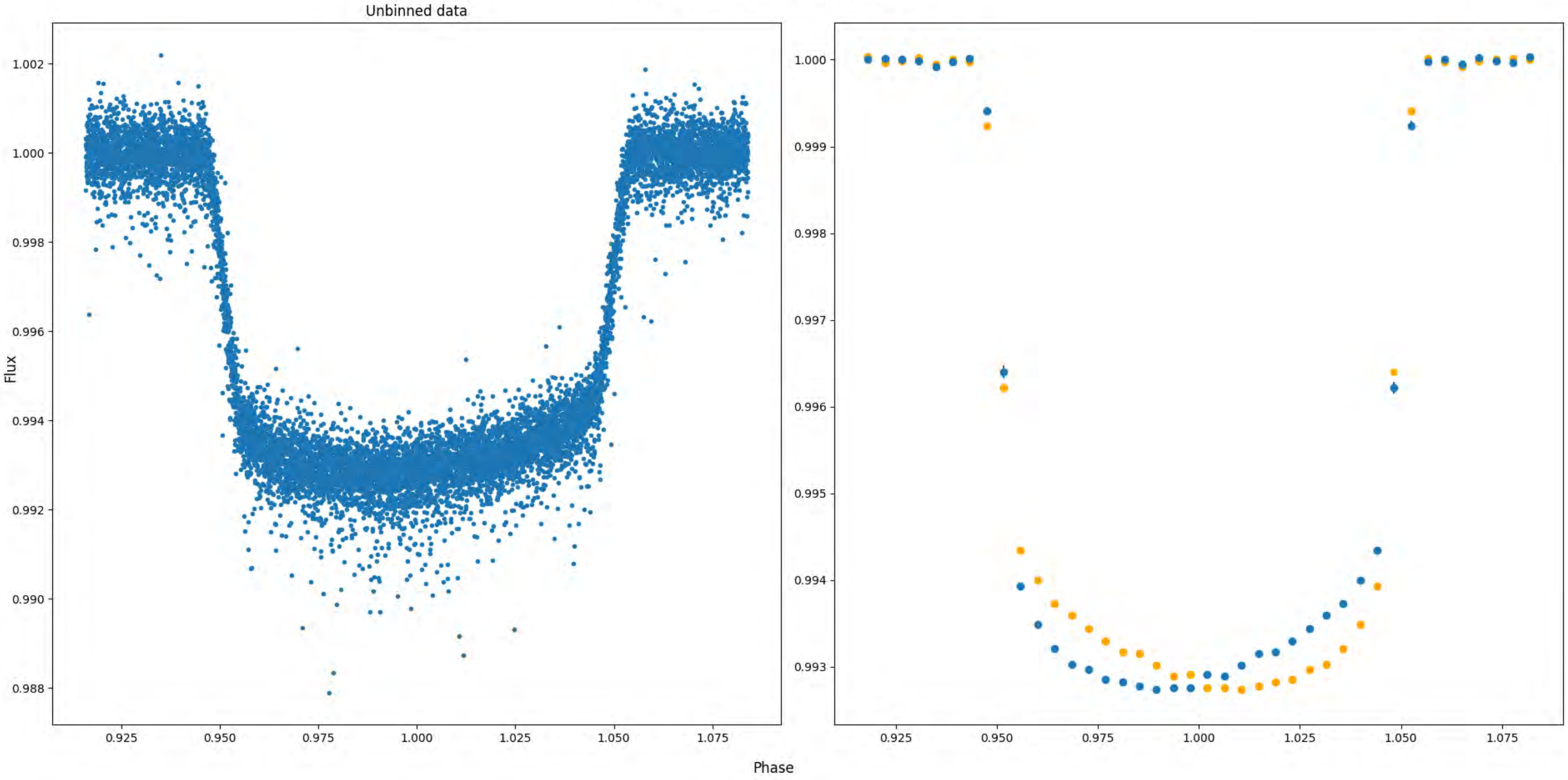
   $\alpha = \frac{1}{N}\sum\frac{b_i - b_{iref}}{\sigma_i^2 + \sigma_{iref}^2}$, where b_i - median value of the bin, σ_i – standard deviation of values in the bin, N – number of bins
3. $0 < \alpha \leq 1$ – symmetric curve, $\alpha > 3$ asymmetric curve
4. Transit duration variation:

$$\delta = \frac{1}{N}\sum\frac{b_{iprevious} - b_{inext}}{\sigma_{iprevious}^2 + \sigma_{inext}^2}$$

