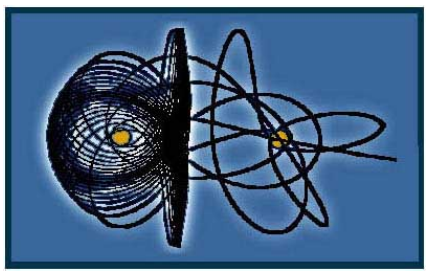
Evolution of the compact planetary system K2-72

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Ural Federal University
named after the first President of Russia B.N.Yeltsin
Institute of Natural Sciences and Mathematics



Introduction

Study of the dynamic evolution of the compact four-planet system K2-72 began with this fact:

- When simulated orbital evolution with nominal orbital elements (Dressing et al. AJ 154 (2017) 207), the system disintegrated after 3 Myr.

Problems

1. Search for conditions for stable orbital evolution. No collisions or planetary ejections on interval 100 Myr.
2. Study of resonance properties. Are resonances necessary for the stability of a compact planetary system in the presence of tides?

Four-planetary system K2-72 (Dressing et al., AJ 154 (2017) 207)

K2-72 is an M2V dwarf aged 1–10 (8.9 ± 1.1) Gyr

$M_\star = 0.27^{+0.08}_{-0.09}\ M_\odot \quad R_\star = 0.33^{+0.03}_{-0.03}\ R_\odot$

Parameter	K2-72 b	K2-72 c	K2-72 d	K2-72 e
$R\ [R_\oplus]$	1.08 ± 0.11	1.16 ± 0.13	1.01 ± 0.12	$1.29^{+0.14}_{-0.13}$
$m\ [M_\oplus]$	$1.39^{+0.58}_{-0.44}$	$1.80^{+0.85}_{-0.63}$	$1.09^{+0.55}_{-0.39}$	$2.65^{+1.18}_{-0.85}$
P [day]	5.577212 ± 0.00042	15.189034 ± 0.0031	7.760178 $^{+0.001496}_{-0.001496}$	24.158868 $^{+0.003726}_{-0.00385}$
e	$0.11^{+0.02}_{-0.09}$	$0.11^{+0.02}_{-0.09}$	$0.11^{+0.02}_{-0.09}$	$0.11^{+0.02}_{-0.09}$
i [deg]	$89.15^{+0.59}_{-0.86}$	$89.54^{+0.32}_{-0.44}$	$89.26^{+0.5}_{-0.7}$	$89.68^{+0.22}_{-0.32}$
g [deg]	7.49^{+120}_{-134}	16.83^{+113}_{-138}	14.28^{+114}_{-137}	11.39^{+117}_{-136}

Density of a planet $\varrho = 2.43 + 3.39(R/R_\oplus)$ g cm^{-3}

for $R < 1.5R_\oplus$ (Weiss & Marcy, ApJL 783 (2014) L6)

Possible resonances in the K2-72 system

1 — K2-72 b, 2 — K2-72 d, 3 — K2-72 c, 4 — K2-72 e

Resonance offsets for K2-72

Planets		MMR	Δ
K2-72 b — K2-72 d	(1–2)	7/5	0.0086
K2-72 d — K2-72 c	(2–3)	2/1	*0.0427*
K2-72 c — K2-72 e	(3–4)	8/5	0.0095

For numerator and denominator values of 10 or less.

$$\text{Resonance offset } \Delta_{ij} = \frac{P_j}{P_i} - \frac{k_i}{k_i - l_i}$$

Posidonius software

Posidonius (Blanco-Cuaresma & Bolmont, EWASS-SS4-2017 (2017))

- *N*-body simulator written in Rust
- Symplectic integrator WHFAST (Rein & Tamayo, MNRAS 452 (2015) 376) without correctors (since tidal forces are velocity dependent)
- Spin evolution is computed for all the bodies by using a midpoint integrator (Bulirsch, 2013)
- Tidal forces, rotational-flattening effects and general relativity corrections are implemented (Bolmont et al., A&A 583 (2015) A116)

Stability: Eccentricity

Variation of masses

- Star mass is minimal, nominal, and maximal: $M_\star = 0.18$, 0.27, and $0.35\ M_\odot$
- Masses of planets are minimal, nominal, and maximal

Orbital elements

- Initial periods P (and semi-major axes a) and inclinations i are minimal, nominal, and maximal
- Initial eccentricities are $e \in \{0.02, 0.03, \ldots, 0.11\}$
- Initial arguments of periapsis are $g \in \{g_{min}, \ldots, g_{max}\}$ with step $\Delta g = 10^\circ$
- Initial longitudes of ascending nodes are $\Omega = 0^\circ$
- Simulation interval is 100 Myr

