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Orbital characteristics of planets of the TRAPPIST-1 system in the habitability zone

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Abstract. This work aims to analyze the secular dynamics of a system composed of a central star and two planets under mutual gravitational influence, in this specific case we consider the TRAPPIST-1 star system. The main objective is to analyze the orbital evolution of the planets that are in the habitable zone of this star. Considering the equations of motion, a system of non-linear differential equations that is numerically integrated using Maple software. Color maps are built to analyze the eccentricity behavior of the two planets considered in the dynamics. The idea is to verify if exoplanets that are in the habitable zone of the star TRAPPIST-1 can migrate from the habitable zone to the warm zone over time. We show the orbital evolution of exoplanets considering different initial values of the eccentricity, we observe whether the periastron can remain in the habitable zone or migrate to the warm zone over time. Therefore, if there is water on its surface, the star temperature can contribute to water evaporation.

Resumo. Este trabalho visa analisar a dinâmica secular de um sistema composto por uma estrela central e dois planetas sob influência gravitacional mútua, neste caso específico consideramos o sistema estelar TRAPPIST-1. O objetivo principal é analisar a evolução orbital dos planetas que se encontram na zona habitável desta estrela. Considerando as equações de movimento, um sistema de equações diferenciais não lineares que é integrado numericamente usando o software Maple. Mapas de cores são construídos para analisar o comportamento da excentricidade dos dois planetas considerados na dinâmica. A ideia é verificar se os exoplanetas que estão na zona habitável da estrela TRAPPIST-1 podem migrar da zona habitável para a zona quente ao longo do tempo. Mostramos a evolução orbital dos exoplanetas considerando diferentes valores iniciais da excentricidade, observamos se o periastro pode permanecer na zona habitável ou migrar para a zona quente ao longo do tempo. Portanto, se houver água em sua superfície, a temperatura da estrela pode contribuir com a evaporação da água.

Keywords. Planet-star interactions – Stability – Celestial mechanics

1. Introduction

TRAPPIST-1 is a cool red dwarf located approximately 39 light years from the Sun in the constellation Aquarius. Three of the seven exoplanets in this system lie in the star habitable zone. Therefore, this work seeks to study the secular dynamics of a triple system composed of a central star and a planet, which is under the gravitational influence of another planet and analyze the effects of the disturbing force due to the third body on the orbital evolution of the planets within of the habitable zone. Starting from the premise of the three-body stellar problem, we use the orbital data of exoplanets from the TRAPPIST-1 system presented in Gillon et al. (2017) and Grimm et al. (2018). For the mathematical modeling we used the equations of motion obtained by Carvalho et al. (2013, 2015, 2016). The modeling of the equations of motion was presented taking into account the elliptical and inclined three-body problem. The equations, which are nonlinear, were developed in closed form to avoid expansions in power series and, in this case, are valid for a variety of applications. Numerical integrations of the developed equations are performed. Applications are made to the exoplanets of the TRAPPIST-1 system to investigate the dynamics of these new planets discovered outside the solar system. The main objective of this work is to investigate the orbital evolution of potentially habitable exoplanets to identify whether, over time, the exoplanet will remain in the habitable zone of the stellar system.

1.1. Methods and Mathematical Models

The modeling of the motion equations is presented in Carvalho et al.(2015, 2016), taking into account the problem of three elliptical and inclined bodies. For orbital perturbations, in this work, we consider the disturbing potential expanded up to the third-order as presented in Carvalho et al. (2016). The triple Hamiltonian system can be written as follows Harrington (1968).

$$F = \frac{Gm_0m_1}{2a_1} + \frac{G(m_0+m_1)m_2}{2a_2} + \frac{G}{a_2}\sum_{j=2}^{\infty} \alpha^j M_j(\frac{r_1}{a_1})^j(\frac{a_2}{r_2})^{j+1}P_j(\cos\Phi) \tag{1}$$

The vector $\mathbf{r_1}$ represents the position of m_1 with respect to m_0 and the vector $\mathbf{r_2}$ is the position of the body m_2 in relation to the center of mass of the inner orbit. Φ is the angle between $\mathbf{r_1}$ and $\mathbf{r_2}$ and $G$is the gravitational constant, P_j these are Legendre polynomials. Therefore, for the model considered in this work, it is necessary to calculate the terms R_2 and $R_3$of the perturbing function due to the terms P_2 and P_3, of the Legendre polynomials, respectively.

$$R_2 = \frac{G}{a_2}\alpha^2 M_2(\frac{r_1}{a_1})^2(\frac{a_2}{r_2})^3 P_2(\cos\Phi) \tag{2}$$

$$R_3 = \frac{G}{a_2}\alpha^3 M_3(\frac{r_1}{a_1})^3(\frac{a_2}{r_2})^4 P_3(\cos\Phi) \tag{3}$$

$$R_0 = \frac{Gm_0m_1}{2a_1} + \frac{G(m_0+m_1)m_2}{2a_2} \tag{4}$$

The disturbing potential given by the Equation (1) can be written as

$$F = R_0 + R_2 + R_3 \tag{5}$$

Table 1. Data from selected exoplanets

EXOPLANETS	TR-1e	TR-1g
(a) semi-major axis[au]	0,02928285	0,0451
(i) Inclination	89.86°	89.710°
(g) argument of the periastron	108.37°	191.34°
(h) longitude of the ascending node	0.1°	0.1°
(e) eccentricity	0.00510	0.00208
(m) mass (times the mass of the Earth)	0.62*mEarth	1.34*mEarth