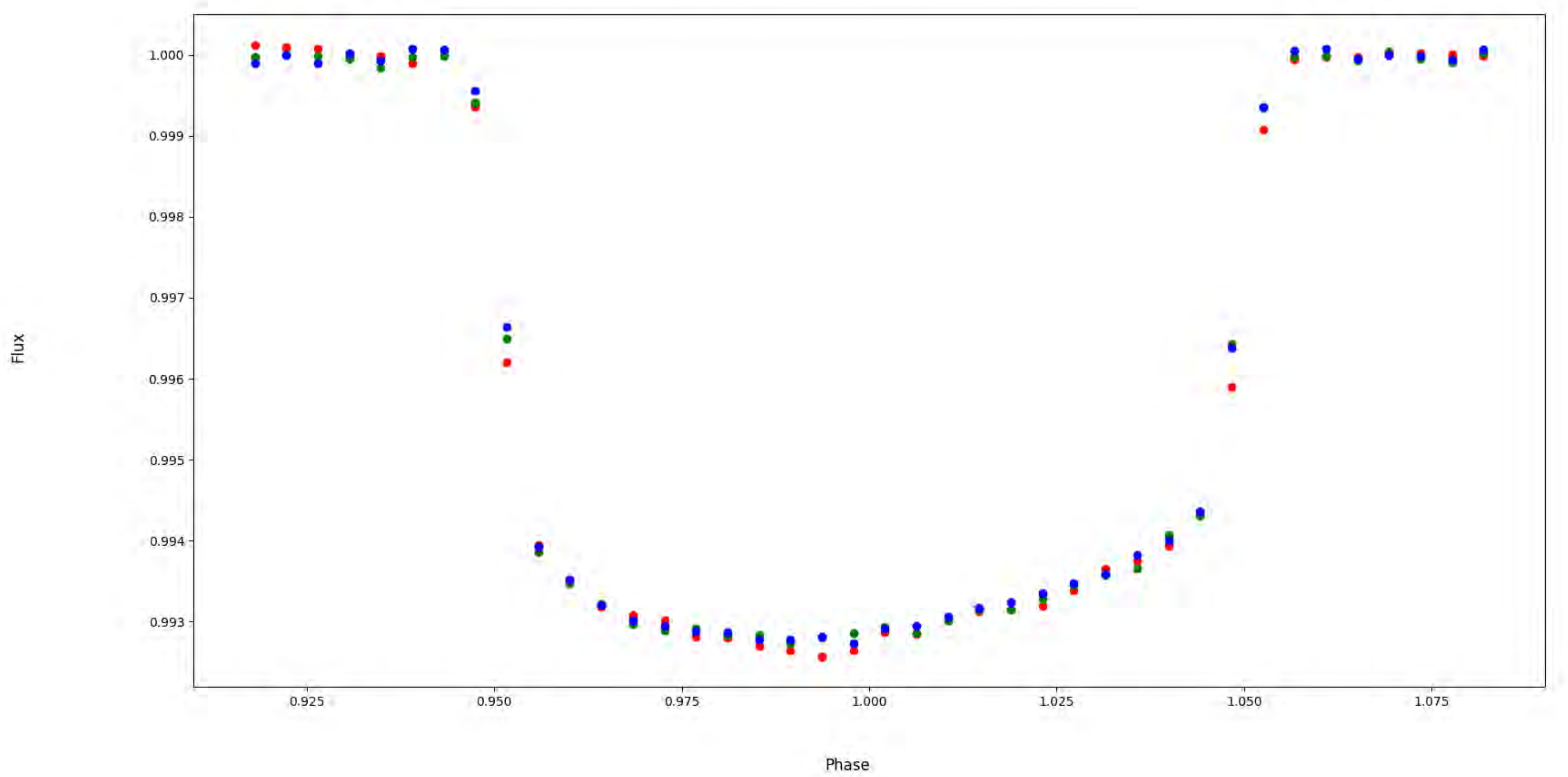
Results

Object	Asymmetry value α (20 bins)	Asymmetry value α (40 bins)
TIC 016740101 aka *KELT-9b*	41.952	21.397
TIC 065412605 aka *TOI-626* (planet candidate)	3.047	1.570
TIC 129979528 aka *WASP-33b*	8.879	5.717
TIC 354619337 aka *MASCARA-1b*	7.062	3.045
TIC 371443216 aka *MASCARA-4b*	6.296	3.322
TIC 399870368 aka *HAT-P-70b*	1.459	0.949