Variation of eccentricities

Intersection of the orbits of planets K2-72 b and K2-72 d

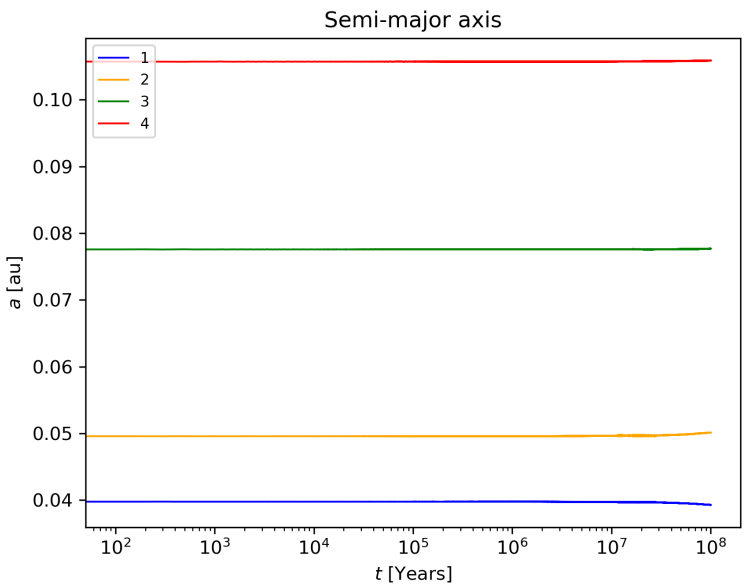
- $Q_b > q_d$
- $e_b = 0.085 - 0.130$ and $e_d = 0.129 - 0.093$, respectively

Initial values of orbital eccentricities, at which the planetary system does not disintegrate

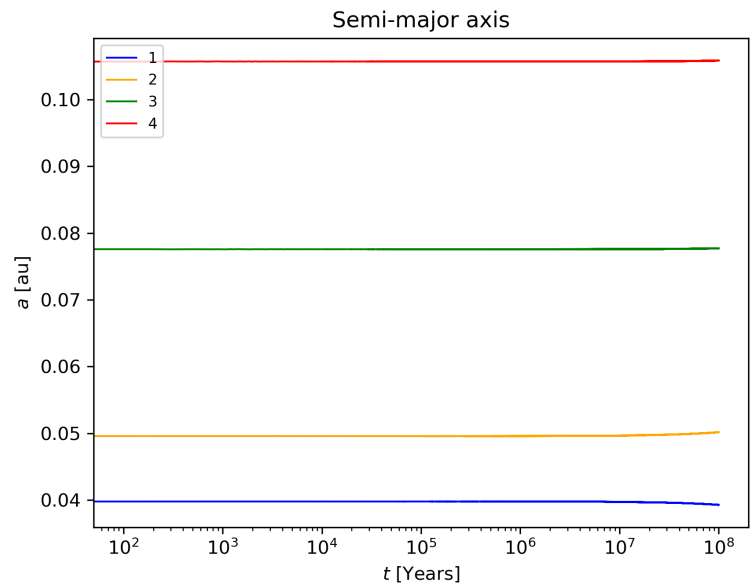
K2-72 b	K2-72 d	K2-72 c	K2-72 e
0.04	0.04	0.04	0.03
0.04	0.04	0.03	0.04
≤ 0.03	≤ 0.03	≤ 0.03	≤ 0.03

Stable solutions

Semi-major axis ($e_0 = 0.03$)



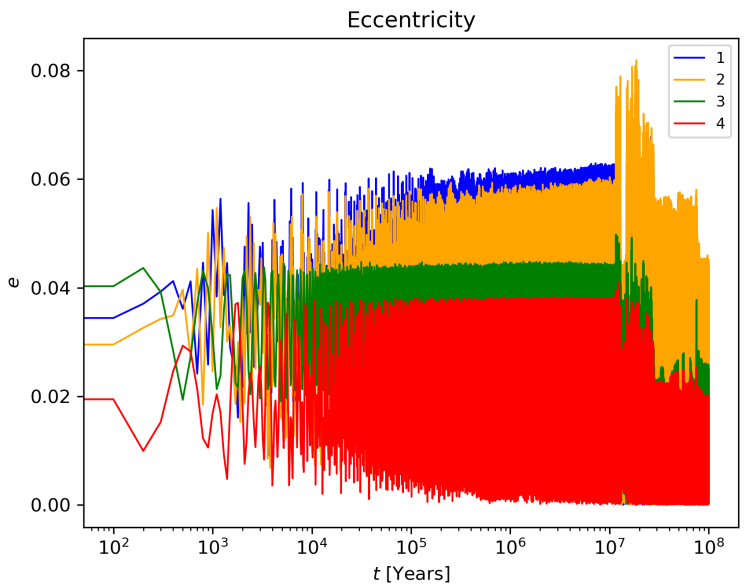
Semi-major axis ($e_0 = 0.02$)



