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Mass determination of outer giant planets in systems Kepler-25, Kepler-65 and Kepler-68 via orbital stability analysis

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Abstract. Exoplanetary systems consisting of a group of objects on internal compact orbital paths, with masses ranging between those of Super-Earths and Mini-Neptunes, have been found to be often accompanied by giant planets on external orbits of moderate eccentricity. Some of these systems are Kepler-25, Kepler-65 and Kepler-68 and it is still not clear how these systems reached their orbital configurations they present. Those are not abundant in recent discoveries possibly because of observational biases or, more interestingly, because of dynamical mechanisms acting on these systems. The external planets in Kepler-25, Kepler-65 and Kepler-68 were discovered by the method of radial velocity, therefore only the minimum values of their masses are known. Assuming the systems to be dynamically stable in the long run, this study aims to set an upper limit for the external giants' masses by performing a series of numerical simulations of the planetary systems' dynamics and by analysing those using various stability criteria. For the three systems of interest, the following aspects are to be examined: time dependent evolution and maximum variation of orbital elements, mean motion resonance (MMR) effects, occurance of crossing orbits, collisions and ejections.

Resumo. Existem sistemas de exoplanetas formados por um conjunto de objetos em órbitas internas e compactas, com massas geralmente entre super-Terras e mini-Netunos, acompanhados por planetas gigantes em órbitas externas de excentricidade moderada. Exemplos deles são os sistemas Kepler-25, Kepler-65 e Kepler-68. Ainda não está claro como esses sistemas atingiram as configurações observadas, as quais não são abundantes. Dessa forma, é possível tratar-se de efeitos de viés observacional ou dinâmicos. Os planetas gigantes externos dos sistemas Kepler-25, Kepler-65 e Kepler-68 foram detectados pelo método da velocidade radial e sabe-se apenas o valor mínimo de suas massas. Assumindo que os sistemas observados são dinamicamente estáveis, este estudo busca impor um limite superior para as massas dos planetas externos a partir da realização de simulações numéricas e da análise dinâmica desses três sistemas utilizando critérios de estabilidade variados. Para os três sistemas, examina-se, portanto, aspectos como: evolução temporal e variações máximas dos elementos orbitais; efeitos de ressonância de movimentos médios; ocorrência de cruzamento de órbitas, colisões e ejeções.

Keywords. Celestial Mechanics – Planets and satellites: dynamical evolution and stability

1. Introduction

Recent exoplanet confirmations attest there is a rich variety of orbital architectures these systems can display, suggesting a growing awareness to celestial mechanics' possibilities as the scientific community advances in transit and radial velocity measuring techniques (Pu & Lai, 2018). Along with this new knowledge comes the challenge to explain mass distribution in planetary systems, meaning the types of planets being discovered - whether rocky or gaseous, highly massive or not, as well as their relative distance to the star and to each other-, and to characterize dynamical evolution in the observed systems. In this context, to study celestial dynamics is interesting not only to explore theoretical predictions, but also to constrain properties of planets. Dynamical phenomena have the potential to sculpt formed systems and actually determine how mass is spacially spread by means of gravitational interactions and dissipative effects, therefore establishing mass value limits (Becker et al., 2017).

In a more specific scenario, compact systems with external giants on moderately eccentric orbits as well as resonant inner planets are not frequent and the feasibility of their configurations ought to be clarified. These type of systems are fertile soil to implement theory and make mass predictions, which enforces the scientific relevance of this research and future observational evidence will be able to verify the prediction power of our current dynamical models in planetary sciences.

2. Methodology

Planetary dynamics of Kepler-25, Kepler-65 and Kepler-68 is studied using numerical integration tools and initial conditions that are in accordance with orbital parameters and planetary masses characterized in previous works. These parameters can be read in Table 1. We use the Mercury integrator for the N-body numerical simulations.

The work is devided in two parts. First, the orbits of all planets in the systems are assumed to be approximately coplanar and the only changing variable in the simulations are the external giants' masses, ranging between the minimum mass observed by radial velocity method and a maximum value of 10 M_J. One aim is to verify the presence or absence of instabilities during simulation time and the sensitivity of the inner planets' dynamics to the increasing of the external planet's mass. To be examined, are the maximum eccentricity of the three systems' internal planets' orbits, the maximum semi-major axis variation, the maximum eccentricity variation and the occurrence of crossing orbits. Simulations will be run for 1 million year predictions, about 70 million times the innermost planet's period, and the Burlisch-Stoer (general) integration method is to be used.

