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Investigation of the dynamical evolution of the compact planetary system K2-72

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Abstract. We consider the dynamic evolution of the compact four-planet system K2-72. The star K2-72 is an M-type dwarf. The system contains three Earth-like planets and one super-Earth. We searched for low-order resonances within the uncertainty of determining the periods of the planets. To determine the resonant combinations of the semimajor axes of the orbits, the ratio of the mean motions of neighboring planets was represented as a segment of a sequence of convergent fractions. We considered a few scenarios for the evolution of the K2-72 system over 100 Myr using the Posidonius software, which allows for tidal interactions. We have shown that the compact planetary system K2-72 likely evolves beyond low-order resonances. A significant change in the semimajor axes of the orbits of the planets K2-72 b and K2-72 d leads to the moving of the adjacent planets b–d and d–c out of the 7/5 and 8/5 resonance regions, respectively. The adjacent planets K2-72 d and K2-72 c are located far from the 2/1 resonance, which excludes the possibility of forming chains of mean motion resonances and, hence, 3-planet mean motion resonances. If the orbital eccentricities do not exceed 0.03, the evolution of the compact planetary system K2-72 over 100 Myr remains stable even in the presence of tidal perturbations.

Keywords: planets and satellites: dynamical evolution and stability

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1 Introduction

At present, several dozen compact planetary systems containing more than two planets with masses of the order of the Earth's mass are known . It is shown that the stable evolution of compact planetary systems requires the presence of resonances that prevent close encounters of planets moving in neighboring orbits (see, for example, the five-planet systems Kepler-80 (MacDonald et al. 2016), K2-138 (MacDonald et al. 2022), and the seven-planet system TRAPPIST-1 (Luger et al. 2017)). In this case, resonances between pairs of planets can form chains. The longest resonance chain known to date exists in the TRAPPIST-1 system: 8/5–5/3–3/2–3/2–4/3–3/2 (Murphy & Armitage 2022). In the K2-138 system, five planets form the longest chain consisting of identical 3:2 resonances (MacDonald et al. 2022). On the other hand, simulation results show that in wide systems with massive planets, chains of high-order resonances can lead to the destruction of planetary systems (Murphy & Armitage 2022).

We consider the dynamic evolution of the compact four-planet system K2-72. The star K2-72 is an M-type dwarf. The system contains three Earth-like planets and one super-Earth. We searched for low-order resonances within the uncertainty of determining the periods of the planets. We considered a few scenarios for the evolution of the K2-72 system over 100 Myr using the Posidonius software (Blanco-Cuaresma & Bolmont 2017), which allows for tidal interactions.

2 Resonance arguments

When analyzing the resonance properties of planetary systems, it is necessary to study the behavior of the resonance arguments. For two planets i and $i+1$, which are in a mean motion resonance $k_i/(k_i–l_i)$, the resonance argument can be given as follows (Huang & Ormel 2022):

$$\varphi_{i,\ i+1,\ i+s} = (k_i - l_i)\,\lambda_i - k_i\lambda_{i+1} + l_i\varpi_{i+s}, \tag{1}$$

where l_i is the order of resonance, λ_i and λ_{i+1} are the mean longitudes of planets i and $i+1$, respectively, ϖ_{i+s} is the longitude of the pericenter of planet i $(s=0)$ or $i+1$ $(s=1)$. For the next pair of planets $i+1$ and $i+2$, which are in resonance $k_{i+1}/(k_{i+1}–l_{i+1})$, the resonance argument is defined as follows:

$$\varphi_{i+1,\ i+2,\ i+1+s} = (k_{i+1} - l_{i+1})\,\lambda_{i+1} - k_{i+1}\lambda_{i+2} + l_{i+1}\varpi_{i+1+s}. \tag{2}$$

Instead of two resonances between two adjacent pairs of planets, one can consider three-body resonances. In this case the three-body resonance is a chain of two two-body resonances $k_i/(k_i–l_i)$ and $k_{i+1}/(k_{i+1}–l_{i+1})$ with the resonance argument which does not depend on the the longitude of the pericenter (Huang & Ormel 2022):

$$\Phi^{p,\ p+q,\ q}_{i,\ i+1,\ i+2} = p\lambda_i - (p+q)\,\lambda_{i+1} + q\lambda_{i+2}, \tag{3}$$

where $p = l_{i+1}(k_i – l_i)$, $q = l_i k_{i+1}$. For three-body resonances we will use the following notation: $(p, –(p+q), q)$.

3 Compact planetary system K2-72

The host star K2-72 is an M2 dwarf with a mass of $0.27^{+0.08}_{-0.09}\ M_\odot$ and a radius of $0.33^{+0.03}_{-0.03}\ R_\odot$. Table 1 gives the parameters of the K2-72 planetary system. The radii R of the planets are expressed in Earth radii $R_\oplus$. Planetary masses m are expressed in Earth masses $M_\oplus$ and calculated from the radii of the planets R, assuming that the density ϱ of a planet depends on its radius as (Weiss & Marcy 2014)

$$\varrho = 2.43 + 3.39\left(\frac{R}{R_\oplus}\right)\ \mathrm{g\,cm^{-3}} \tag{4}$$

for $R < 1.5\ R_\oplus$. The orbital elements P, e, i, and g are the period, eccentricity, inclination, and periapsis argument, respectively. The moment T_{conj} corresponds to the conjunction of the planet with the star.

Table 1. Parameters of the planetary system K2-72 (Dressing et al. 2017).