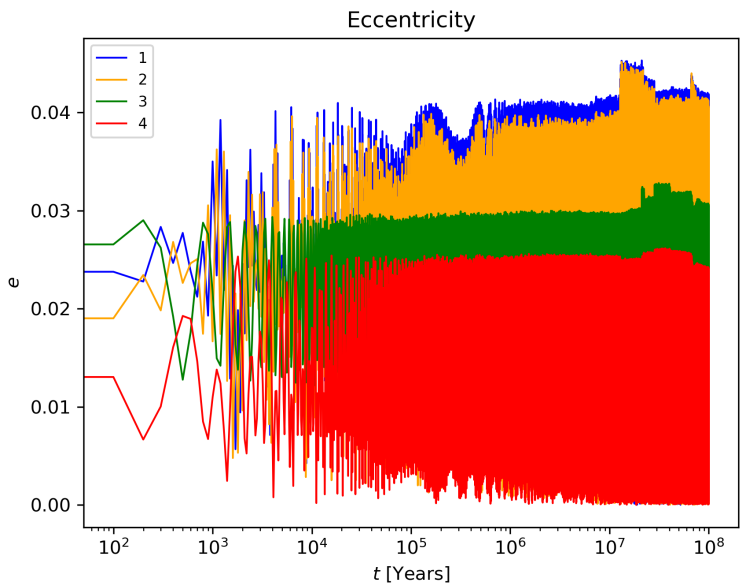
1 — K2-72 b, 2 — K2-72 d, 3 — K2-72 c, 4 — K2-72 e

Stable solutions

Eccentricity ($e_0 = 0.03$)



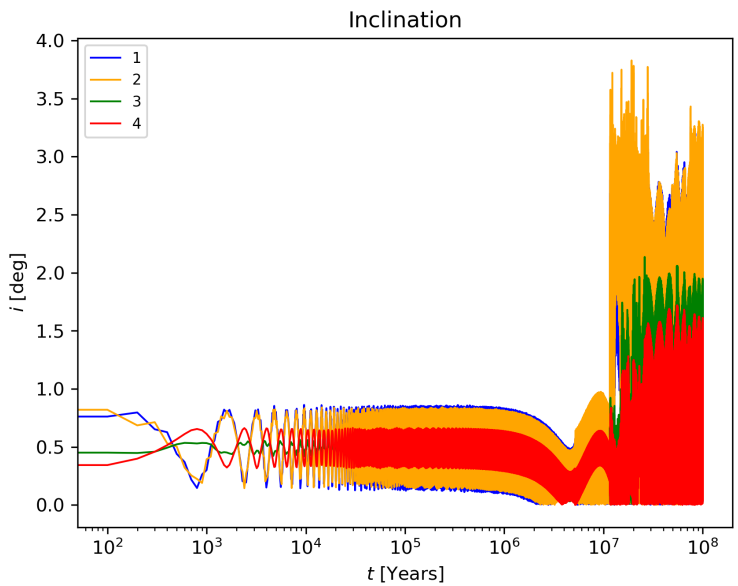
Eccentricity ($e_0 = 0.02$)



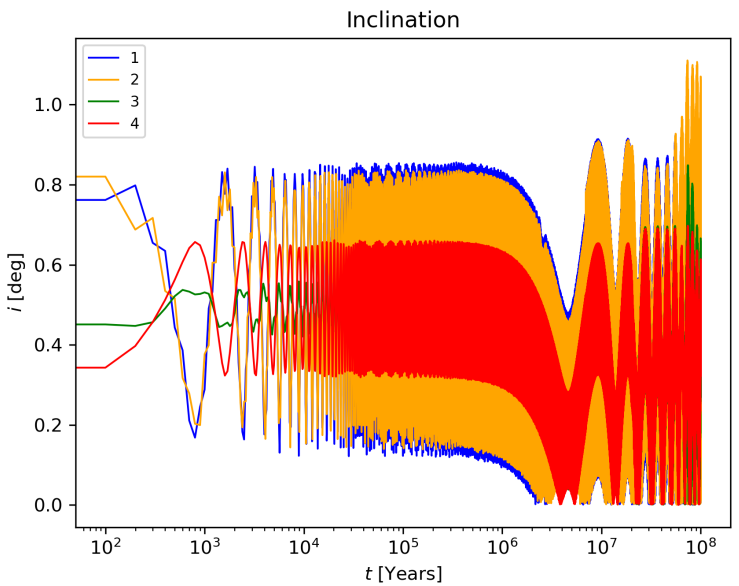
1 — K2-72 b, 2 — K2-72 d, 3 — K2-72 c, 4 — K2-72 e

Stable solutions

Inclination ($e_0 = 0.03$)



Inclination ($e_0 = 0.02$)



