From transits and dynamical stability of exoplanets to eclipsing binaries

Overview of my previous and current research

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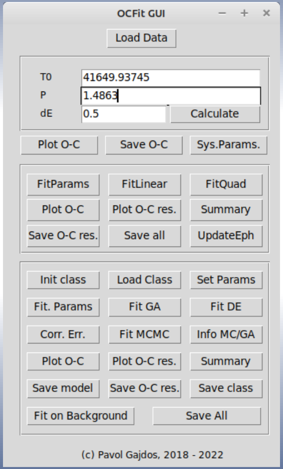
About me…

- come from Prešov (east of Slovakia)
- studied at Šafárik University in Košice
- bachelor and master thesis - analysis of exoplanetary transits and TTVs from *Kepler* - supervisor Štefan Parimucha
- PhD thesis - dynamical stability of multiplanetary systems - supervisor Martin Vaňko

Software OCFit

- analysis of O-C diagrams of eclipsing binaries and transiting exoplanets
- written in Python + GUI using Tkinter
- standard models of O-C changes: linear/quadratic trend, light-time effect, apsidal motion
- fitting using genetic algorithms, differential evolution and Monte Carlo simulations
- available on PyPi and GitHub - source code + Windows executable

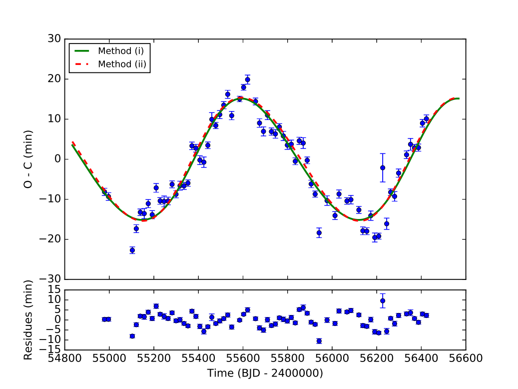


Kepler-410: Transit-timing variations (TTV)

- amplitude ≈ 15 min., period 970 – 975 days
- studied using 2 analytical models:

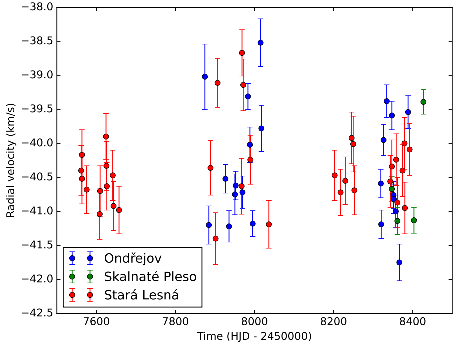
1. Light-Time effect – $M_3 \approx 2.1\ M_\odot$
2. Agol's model – $M_3 \approx 0.9\ M_\odot$

⇒ additional star-mass body on the orbit with a period 970 days



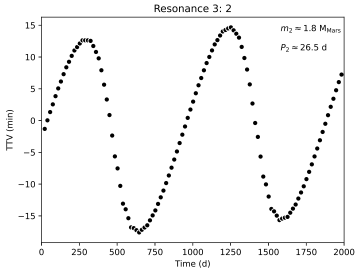
Radial velocity (RV) measurements

- expected changes with an amplitude $25 - 30$ km/s and a period ~ 970 days
- observations on 3 observatories (SR+ČR) during 3 seasons (2016 – 2018)
- from observations – amplitude $\lesssim 400 - 700$ m/s
- our hypothesis about star-mass originator of TTV changes could be excluded
- moreover, any close brown dwarf or massive hot Jupiter isn't presented in the system



