Transit-timing variations of exoplanet Kepler-410 Ab

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Contents

Introduction

- exoplanets – one of the main topics of current astrophysical research
- multiple projects focused on the search of exoplanets (*Kepler*, *TESS*, etc.)
- 3925 confirmed exoplanets, 657 planetary systems
- wide scope for further research
- study dynamics and stability of the planetary systems $\rightarrow$ their formation and evolution
- resonant interaction – a key factor of the orbital stability

Methods for searching for exoplanets

- transits
  - the simplest and most successful method (mission *Kepler*)
  - watching for the regular drops of the brightness of the parent star
- radial velocities (RV)
  - the shift of the spectral lines as the result of the Doppler effect
  - determination of the mass of the planet (combination with transits)
- transit-timing variations (TTV)
  - gravitational interactions of the another body in the system

Mean-motion resonances

- small but regular perturbation has a significant influence on the behaviour of the studied body
- mean-motion resonance (MMR) – if the ratio (at least approximately) works

$$\frac{P_1}{P_2} = \frac{n_2}{n_1} = \frac{p}{p-q}$$

- the most common type of resonance – planets, moons, asteroids, etc.
- bodies are regularly in the same configuration
- significantly affects the stability of the system – stabilize or destabilize orbit

Effect of resonances on the TTV

- resonances – the main source of the TTV in the known exoplanetary systems
- period of the TTV depends on the distance from the exact MMR

$$P_{\mathrm{TTV}} = \frac{1}{|p/P_1 - (p-q)/P_2|}$$

- amplitude of the TTV of the 1^{st} planet caused by the 2^{nd} planet depends mainly on the mass of the 2^{nd} planet and the order of the resonance

$$\delta t_1 \propto P_1 \frac{m_2}{M_\star} \frac{a_1}{a_2} \; f(a_1, a_2, P_1, P_2)$$

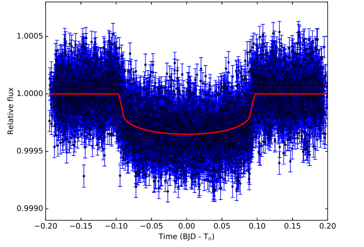
- determination of the masses of two transiting exoplanets in the resonance (both with TTV)
- if only one planet $\Rightarrow$ unknown order of the resonance $\Rightarrow$ we cannot exactly tell what planet causes TTV

Numerical simulations

- solving the *n*-body problem – no analytical solution
- numerical integration of the orbits – e.g. using package Mercury6 or Swift
- wide opportunities in celestial mechanics
- commonly used also in the study of exoplanetary systems:
    - simulation of TTV
    - resonant interaction between planets
    - long-term stability of the planetary systems

Exoplanetary system Kepler-410

- brightness V 9.5 mag
- distance 148.16 ± 0.49 pc (GAIA - DR2)
- Kepler-410 A – 1.352 $R_\odot$, 1.214 $M_\odot$, spectral type F6IV
- Kepler-410 B (Adams *et al.*, 2012) – distance 1.63″ ⇒ 250 AU; a red dwarf (4850 K)
- transiting exoplanet Kepler-410 Ab
  - discovered in 2013 (Van Eylen *et al.*, 2014)
  - size of Neptune – 2.647 $R_\oplus$
  - orbital period – 17.8336313 d
  - semi-major axis – 0.1426 AU

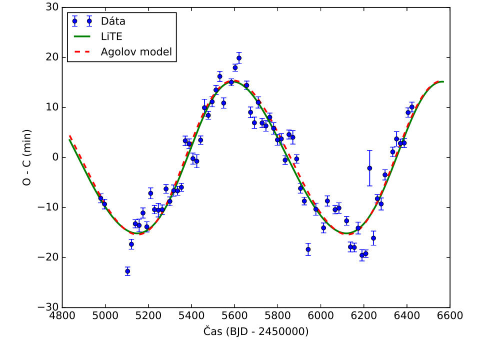


TTV

- amplitude ≈ 15 min., period 970 – 975 days
- studied also in a paper Gajdoš *et al.* (2017) using two analytical models:

1. Light-Time effect (Irwin, 1952) – $M_3 \approx 2.1\ M_\odot$
2. model by Agol *et al.* (2005) – $M_3 \approx 0.9\ M_\odot$

⇒ another body with stellar mass on the orbit with orbital period 970 days



RV measurements

- expected variation with an amplitude $25-30$ km/s and a period ~ 970 days
- measurements from three observatories (SR+ČR) during three observing seasons (2016 – 2018)

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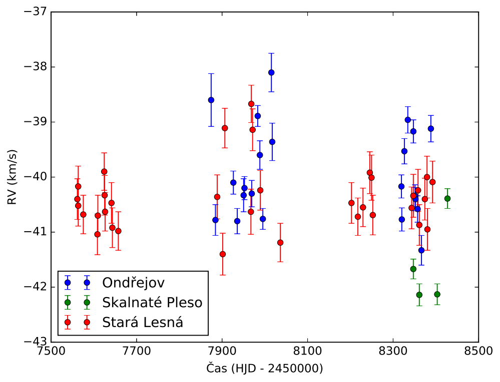
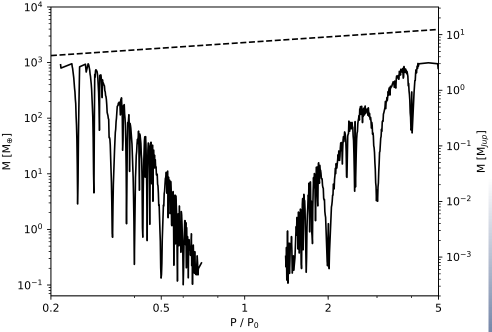
- from the observations – amplitude $\lesssim 600-800$ m/s
- the stellar originator of TTV could be excluded
- the existence of close brown dwarf or massive hot jupiter is also unlikely



Resonant interaction

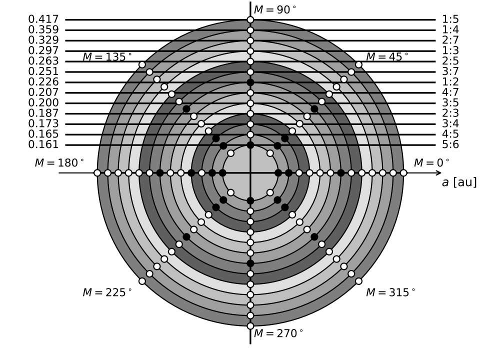
- another interpretation of observed TTV → resonances between exoplanet Kepler-410 Ab and other (unknown) planet
- analysis using numerical simulations
- determination of the mass of the planet for different orbital periods
- in MMR – small planets with a mass 0.1 – 3 $M_{\oplus}$
- many possible explanations – different couples of M, P
- RV measurements – no constraint on a range of possible planets



Stability of the resonance

- determine the most probable explanation of TTV caused by the resonances
- studying long-term stability (5000 years) of the significant MMR

- interior resonances are less stable
- most of exterior resonances are stable
- resonance 1:2 is unstable



Conclusions

- observed variations of the times of transit of exoplanet Kepler-410 Ab
- RV measurements excluded existence of another close star ⇒ rejection of the previous explanation of TTV (Gajdoš *et al.*, 2017)
- possible origin of TTV – small planet close to the MMR
- determine the most probable option – stability of the resonances + statistical distribution of resonances among the known systems (Wang & Ji, 2014)
- explanation of TTV - a planet with a mass of 1.5 M_{Mars} close to the exterior resonance 2:3 (period 26.5 days)
- hardly detected by current instruments
- results already published in a paper Gajdoš *et al.* (2019)

Thank you for your attention!

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