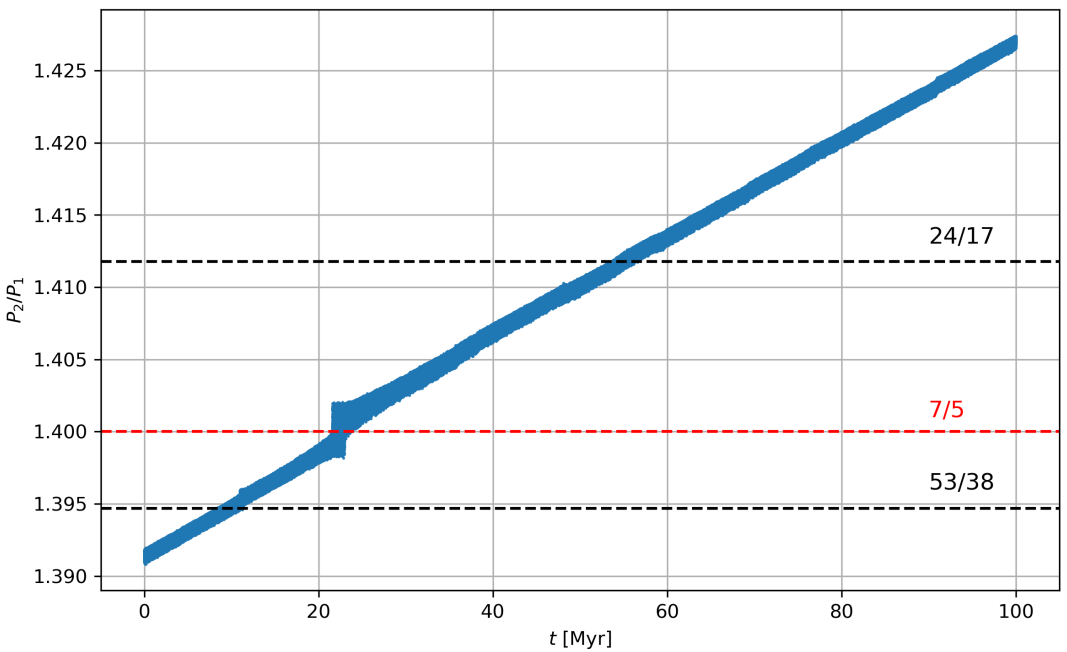
1 — K2-72 b, 2 — K2-72 d, 3 — K2-72 c, 4 — K2-72 e

Resonances: Variation of masses

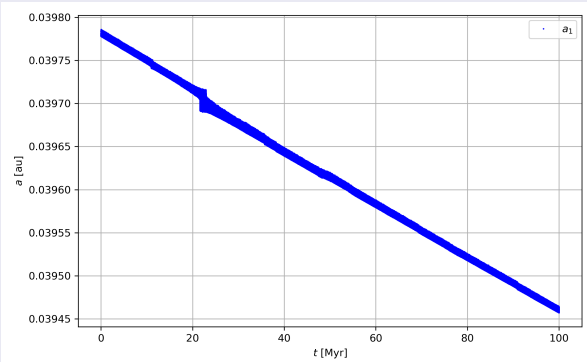
K2-72 b and K2-72 d (1–2) $M_\star = 0.27\ M_\odot$