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	$7.760178^{+0.001496}_{-0.001496}$	$24.158868^{+0.003726}_{-0.003850}$
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}

4 Numerical simulations

For compact systems, an important factor affecting their evolution is tidal interaction; therefore, we considered a few scenarios for the evolution of the K2-72 system over 100 Myr using the Posidonius software (Blanco-Cuaresma & Bolmont 2017), which takes into account tidal interactions. At nominal values of the periods and eccentricities, the simulation ended with the decay of the system 3 Myr after the start of integration. This is because at eccentricities of 0.11 the distance at the apocenter of the planet K2-72 b orbit becomes greater than the distance at the pericenter of the planet K2-72 d orbit. If the initial eccentricities of orbits of all the planets are set equal to the minimum value of 0.02, the system remains stable over the entire considered interval of 100 Myr for all star masses from 0.18 to 0.35 $M_\odot$.

The results of the simulations including tidal interactions show that the compact four-planet system K2-72 can have a stable dynamical evolution in the absence of low-order resonances. Based on the results of numerical simulations with the Posidonius software, we obtained the limits on the maximum eccentricities of the orbits of the planets at which the system remains stable over 100 Myr (see Table 2). If the initial eccentricity values are greater than those given in Table 2, the system decays. If the orbital eccentricities do not exceed 0.03, the evolution of the compact planetary system K2-72 over 100 Myr remains stable even in the presence of tidal perturbations. In the case the initial eccentricities of the orbits of the three planets are equal to 0.04, the eccentricities of the orbits of one of the planets K2-72 d or K2-72 e should not exceed 0.03 to ensure the stability of the system.

Table 2. Initial values of orbital eccentricities e_0 at which the planetary system does not disintegrate.

Initial	K2-72 b	K2-72 c	K2-72 d	K2-72 e
e_0	0.04	0.04	0.04	0.03
e_0	0.04	0.04	0.03	0.04
e_0	≤ 0.03	≤ 0.03	≤ 0.03	≤ 0.03

5 Resonant properties of K2-72

In Dressing et al. (2017) it was noted that the orbital periods of the planets are close to commensurability, and it was suggested that mean-motion resonances (MMR) may exist in the K2-72 system. We performed a search for possible resonances in the system for the case when the numerator and denominator in the approximation $k_i/(k_i - l_i)$ of the ratio of the periods P_j/P_i of adjacent planets i and j do not exceed 10. For each resonance, we estimated the resonance offset (Charalambous et al. 2023):

$$\Delta_{ij} = \frac{P_j}{P_i} - \frac{k_i}{k_i - l_i}. \tag{5}$$

Table 3 gives the potential mean-motion resonances and resonance offsets Δ (Eq. 5) for adjacent planets of the K2-72 system. The arrangement of planets in the system in order of distance from the star: 1—K2-72 b, 2—K2-72 d, 3—K2-72 c, 4—K2-72 e.

Table 3. Mean-motion resonances and resonance offsets for the K2-72 system.

Adjacent 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

We have shown that the compact planetary system K2-72 likely evolves beyond low-order resonances. A significant change in the semimajor axes of the orbits of the planets K2-72 b and K2-72 d leads to the moving of the adjacent planets b–d and d–c out of the 7/5 and 8/5 resonance regions, respectively. The adjacent planets K2-72 d and K2-72 c are located far from the 2/1 resonance, which excludes the possibility of forming chains of mean motion resonances and, hence, three-planet mean motion resonances (see Fig. 1).

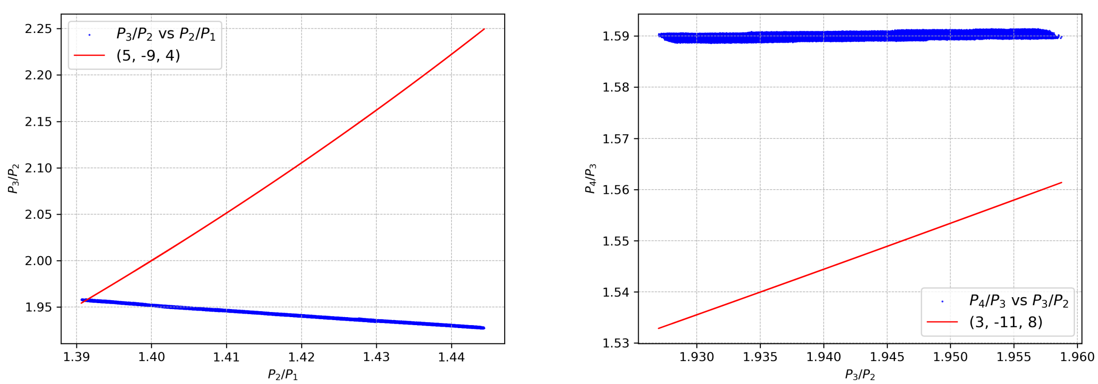

Fig. 1. Evolution of the period ratios of adjacent planets in the K2-72 system over 100 Myr: P_3/P_2 vs P_2/P_1 (left panel) and P_4/P_3 vs P_3/P_2 (right panel). The blue dots correspond to the ratio of the periods of adjacent planets, the red lines show the positions of the three-body resonances. The system evolves from left to right.

6 Conclusions

The study shows that the compact planetary system K2-72 is not resonant. Under the initial conditions corresponding to the masses and orbital elements of the planets determined from observations with their errors taken into account, the evolution of the K2-72 system is stable and regular over of 100 Myr for initial orbital eccentricities not exceeding 0.3.

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