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Orbital evolution of the GJ 667Cc exoplanet

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Abstract. In this work, we analyze the secular dynamics of a system composed of a central star and two planets under mutual gravitational influence. We consider the coplanar system formed by the star GJ 667C and the planets GJ 667Cb and GJ 667Cc. In this work, we investigate the orbital evolution of the potentially habitable super-Earth GJ 667Cc to identify if, over time, the exoplanet will remain in the habitable zone of the star system. We show that the orbital evolution of the planet GJ 667Cc depends on the initial value of the eccentricity, where the periastron of the orbit can remain in the habitable zone or migrate to the hot zone over time, depending on this parameter. Considering a star system with only two planets. In continuity of this work, the orbital evolution will be analyzed with the addition of other planets of this stellar system.

Resumo. Neste trabalho, analisamos a dinâmica secular de um sistema composto por uma estrela central e dois planetas sob influência gravitacional mútua. Consideramos o sistema coplanar formado pela estrela GJ 667C e os planetas GJ 667Cb e GJ 667Cc. Neste trabalho, investigamos a evolução orbital da super-Terra potencialmente habitável GJ 667Cc para identificar se, com o passar do tempo, o exoplaneta permanecerá ou não na zona habitável do sistema estelar. Mostramos que a evolução orbital do planeta GJ 667Cc depende do valor inicial da excentricidade, onde o periastro da órbita pode permanecer na zona habitável ou migrar para a zona quente ao longo do tempo, dependendo deste parâmetro. Considerando um sistema estelar com apenas dois planetas. Na continuidade deste trabalho, a evolução orbital será analisada com a adição de outros planetas desse sistema estelar.

Keywords. Celestial mechanics – Planet-star interactions – stability

1. Introduction

The GJ 667C system is a triple star system in the constellation Scorpius. In this work, we analyze the secular dynamics of a system composed of a central star (GJ 667C) and two planets (GJ 667C b, c), which are under mutual gravitational influence. In Carvalho et al. (2015) is investigated the secular dynamics of an exoplanet that moves around a central star disturbed by a brown dwarf. The disturbing potential is presented in closed form up to the fifth-order in a small parameter when the outer orbit is elliptical, planar and fixed in space. In an interesting paper Mardling (2013), where modern applications of celestial mechanics, including the study of exoplanet systems, have been presented in two generalizations of two classical expansions of the three-body perturbing function, simplifying considerably their original form. Focusing on coplanar systems. An interesting point is that it is only necessary to define a single disturbing function. In contrast, in the classical expansions one distinguishes between an "internal" and "external" disturbing function. Here in this present work, the mathematical modeling is considered from Mardling (2013), rather than using the approach presented in Carvalho et al. (2015). The choice was to consider a more modern modeling, as commented above. The double-averaging disturbing function up to the order octupole is given by equation (47) in Mardling (2013). The GJ 667C triple star system is a great research instrument, especially the planet GJ 667Cc that is in the habitable zone of the star GJ 667C and undergoes perturbations of the planet GJ 667Cb. The main objective of this work is to investigate the orbital evolution of the potentially habitable super-Earth GJ 667Cc to identify if over time the exoplanet will remain or not in the habitable zone of the star system. An analysis of the effects of disturbing force due to the third body in the orbital evolution of the planet is presented. In particular, we investigate the shape (eccentricity) of this orbit.

1.1. Results

For coplanar secular systems, only the rates of change of the eccentricities and longitude of the periastron are of interest. Considering the disturbing potential up to the octopole order (see Naoz et al. (2011)) given by equation (47) in Mardling (2013) and replacing in the Lagrange planetary equations, we get

$$\frac{de_i}{dt} = -n_i \frac{\left(45\,{e_i}^2+60\right)\sin(\varpi_i-\varpi_o)(m0-m1){a_i}^4 e_i\,\sqrt{-{e_i}^2+1}m2}{64\left(-{e_o}^2+1\right)^{5/2}(m0+m1)^2 {a_o}^4} \tag{1}$$

$$\begin{aligned}\frac{d\varpi_i}{dt} &= -n_i\Big(\frac{135\cos(w\varpi_i-\varpi_o){a_i}^3\sqrt{-{e_i}^2+1}m2}{64(-{e_o}^2+1)^{5/2}(m0+m1)^2{a_o}^4 e_i}\Big(\frac{16a_o e_i(m0+m1){e_o}^2}{45}+\\ &\quad (m0-m1)a_i({e_i}^2+4/9)e_o-\tfrac{16}{45}a_o e_i(m0+m1)\Big)\Big)\end{aligned} \tag{2}$$

$$\frac{de_o}{dt} = n_o \frac{\left(45\,{e_i}^2+60\right)m1\,(m0-m1){a_i}^3 e_i\,\sin(\varpi_i-\varpi_o)m0}{64\,(m0+m1)^3 {a_o}^3\left({e_o}^2-1\right)^2} \tag{3}$$

$$\begin{aligned}\frac{d\varpi_o}{dt} &= n_o\Big(\frac{45m1{a_i}^2m0}{16(m0+m1)^3{a_o}^3 e_o({e_o}^2-1)^3}\big(({e_i}^2+4/3)({e_o}^2+1/4)\times\\ &\quad (m0-m1)a_i e_i\cos(\varpi_i-\varpi_o)+2/5a_o e_o(e_o-1)\times\\ &\quad (e_o+1)(m0+m1)({e_i}^2+2/3)\big)\Big)\end{aligned} \tag{4}$$

Here $m0$ and $m1$ are the masses of the bodies forming the inner orbit, $m2$ is the mass of the outer body, with ϖ_i and ϖ_o the corresponding longitudes of periastron. We will use the subscripts i and o to represent quantities associated with the inner and outer orbits respectively (see Mardling (2013)). Where n_i and n_o are the mean motions of the inner and outer orbits, respectively. Here a_i and e_i, a_o and e_o are the semi-major axis and eccentricity of the inner and outer orbits, respectively.