$(m_b)_{min} = 0.98\ M_\oplus$ $(m_d)_{min} = 0.67\ M_\oplus$

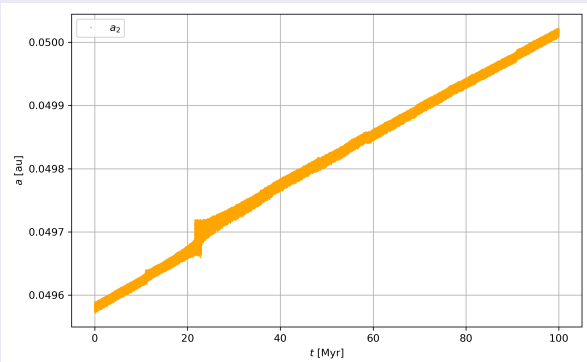
Ratio of periods P_d/P_b



Semi-major axis a_b



Semi-major axis a_d

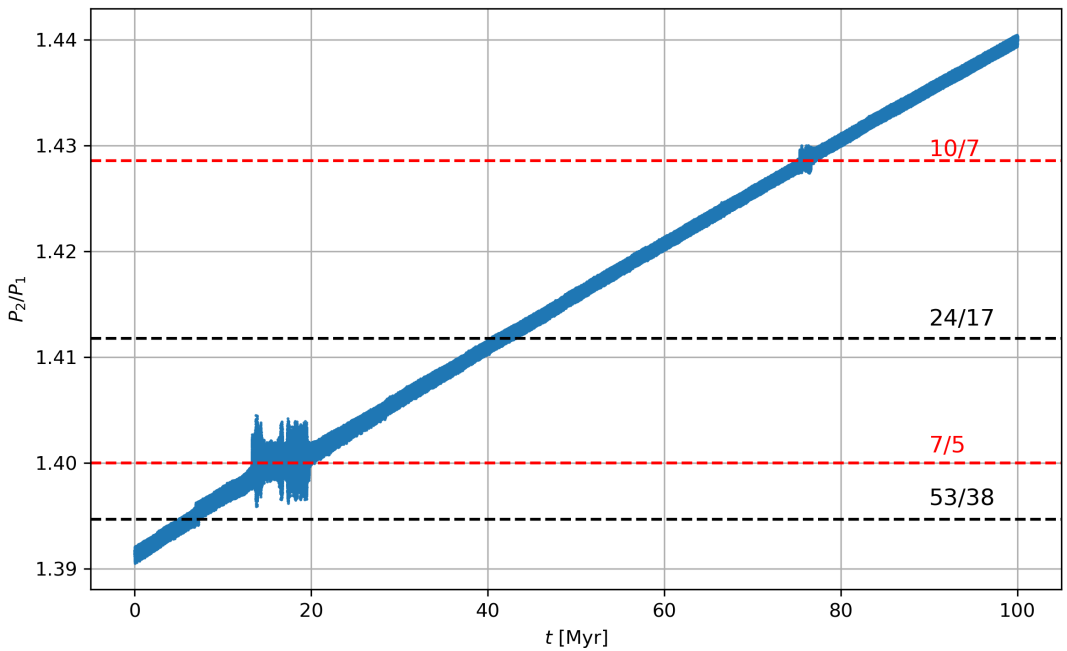


Resonances: Variation of masses

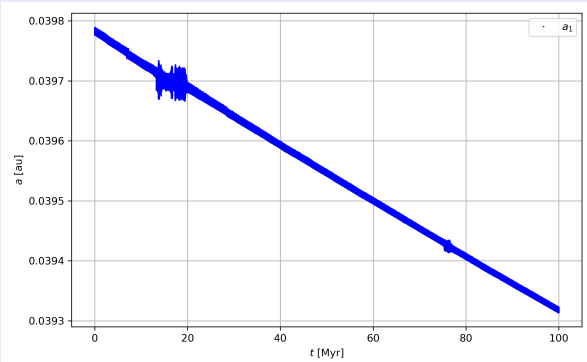
K2-72 b and K2-72 d (1–2) $M_\star = 0.27\ M_\odot$

$m_b = 1.39\ M_\oplus$ $m_d = 1.06\ M_\oplus$

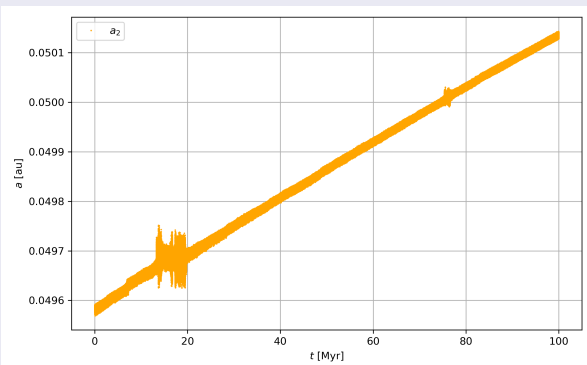
Ratio of periods P_d/P_b



Semi-major axis a_b



Semi-major axis a_d

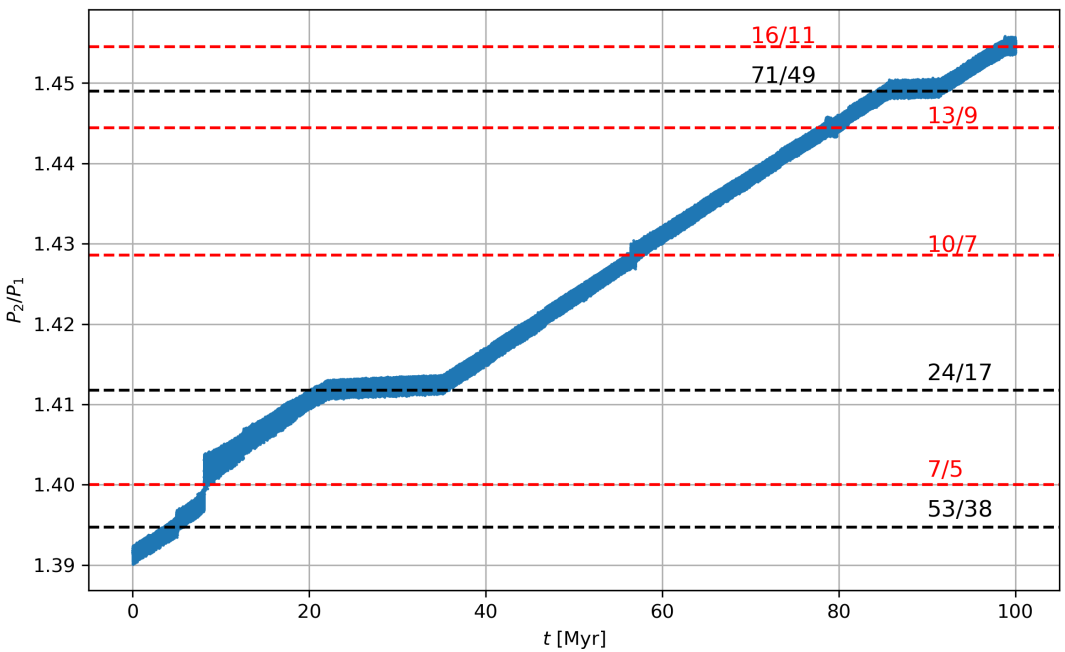


Resonances: Variation of masses

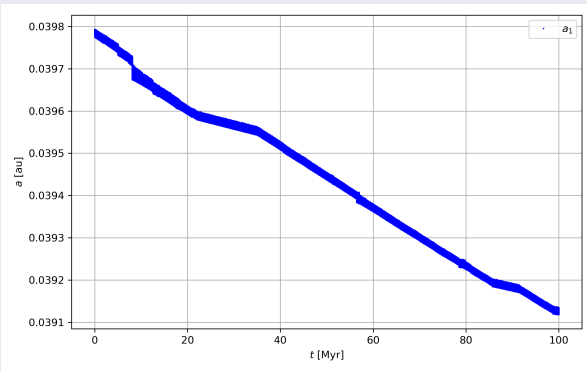
K2-72 b and K2-72 d (1–2) $M_\star = 0.27\ M_\odot$