KELT-9b lightcurve

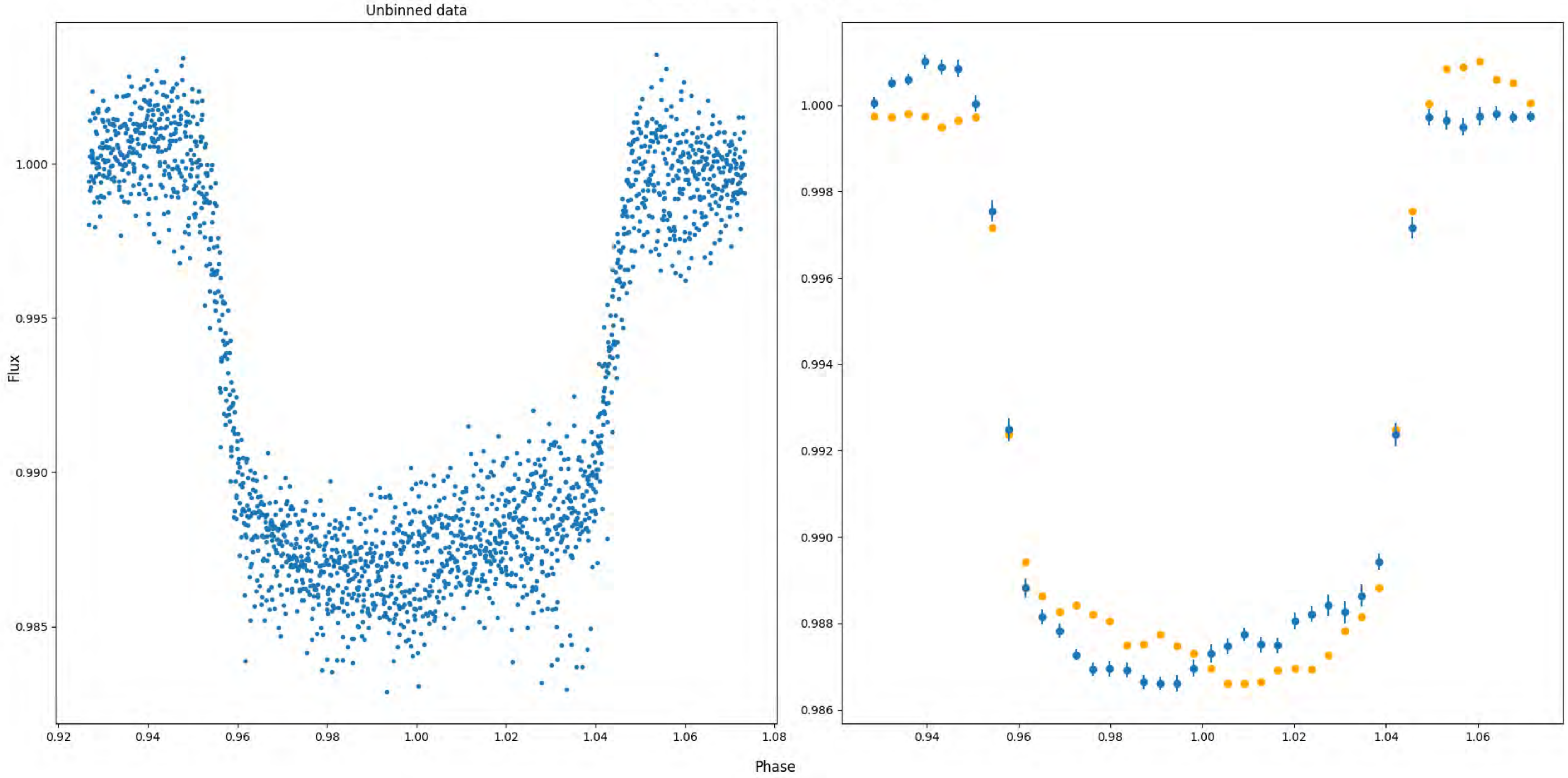


TIC 016740101 transit duration variation

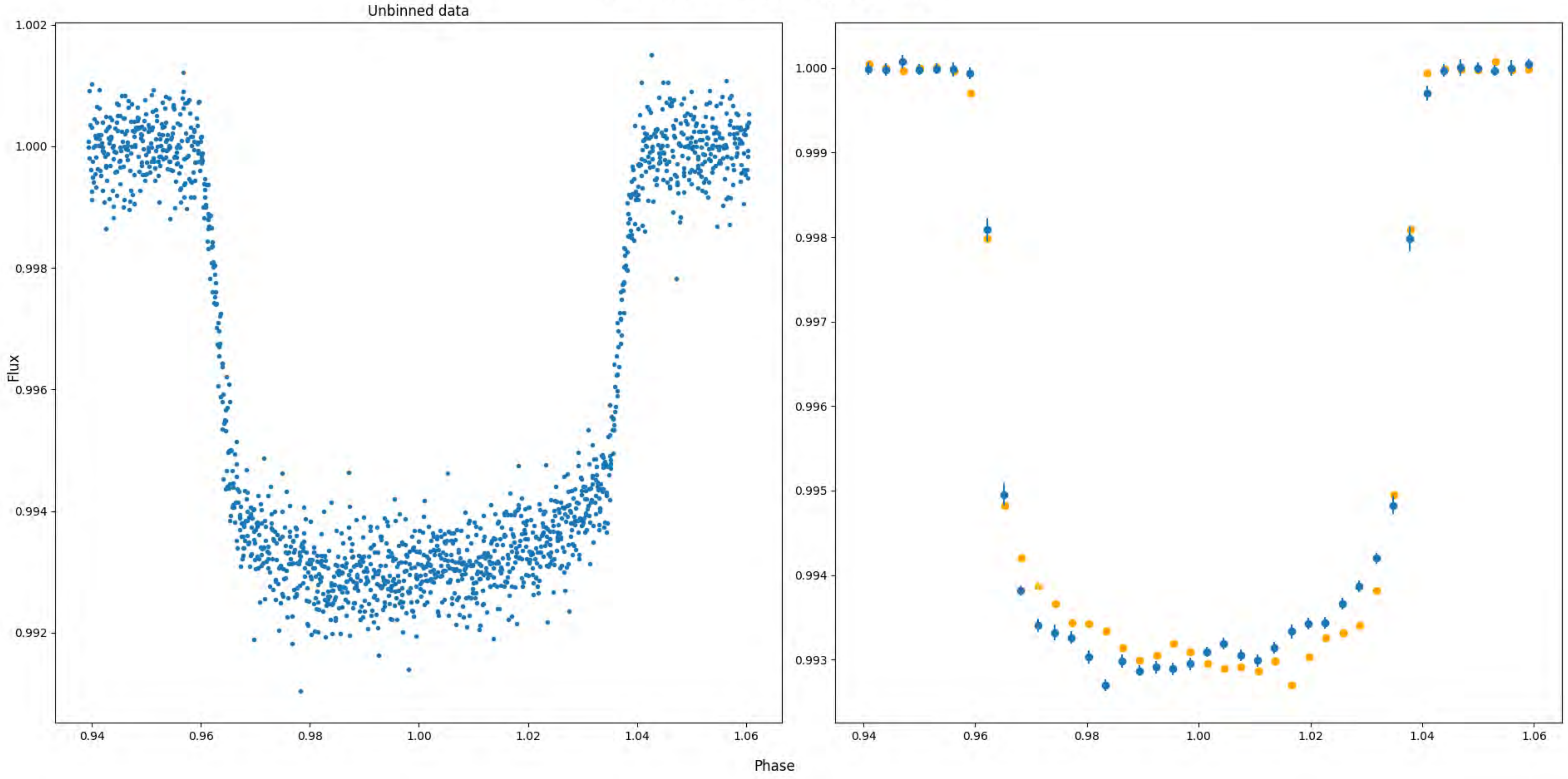


Transit duration variation between three separate periods of observations by TESS: between sectors 14-15 and 41 (δ = 1.805), sectors 41 and 55 (δ = 1.047), and sectors 14-15 and 55 (δ = 2.012).