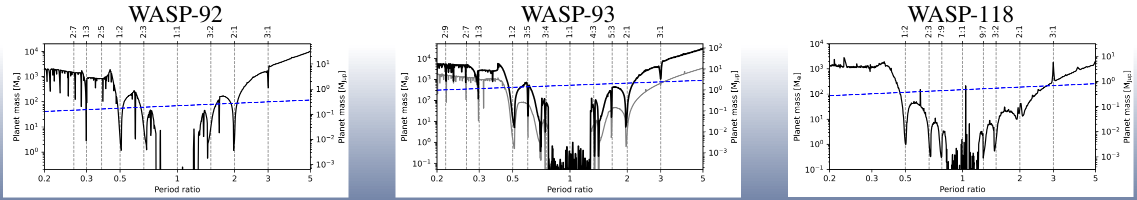
Probable scenario

- possible explanation of TTV – small planet close to MMR
- statistical distribution of resonances in known systems – mainly resonances 2:1 and 3:2
- stability analysis – resonance 2:1 is unstable
- explanation of TTV – planet with a mass of 1.8 M_{Mars} close to the outer resonance 3:2 (orbital period 26.5 days)
- undetectable using current instruments



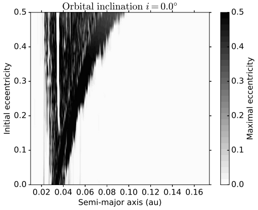
WASP-92 b, WASP-93 b and WASP-118 b: TTVs and upper-mass limits

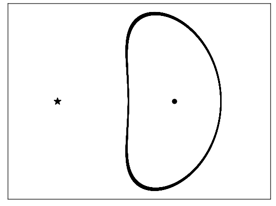
- without significant changes on TTV diagrams
- upper-mass limits are very similar for all 3 systems - significant effect of resonances
- presence of Earth-like or super-Earth planet is still possible – mainly WASP-92 and WASP-93
- WASP-118 – data from *Kepler-K2* $\rightarrow$ better precision and lower limit

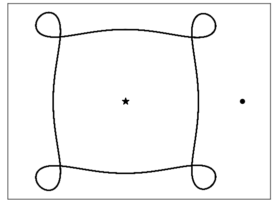


Long-term stability

- searching for stable orbits close to the transiting planets – possible existence of additional hypothetical bodies
- maximal eccentricity method + large number of testing particles on different orbits
- maps of stability are nearly same for all studied systems
- strong influence of initial eccentricity, neglected effect of orbital inclination
- effects of orbital resonance, capturing of testing particles on satellite-like orbits

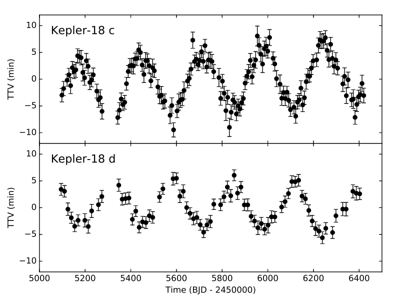






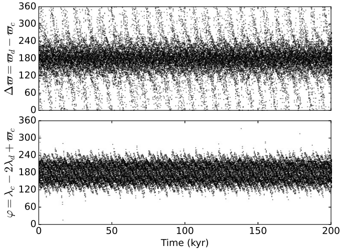
System Kepler-18

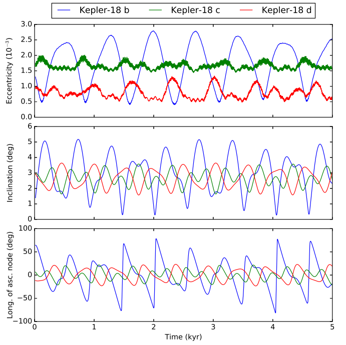
- triple planets – size of super-Earth or Neptune ($2-7\,R_\oplus$)
- orbital periods (3.5 to 14.8 days) close to the MMR 4:2:1
- observed TTVs for Kepler-18 c and d
    - anti-correlated
    - amplitude $\sim$ 5 minutes
    - period 270 days
    - in agreement with theoretical model for a resonance 2:1



Resonant interaction

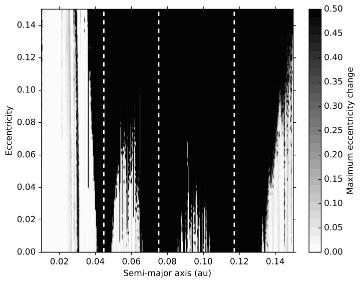
- libration of resonant angle $\varphi = \lambda_{\rm c} - 2\lambda_{\rm d} + \varpi_{\rm c}$ and circularization of apsidal angle $\Delta\varpi = \varpi_{\rm d} - \varpi_{\rm c}$
- type of resonance – apocetric libration
- long-term quasi-periodic changes of planetary orbital elements
- changes of orbital inclination up to 5°
- possible effect on observability of transits