$(m_b)_{max} = 1.92\ M_\oplus$ $(m_d)_{max} = 1.59\ M_\oplus$

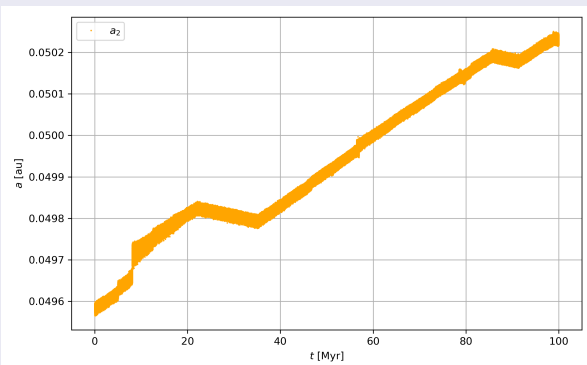
Ratio of periods P_d/P_b



Semi-major axis a_b



Semi-major axis a_d



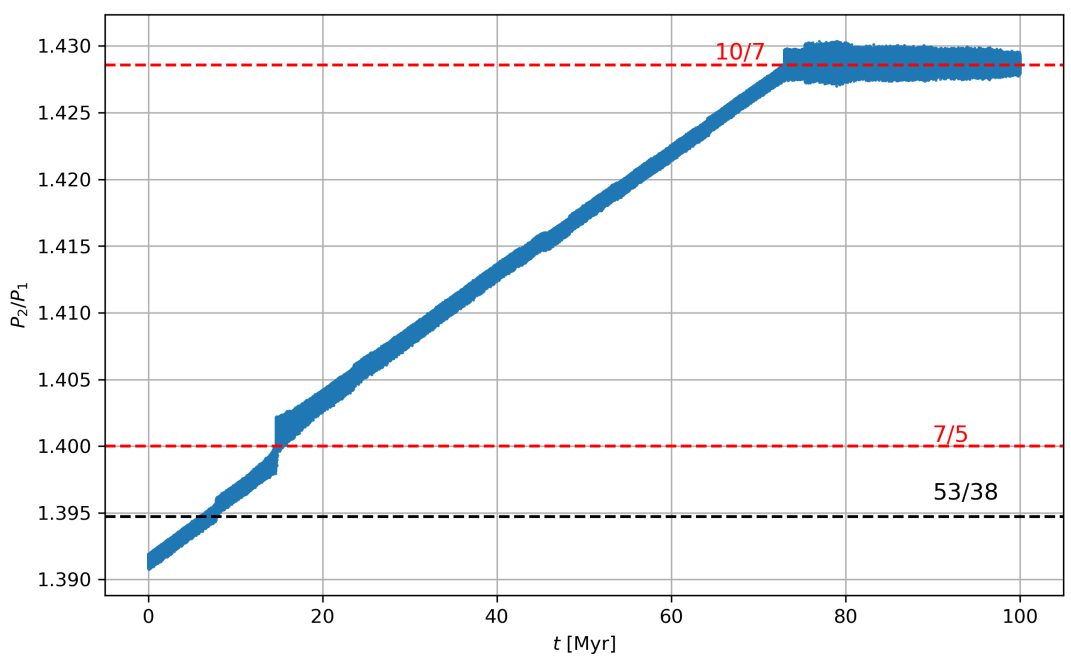
Resonances: Variation of masses

K2-72 b and K2-72 d (1–2)

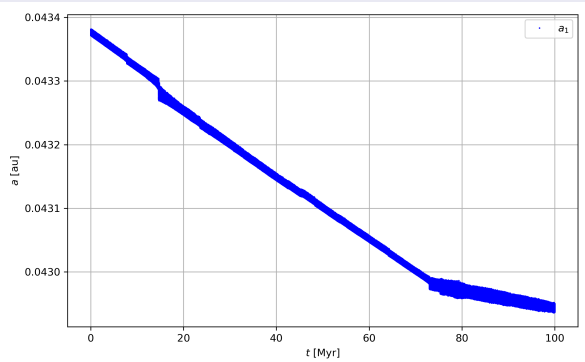
$M_{\star\,max} = 0.35\ M_\odot$

$m_b = 1.39\ M_\oplus \qquad m_d = 1.06\ M_\oplus$

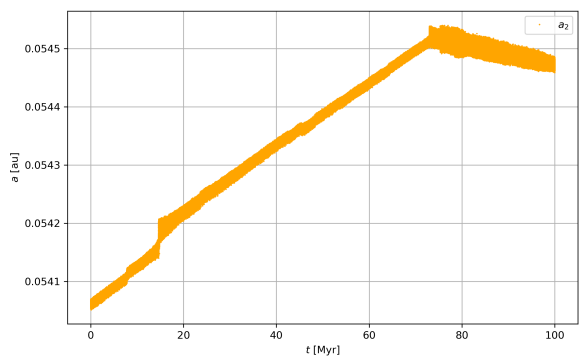
Ratio of periods P_d/P_b



Semi-major axis a_b



Semi-major axis a_d



Variation: Star rotation period

M dwarf stars rotation periods P_{rot} depend on ages τ (Engle and Guinan, RNAAS, 2018):

$$P_{rot}(days) = \frac{\tau(Gyr) - 0.012}{0.061}$$

$\tau = 1$ Gyr, $P_{rot} = 16$ days $\qquad$ $\tau = 10$ Gyr, $P_{rot} = 164$ days