Afterwards, dynamical mean motion resonance maps are to be built for systems Kepler-25 and Kepler-65: both present a near commensurability of orbital periods between two of their internal planets. Kepler-25's planets b and c are in a near 2:1 MMR, while Kepler-65's planets c e d are in a near 7:5 MMR. In addition, we analyze the time variation of the critical angles of both MMRs and discuss their regimes of oscillation or circulation.

Observed Systems' Parameters										
Systems' Properties	Kepler-25			Kepler-65				Kepler-68		
M* ($M\odot$)	1.22			1.199				1.079		
R* ($R\odot$)	1.36			1.399				1.243		
Planet	b	c	d	b	c	d	e	b	c	d
Planetary mass ($M\oplus$)	8.7	15.2	0.226 M_J	2.4	5.4	4.14	0.653 M_J	7.65	2.04	0.77 M_J
Semi-major axis a (au)	0.0709	0.114	0.515	0.0347	0.0676	0.0841	0.8445	0.072	0.1057	1.728
Eccentricity e	0.0029	0.0061	0.13	0.028	0.020	0.014	0.283	0.0	0.0	0.112
T (days)	6.238	12.721	122.4	2.155	5.859	8.132	258.8	5.398	9.6051	634.6
I (º sky plane)	92.7	92.827	-	92.2	92.33	92.35	-	87.60	86.93	-

Table 1. Kepler-25, Kepler-65 and Kepler-68 observed systems' parameters: initial conditions input for the 1 million year long simulations. The external giants' masses, given in M_J, are their minimum values determined by radial velocity (Millis et al., 2019; Gilliland et al., 2013).

3. Results

Figures were built using coplanar simulations' results. Figure 1 illustrates the maximum eccentricity variation for the inner planets of systems Kepler-25, Kepler-65 and Kepler-68 as a function of the respective external giants' masses for these systems, as these vary up to 10 M_J. For all three planetary systems studied, similar conclusions were obtained and simulations' results indicate fairly stable dynamical behavior. For all external planetary mass values that were tested and a simulation time of one million years, neither ejections nor planet-planet collisions nor planet-star collisions were obtained. Moreover, none of the simulations have resulted in orbital crossing of the inner planets, even though orbits might be significantly tightened together. Hence, ressonant mechanism is not necessary to prevent the inner planets from colliding with each other.

Furthermore, maximum eccentricity and maximum eccentricity variation values grow as the external giant's mass increase, as expected, with systems Kepler-25's and Kepler-65's innermost planetary orbits exhibiting a somewhat irregular behavior for external giants' masses larger than 6 M_J. However, since the actual maximum variation values are small, it is an arbitrary choice to define a specific limit value of eccentricity variation as stability criterion to determine an upper mass limit for the external planets in these coplanar simulated cases.

Figure 2 shows the dynamical map on maximum eccentricity variation for system Kepler-25. The map shows the typical V-shape structure associated with the 2:1 MMR between planets Kepler-25b and Kepler-25c. 22500 simulations were run, varying the initial semi-major axis and eccentricity for the system's less massive planet, Kepler-25b. Regions resulting in regular motion are colored in blue, whereas those more disturbed by the resonance are identified with warmer colors. The color value represents the maximum eccentricity variation of planet Kepler-25b in each simulation. The red point indicates the current values of semi-major axis and eccentricity of Kepler-25b (Millis et al., 2019). According to the map, Kepler-25b's observed orbital semi-major axis and eccentricity lead the system to an evolution characterized by small amplitude of eccentricity due to resonant forcing, in a time scale of a thousand days.

4. Conclusions

Systems Kepler-25, Kepler-65 and Kepler-68 reveal, at first analysis, fairly stable behavior for as long as one million years of simulation, for a large range of external giants' mass values, which is in accordance with the fact that the external orbits present large semi-major axis values compared to those of the innermost planets in the three systems. None of the systems exhibited neither collisions nor ejections and the apocentric distance of the innermost planetary orbits do not equal nor overtake the pericentric distance of other inner planets in any moment during simulations, which indicates an absence of crossing orbits events. This does not mean, however, that close encounters do not happen, which might point to instabilities and is still to be investigated in future work.