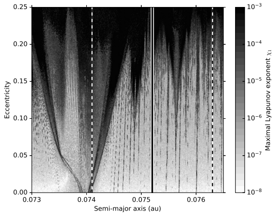


Maps of stability

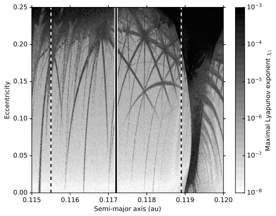
- map of region close to resonance of planets Kepler-18 c and d → complex structure
- orbits stable in wide interval of parameters
- unstable strips for exact resonance



Kepler-18 c



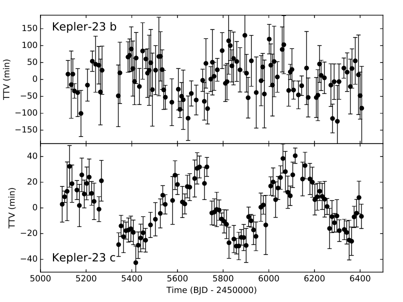
Kepler-18 d



- islands of stability between orbits of known planets
- possible structures similar to asteroid belts

System Kepler-23

- three exoplanets – size of Saturn to Neptune ($15 - 60\,M_{\oplus}$)
- possible resonance (9:6:4) – periods 7.1 to 15.2 days
- very shallow transits (≈ 0.1 mmag)
- big uncertainties in transit time determination
- observed TTVs for Kepler-23 b and c
  - period 470 days
  - amplitude 60 – 90 minutes (for Kepler-23 b) and 20 – 30 minutes (for Kepler-23 c)
  - theoretical calculation for resonance 3:2 $\rightarrow$ similar period of TTVs
  - simulated TTV $\rightarrow$ over-estimated masses of planets

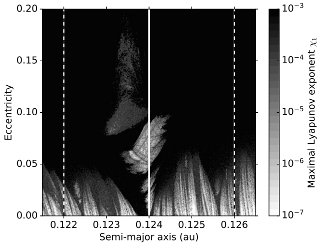


System stability

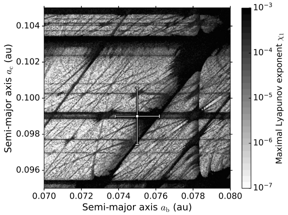
- chaotic behaviour and sequential system disintegration
- only in simulations
- real system is stable

  ⇒ wrongly determined parameters

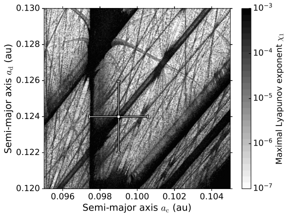
Kepler-23 d



Kepler-23 b and c



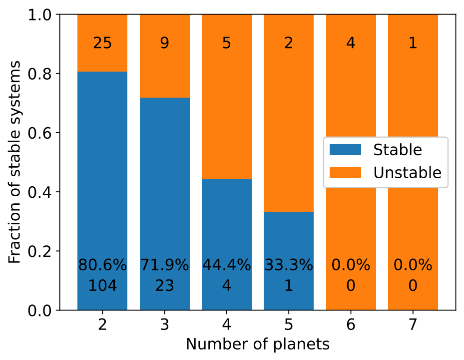
Kepler-23 c and d



- source of instability – pair of planet Kepler-23 c and d – unstable strip for a resonance 7:5
- change of a some of these 2 planets – stabilization of the system
- island of stability on map of $a - e$ for Kepler-23 d

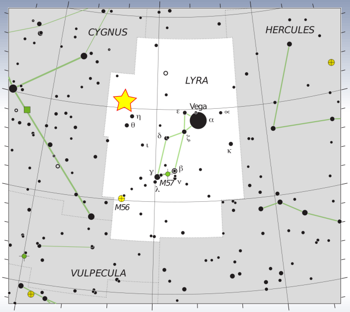
Statistical analysis of stability of multiplanetary systems