Semi-major axes drift

Variation of parameters

- Masses of star $M_\star$ and planets m_p: from min to max
- Star's rotation period P_{rot}: from 16 to 164 days
  (Star's age τ: from 1 to 10 Gyr)
- Dissipation factor for M dwarf stars: $Q'_\star = 10^6 - 10^9$
  (Wu+, ApJ 963 (2024) 34)

Semi-major axes drift da/dt

Planet	da/dt [au/yr]
K2-72 b	$-(3.2 - 8.1) \times 10^{-12}$
K2-72 d	$+(4.3 - 7.1) \times 10^{-12}$
K2-72 c	$+(0.8 - 2.1) \times 10^{-12}$
K2-72 e	$+(0.9 - 2.2) \times 10^{-12}$

Ratio of periods P_2/P_1

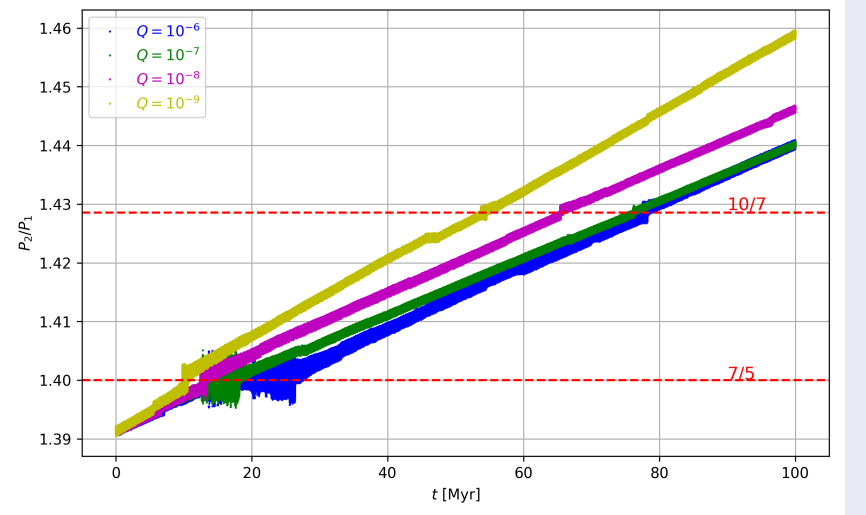
K2-72 b and K2-72 d (1–2)

$M_\star = 0.27\ M_\odot$ $m_b = 1.39\ M_\oplus$ $m_d = 1.06\ M_\oplus$

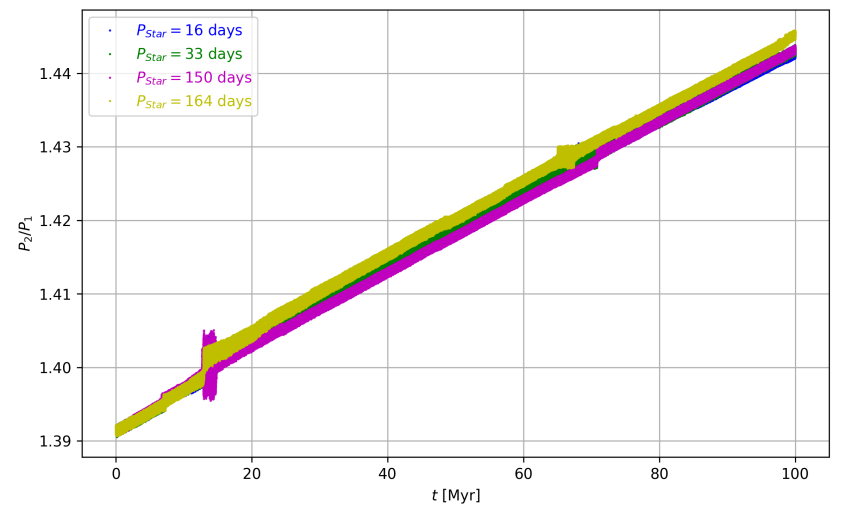
$P_{rot} = 150$ days

$Q'_\star = 10^6$

Variation: Dissipation factor $Q'_\star$



Variation: Star's rotation period P_{rot}



Orbital decay

Planetary orbital decay: K2-72 b

- Based on (Barker, MNRAS 498 (2020) 2270-2294) for $P_{rot} = 147$ days

$$t_{\rm fall} \approx 6.66 \times 10^{11} \left(\frac{Q'_\star}{10^4} \right) \rm yr$$