The dynamical map built for the Kepler-25 system indicates that planet Kepler-25b is out of the typical ressonant V-shape structure although planet b is in a near 2:1 mean motion resonance with planet Kepler-25c. For this system, the critical angles' evolution is also to be studied in future work. Succeeding simulations allowing planetary orbit inclinations and a random selection of initial orbital angle conditions might show results closer to the reality of the three systems. Any instabilities that arise will be an indication of limiting mass values for the external giants in Kepler-25, Kepler-65 and Kepler-68, which could not be determined in the first set of coplanar simulations presented in this paper. Besides, system Kepler-65 seems to have a near 7:5 MMR between its planets c and d, which has yet to be approached in further research and might influence significantly in the orbital stability analysis of this system.

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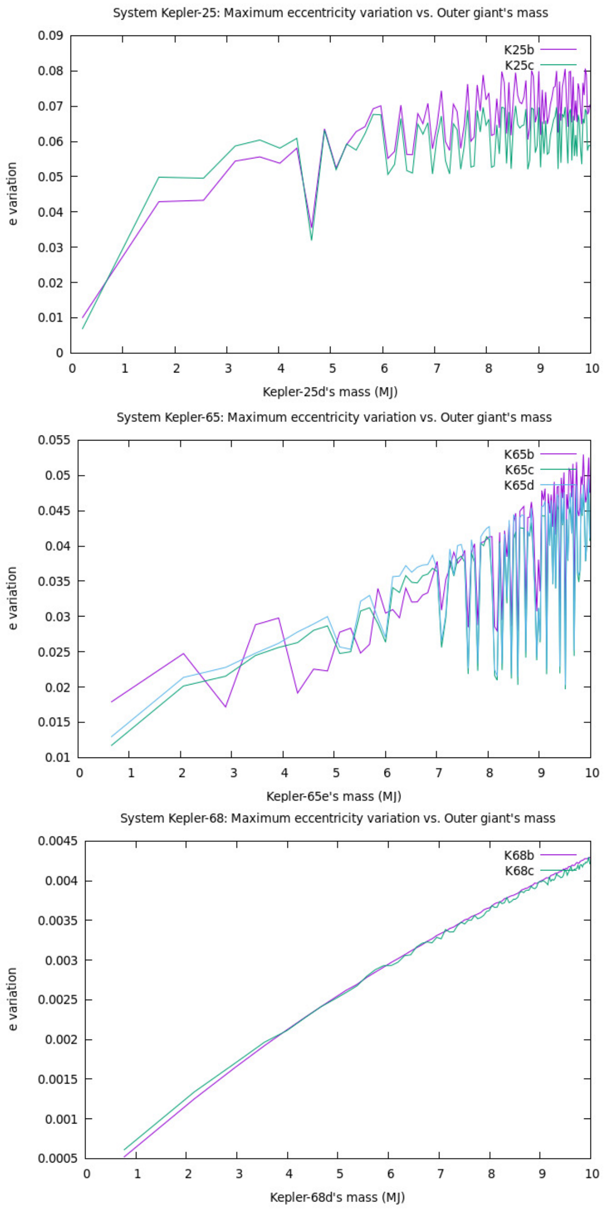

Figure 1. Maximum varitation of orbital eccentricity for the innermost planets in systems Kepler-25, Kepler-65 and Kepler-68 as function of the systems' external planet's mass for simulated coplanar scenarios.

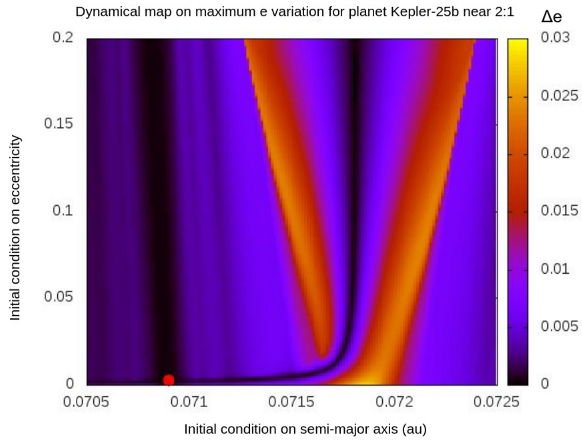

Figure 2. Dynamical map on maximum eccentricity variation for system Kepler-25's planet b in near 2:1 mean motion resonance with planet Kepler-25c.