- studied 178 multiplanetary systems
- calculated Lyapunov time, MEGNO and SPOCK indicators
- about 75% are stable over 10^7 orbits
- systems with many planets are mostly unstable
- systems with less massive planets are generally more stable
- strong effect of resonances (3:2 and 2:1)



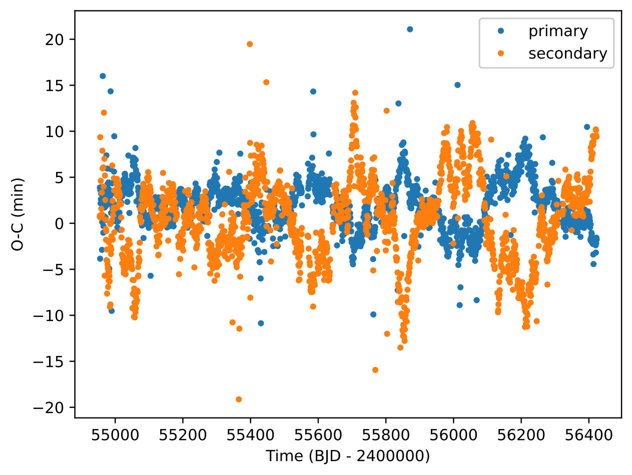
Eclipsing binary KIC 7023917

Magnitude	10.1 V
Paralax	2.337 mas
Distance	$\sim$ 428 pc
Orbital period	0.7728 day (18.5 h)
Temperature (primary)	7460 K
Spec. type (primary)	A7 III



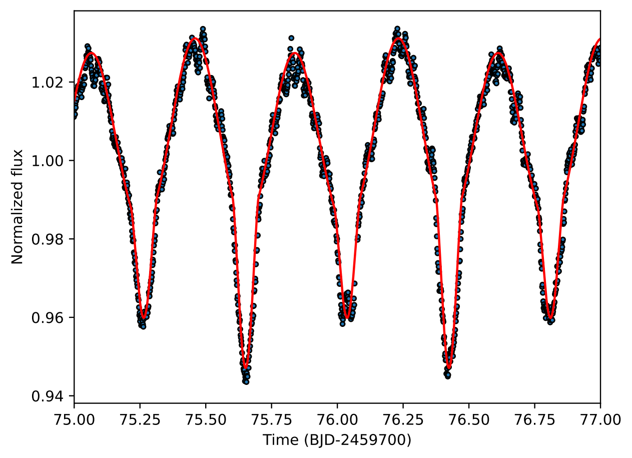
O-C diagram

- Kepler long-cadence data
- anti-correlated changes - apsidal motion?
- amplitude 5 minutes
- period 200-300 days (very fast for AM)
- additional effects...



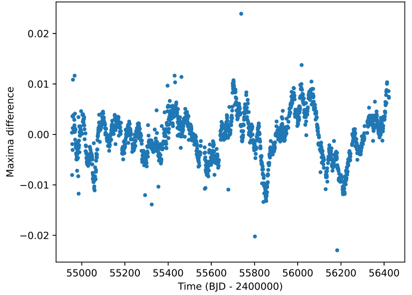
Light-curve analysis

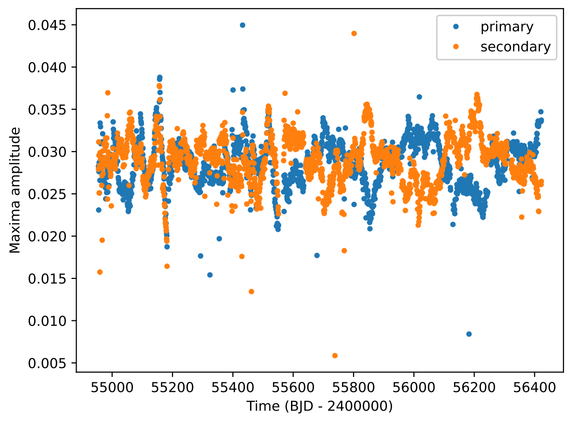
- TESS - sectors 14, 40, 41 and 54; 2-min. cadence
- evidence of spots
- short-period pulsations
- Kepler - only spots