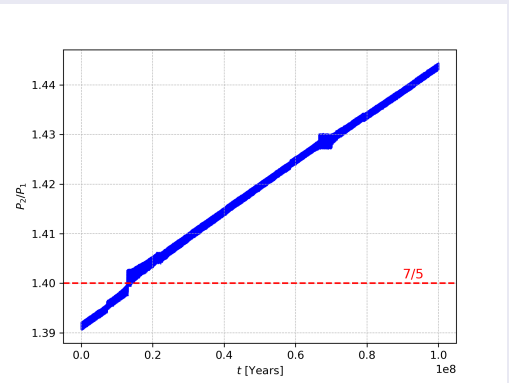
- $Q'_\star = 10^6$
- $t_{\rm fall} \approx 6.66 \times 10^{13}$ yr $= 66\,600$ Gyr $\approx$ 5000 ages of the Universe

- The lifespan of a red dwarf with $M_\star = 0.27\ M_\odot$ is approximately $100 - 500$ Gyr (Adams+, RMxAC 22 (2024) 46).

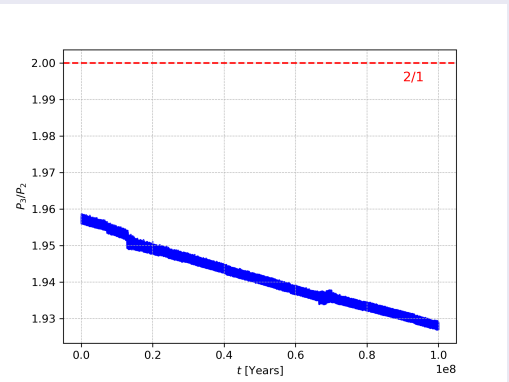
Trapping the resonances in the past

"*Resonant configurations are expected to be more common in younger systems*" (Dai+, AJ 168 (2024) 239).

- Approximately 120 Myr ago the planets K2-72 b and K2-72 d (1–2) were near the 4/3 resonance
- Approximately 155 Myr ago the planets K2-72 d and K2-72 c (2–3) were near the 2/1 resonance



K2-72 b and K2-72 d (1–2)



K2-72 d and K2-72 c (2–3)

Trapping the resonances in the past

$$T_0 = -155 \text{ Myr} \quad M_\star = 0.27\ M_\odot$$

$$m_b = 1.39\ M_\oplus \quad m_d = 1.06\ M_\oplus \quad m_c = 1.75\ M_\oplus \quad m_e = 2.65\ M_\oplus$$

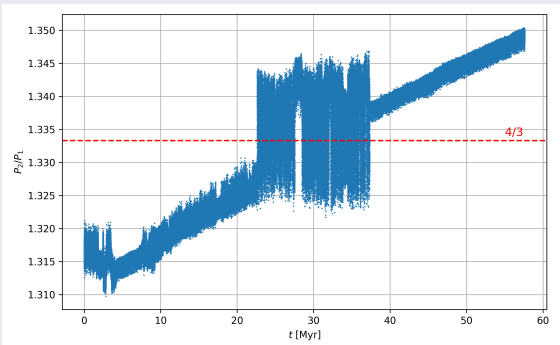
$$e_b = e_d = e_c = e_e = 0.02$$

K2-72 b and K2-72 d (1–2)

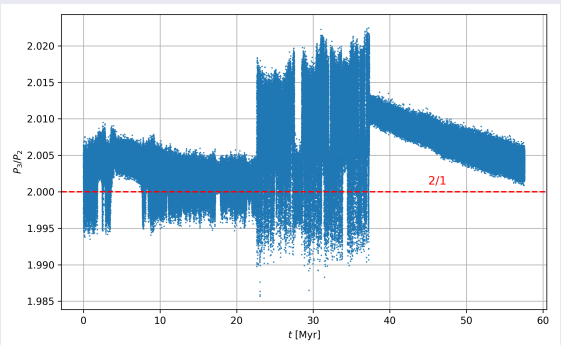
K2-72 d and K2-72 c (2–3)

K2-72 c and K2-72 e (3–4)

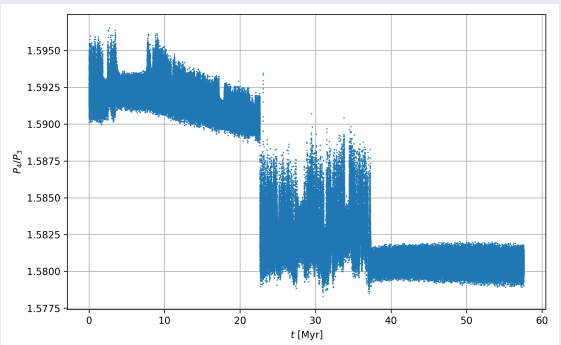
P_d/P_b



P_c/P_d



P_e/P_c



Resonant angles circulate.

Conclusions and future plans

Conclusions

- Currently, the compact planetary system K2-72 likely evolves beyond low-order resonances.
- The results depend significantly on the masses of the star and the planets.
- If the orbital eccentricities do not exceed 0.03, the evolution of the compact planetary system K2-72 over 100 Myr remains stable in the presence of tidal perturbations.

Future plans

- To investigate the conditions under which the system traps low-order resonances (2/1 and 4/3) without disintegrating.

Thank you for your attention!