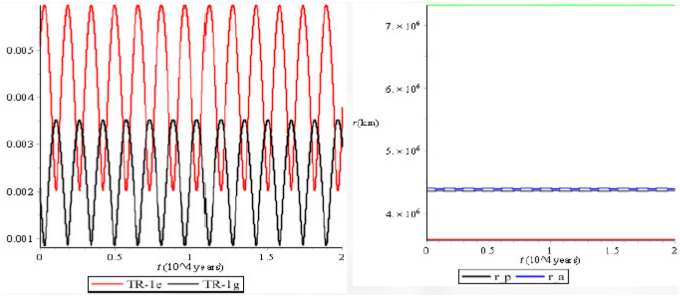

Figure 1. TR-1g e0 = 0.00208 / TR-1e; e0 =0.000510.

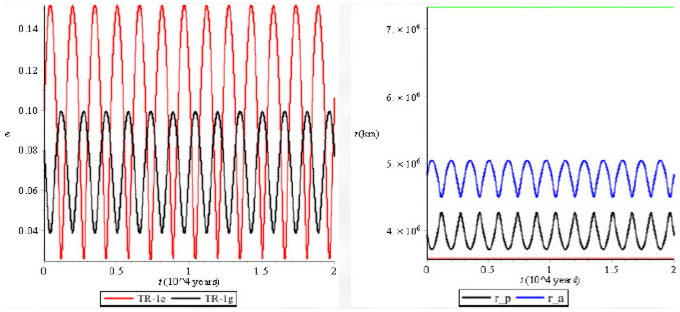

Figure 2. TR-1g e0 = 0.08 / TR-1e; e0 =0.1.

Replacing Equation (5) in the Lagrange Planetary Equations, a system of non-linear differential equations, via Software Maple to perform the numerical simulations.

1.2. Results

To perform the simulations we use the eccentricity values of the planets TRAPPIST-1e (TR-1e) and TRAPPIST-1g (TR-1g) given in Table 1, data obtained from Gillon et al. (2017) and Grimm et al. (2018). We present the eccentricity (*e*) versus time (*t*) graphs of each object, as well as a color map to observe the behavior of these orbits over time. Therefore, Fig. 1 and 2 (left figures) show the behavior of the eccentricity (we consider two initial values) in relation to time (red and black) of the exoplanet TR-1e disturbed by the exoplanet TR-1g with the disturbing potential expanded up to the third order (R2+R3) due to third body perturbation. Fig. 1 and 2 (right figures) show the region of the habitable zone between the horizontal lines. Fig. 3 shows that for different ordered pairs of the inclination and longitude of the ascending node (i1, h1), respectively, the maximum eccentricity is obtained according to the color scale. Darker colors indicate that TR-1e has entered the hot zone due to the gravitational perturbation of TR-1g.

Therefore, we present the graphics of each object, using the information listed in Table 1.

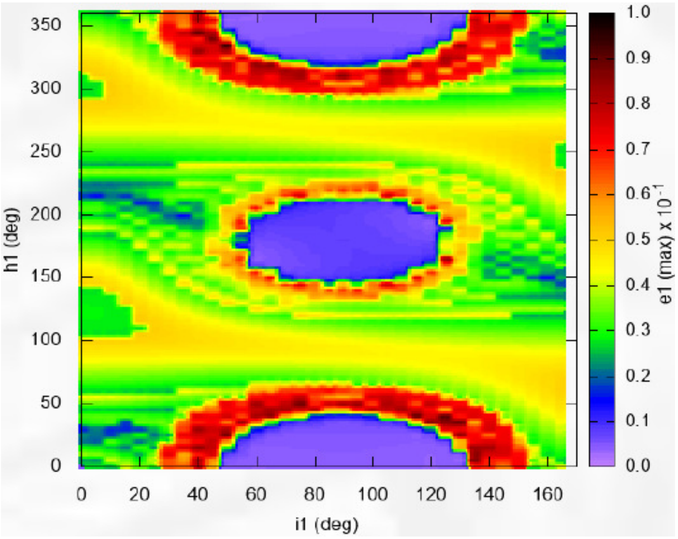

Figure 3. Color map of the variation of the inclination (i1) × longitude of the ascending node (h1) × eccentricity (e1) of the TR-1e.

2. Conclusions

From this analysis, we verify the orbital behavior of the TR-1e that remains within the habitable zone for the eccentricity value given in Table 1. Now, by changing the initial eccentricity, the planet approaches the hot zone, and of course, increasing the eccentricity value the planet migrates to the hot zone. But, as shown in Fig.3, the planet will enter the hot zone depending on the value of the longitude of the ascending node (value not yet calculated) and also the inclination, even keeping the inclination value given in Table 1, we show that the migration to the hot zone depends on the initial value of the longitude of the ascending node. Thus, it is considerable that new studies are carried out aiming at this system to analyze the orbital evolution of exoplanets.

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