O'Connell effect

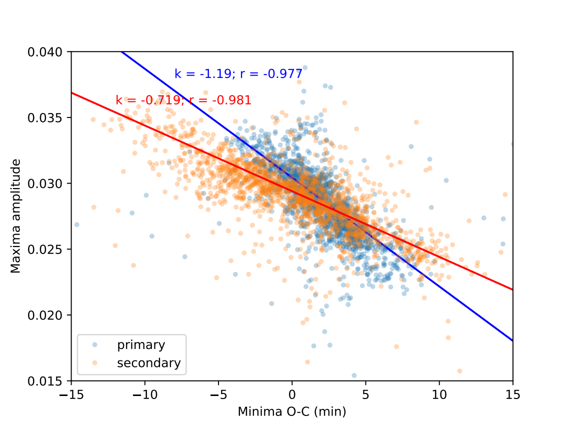
- different heights of maxima
- result of stellar spot(s)
- analyzed mainly Kepler data
- similar curves to O-C diagram





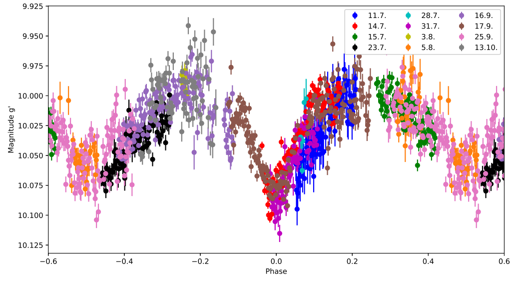
O'Connell & O-Cs

- strong correlation between heights of maxima and O-C (∼98%)
- anti-correlated
- same reasons for both
- deformation of LC
- effects of stellar spots?



Ground-based photometry

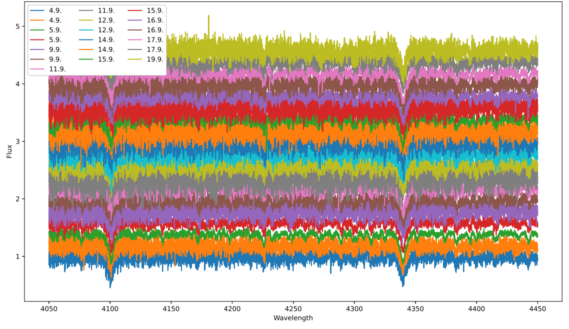
- multi-colour photometry - Sloan's g', r', i' filters - 11 nights
- 15-cm Maksutov-Newton telescope + G2-8300 camera - Astronomical Observatory at Kolonica saddle
- preliminary processing - manually determined offsets between different nights (problems with i' filter)



Spectroscopy & radial velocities

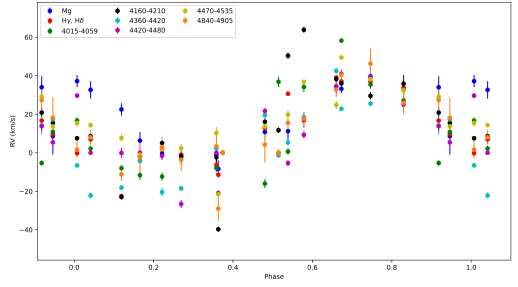
- 2-m Perek telescope in Ondřejov - OES spectrograph - 19 spectra
- not very good quality - faint star (10 mag) + short exposure time (0.5h)
- short orbital period (18h) - blurring lines during exposure

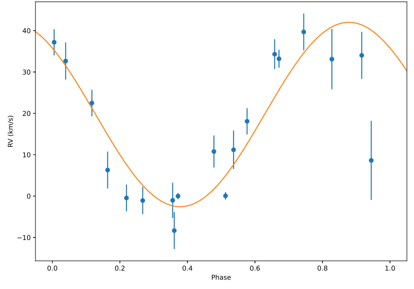
- stellar pulsations, rotation (?)
- SB1 type - no lines detected from secondary (cooler star + spectra quality)