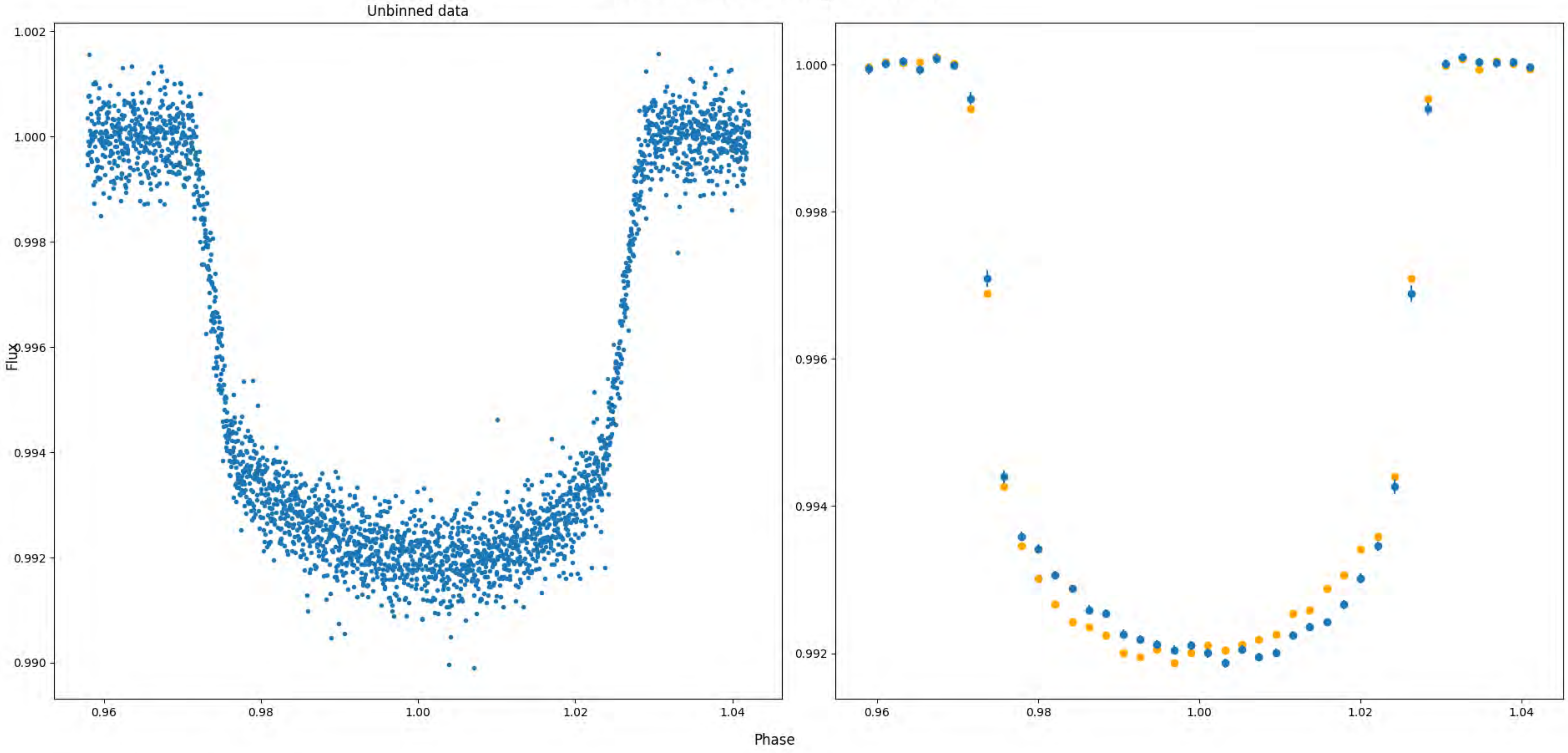
WASP-33b lightcurve



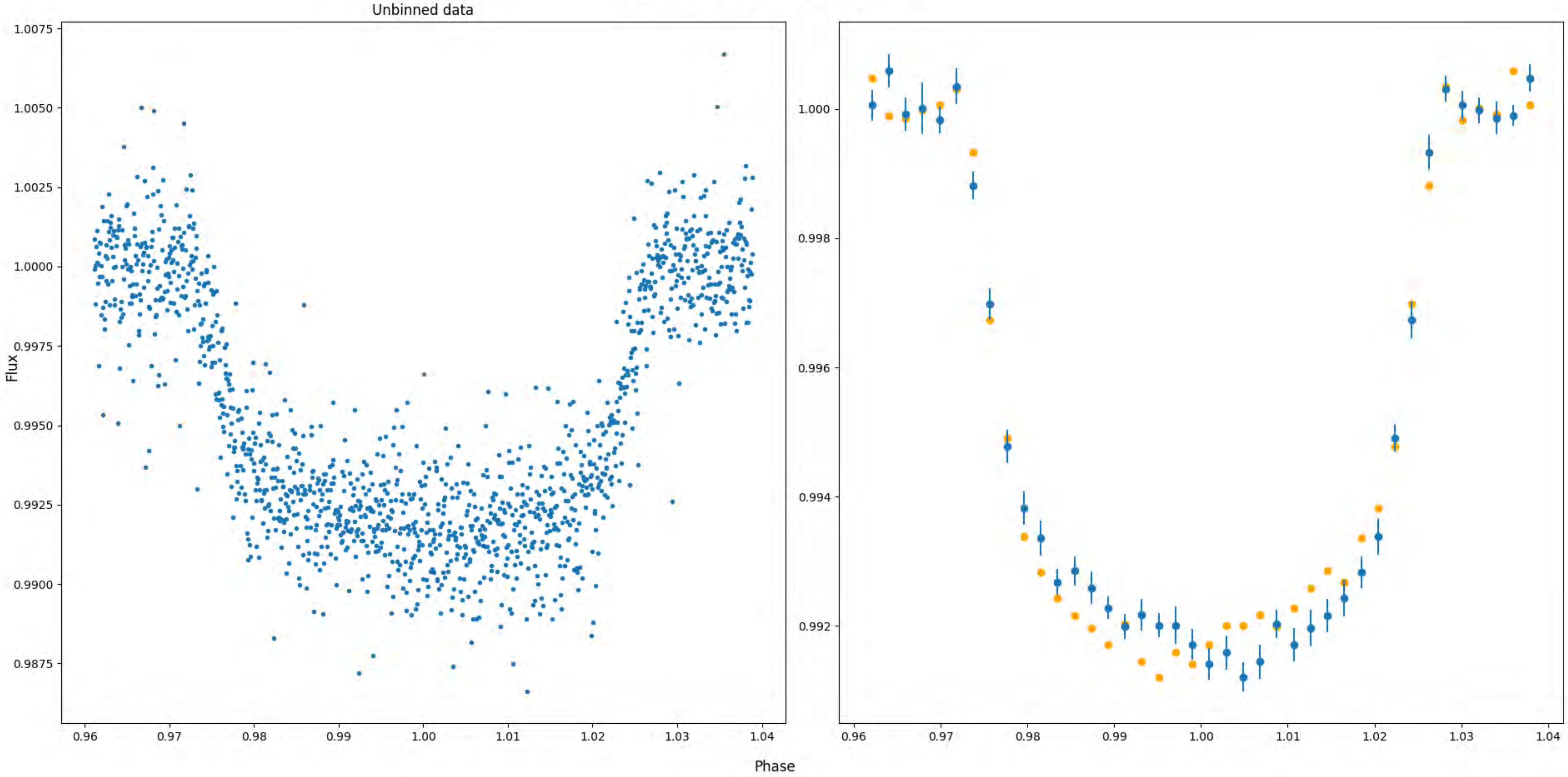
MASCARA-1b lightcurve



MASCARA-4b lightcurve

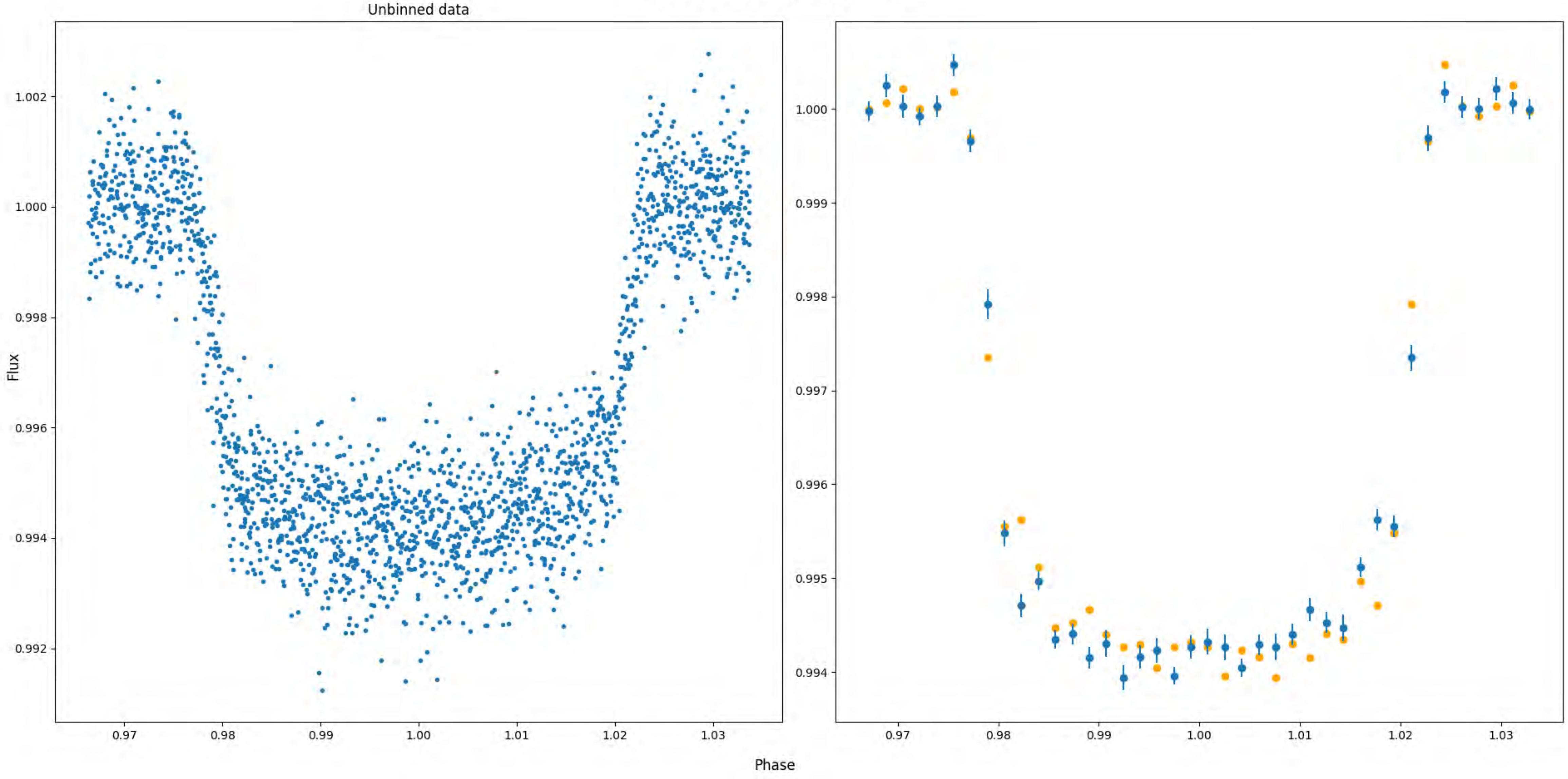


HAT-P-70b lightcurve

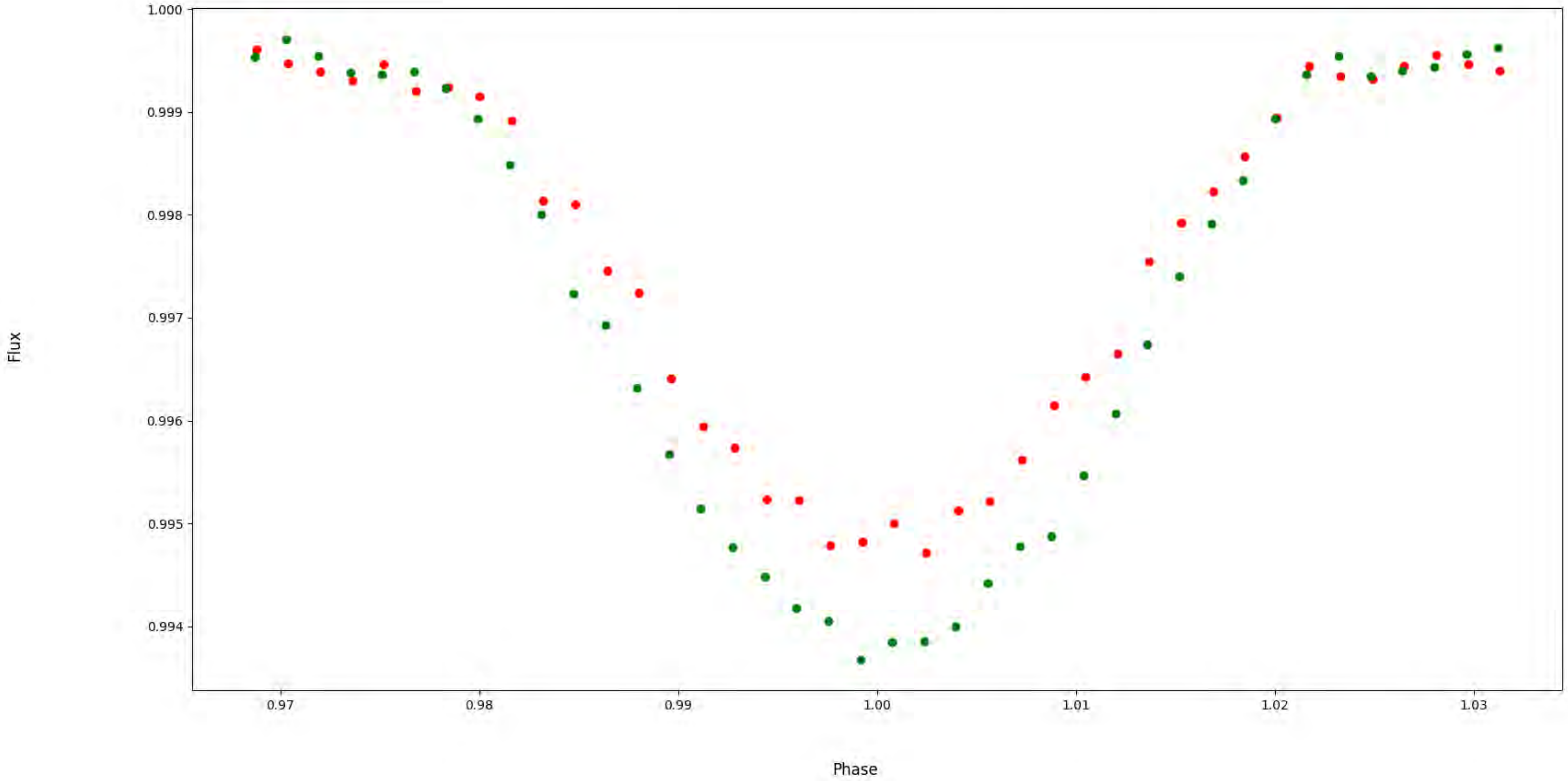


Asymmetry values - 0.949 for 40 bins, 1.934 for 20 bins

TOI 626 lightcurve



TIC 117789567 transit duration variation



TDV value for the TIC 117789567 δ = 14.117.

Conclusions and future work

- Found 6 asymmetric transits and one object showing TDV from 64 hot Jupiters