To perform the simulations we used the eccentricity values of the planets GJ 667Cb and GJ 667Cc obtained from Tab. 5 in Makarov and Berghea (2014). We show here the result of only two simulations. The Eqs. (1), (2), (3) and (4) were numerically

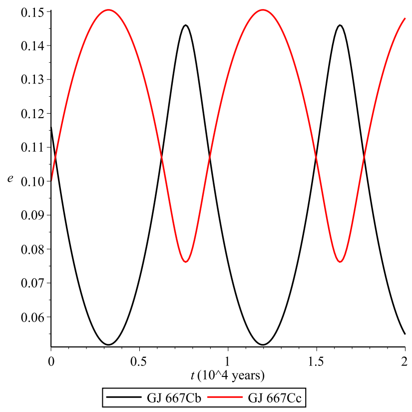

FIGURE 1. e versus t. Initial conditions $e_b = 0.116$ and $e_c = 0.1$.

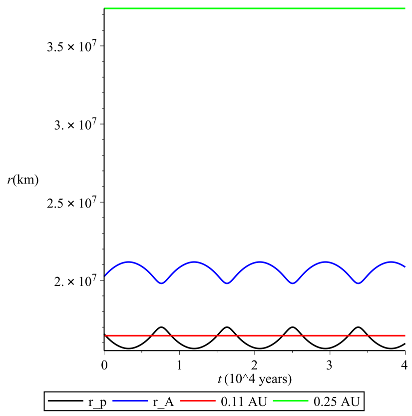

FIGURE 2. r versus t. Initial conditions $e_b = 0.116$ and $e_c = 0.1$.

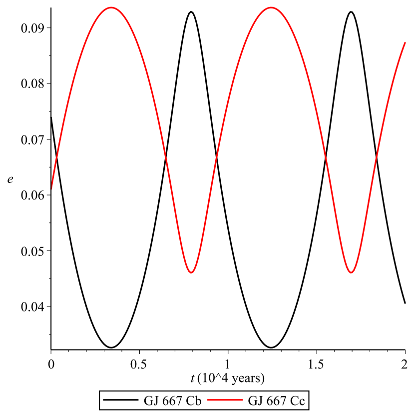

FIGURE 3. e versus t. Initial conditions $e_b = 0.074$ and $e_c = 0.061$.

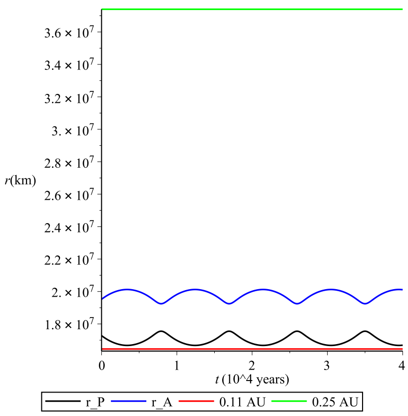

FIGURE 4. r versus t. Initial conditions $e_b = 0.074$ and $e_c = 0.061$.

integrated to analyze the behavior of the orbit of the planet GJ 667Cc. Figures 1 and 3 show that when the eccentricity of planet GJ 667Cc increases, the eccentricity of planet GJ 667Cb decreases and vice versa. Note that the eccentricity of the planet GJ 667Cb is more disturbed than planet GJ 667Cc. Comparing Figs. 1 and 3 we have that smaller the initial value of the eccentricity smaller the amplitude of variation. Figures 2 and 4 show the behavior of the position of the periastron (black curve) and of the apoastron (blue curve) of the planet GJ 667Cc. The red and green lines delimit the region of the habitable zone. Note that for greater eccentricity of the planet GJ 667Cc the orbit migrates from the habitable region to the hot zone of the star (see Fig. 2). For smaller values of the eccentricity the orbit is more stable, it remains within the habitable zone (see Fig. 4). In the continuity of this work we will analyze the stability of the orbit of the planet GJ 667Cc considering the interaction of other planets of the star system GJ 667C.

2. Conclusions

We consider the coplanar system formed by the star GJ 667C and the planets GJ 667Cb and GJ 667Cc. The planets are mutually perturbed and the disturbing potential due the mutual gravitational interaction is obtained from an interesting paper (Mardling (2013)). We verified that the orbital evolution of the planet GJ 667Cc depends on the initial value of the eccentricity, where the periastron of the orbit can remain in the habitable zone or migrate to the hot zone over time. It is important to determine the precise value of the eccentricity to check if the orbit of planet GJ 667Cc is in the habitable zone or not. The planet is in the habitable zone, but near the border of the hot zone, then great variations of the eccentricity cause migration between the regions. In this way we consider that the orbit of the planet GJ 667Cc is unstable for great values of eccentricity. Here we consider a star system with only two planets. In the continuity of this work will be analyzed the gravitational effect of the other planets of the GJ 667C star system.

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