Spectroscopy & radial velocities

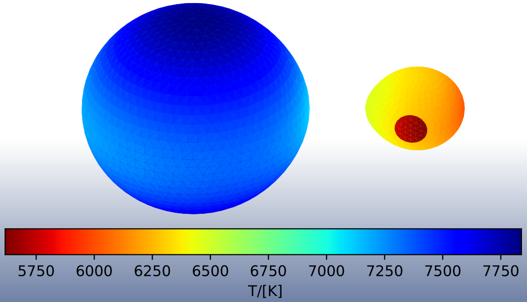
- best results for Mg triplet (516 – 519 nm)
- semi-amplitude 22.3 km/s, eccentricity <0.1 (could be fixed to 0 - short orbital period)
- mass function $9 \cdot 10^{-4}$ $M_\odot$ + inclination from LC - mass ratio ~ 0.1





Model of Eclipsing Binary

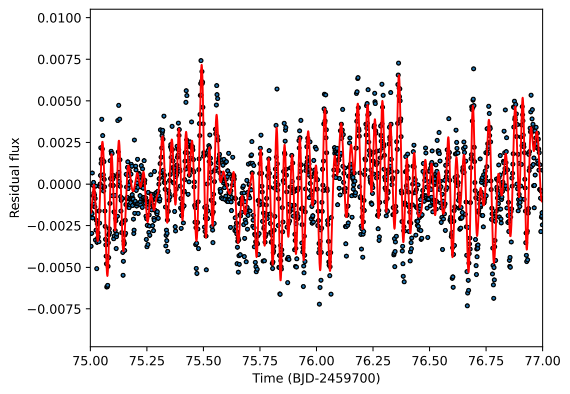
- used software ELISa
- assumed one cold spot on secondary component
- second spot?



Temperature (primary)	7460 K (fixed)
Temperature (second.)	6200 - 6400 K
Spec. type (primary)	A7 III (fixed)
Spec. type (second.)	F7 - F8
Mass ratio	0.11
Inclination	58.6°
Spot radius	$\sim$20°

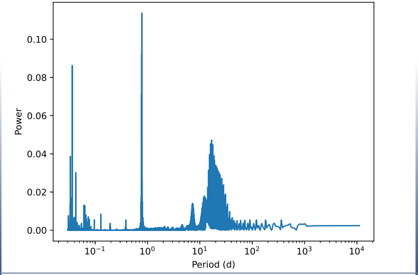
Residual light curve

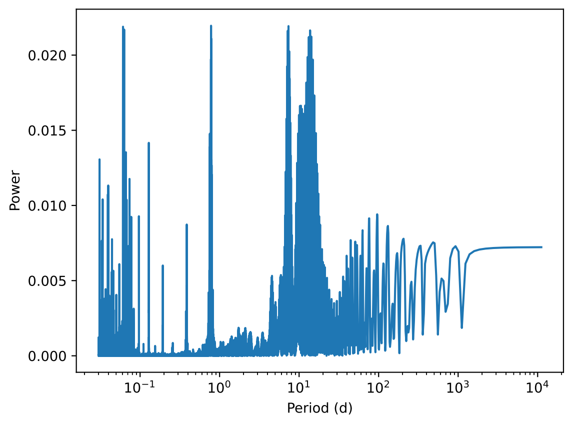
- TESS LC – short-periodic signal in residuals
- amplitude few mmag
- period 50 minutes
- not visible in Kepler data - very short period



Pulsations

- period analysis of residuals (GLS)
- multiple frequencies
- orbital period bias, long periods (TESS?)
- $\sim$50-100 minutes - δ Scuti





Our plans to the future

- process ground-based photometry - transformation to standard magnitude - problems with offsets!
- colour indexes - estimation of temperatures
- fit spectra - stellar parameters (poor quality?)
- re-fit photometry data using values from RV (q, e?) - Kepler+TESS+ground (together/separate?) - done for Kepler & TESS
- explain low mass ratio - maybe mass transfer in the past (secondary star nearly fills Roche lobe)?
- star-spot tracking (changes of size and position over time) - compare with O-Cs - in progress (found correlation with spot radius and O'Connell effect)
- detecting pulsation modes, time-evolution of pulsations
- pulsations as source of O-Cs - resonances, beats etc.