- Some transits require improvement and further detrending for better results
- Conducting additional observation of the most interesting objects (PHD thesis)

Questions from the opponent

What is the connection between values K and K_1 in equations 1.1.3 and 1.1.4?
Answer:

The K value is radial-velocity semi-amplitude and comes from eq. 1.1.2 :

$V = V_0 + K[\cos(\omega + \nu) + e\cos\omega]$ (1.1.2),

and it is given by

$K = \frac{2\pi}{P}\frac{a\sin i}{\sqrt{1-e^2}}$ (1.1.3).

Using the 3rd Kepler's law as

$G(M_1 + M_2) = \frac{4\pi^2 a^3}{P^2}$, where a = a_1 + a_2 and relation $m_1 a_1 = m_2 a_2$, we will get

$G(M_1 + M_2) = \frac{4\pi^2 a_1^3}{P^2}\frac{(m_1+m_2)^3}{m_2^3}$

After substituting a_1 and reductions, we get eq. 1.1.4

$\frac{(m_2 \sin i)^3}{(m_1+m_2)^2} = \frac{P}{2\pi G} K_1^3 (1 - e^2)^{3/2}$ (1.1.4)

Where K_1 is the radial-velocity semi-amplitude of more massive component, the star.

Literature

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2. KELT-9 b's Asymmetric TESS Transit Caused by Rapid Stellar Rotation and Spin–Orbit Misalignment, Ahlers et al., 2020

3. The clockwork is moving on a combined analysis of TESS and Kepler measurements of Kepler-13Ab, M. Szabo, T. Pribulla et al., 2020

4. Mining the Ultra-Hot Skies of HAT-P-70b: Detection of a Profusion of Neutral and Ionized Species, Bello-Arufe et al., 2021

5. Rapidly rotating stars and their transiting planets: KELT-17b, KELT-19Ab, and KELT-21b in the CHEOPS and TESS era, Garai et al., 2022

6. The effects of stellar gravity darkening on high-resolution transmission spectra, Cauley et Ahlers, 2020

7. Gravity-Darkening Analysis of Misaligned Hot Jupiter MASCARA-4 b, Ahlers et al., 2019