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Particle dynamics of the ring around the dwarf planet Haumea

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Abstract. This work analyzes the dynamics of particles around Haumea's ring, identifying their main characteristics regarding stability and instability, as well as the behavior of individual particles. The main orbital perturbations are taken into account, which are: the perturbation due to the non-uniform mass distribution of Haumea, the perturbation of the third body (Namaka and Sun) and solar radiation pressure. We show, using color maps, the effect of each perturbation alone on the rate of change of the eccentricity. Considering all perturbations, we verified the dominance of the C_{22} harmonic, which referes to Haumea's ellipticity and equatorial non-sphericity, since particles remain stable within the ring system and with minimal eccentricity change.

Resumo. Este trabalho busca analisar a dinâmica das partículas do anel de Haumea identificando suas principais características quanto a estabilidade e instabilidade, além do comportamento de partículas individuais. Para este estudo leva-se em conta as principais perturbações orbitais, sendo: a perturbação devido a distribuição não uniforme de massa de Haumea, a perturbação do terceiro corpo (Namaka e o Sol) e à pressão de radiação solar. Mostramos, usando mapas de cores, o efeito de cada perturbação isoladamente na taxa de variação da excentricidade. Considerando todas as perturbações, verificamos a dominância do harmônico C_{22}, que se refere à elipticidade e não esfericidade equatorial de Haumea, visto que as partículas permanecem estáveis dentro do sistema do anel e com mínima variação de excentricidade.

Keywords. Celestial mechanics– Planets and satellites: rings – Minor planets, asteroids: individual: Haumea

1. Introduction

Haumea, originally called EL61 2003, is a Kuiper Belt dwarf planet, with a distance of 6,452,000,000 km or 43.13 astronomical units from the Sun. The dwarf planet has an ellipsoidal shape, with a radius of approximately 620 km, which is about 1/14 of the Earth's radius, an orbital period of 285 Earth years around the Sun and a 4 hours rotation period. It was discovered in 2004 but was only recognized as a dwarf planet by the International Astronomical Union in 2008. Haumea has two natural satellites, its moons Namaka and Hi'iaka, and in 2017, by stellar occultation, a ring of particles was discovered around the dwarf planet, in a region close to the 3:1 resonance between the Haumea spin and the mean motion of the particles in the ring. This work aims to analyze the dynamics of the ring particles around the dwarf planet Haumea, considering perturbations related to the non-uniform mass distribution of this dwarf planet with harmonic coefficients J_2 and J_4, referring to the flattening of this dwarf planet, mainly at the poles, and the term C_{22} , which is linked to Haumea's equatorial ellipticity and non-sphericity, the perturbation of the third body (Namaka and the Sun), and the direct solar radiation pressure (SRP). The analysis of the particles can help to identify more characteristics of the ring, in terms of stability and instability, in addition to providing information that will clarify its composition and origin.

2. Methodology

The disturbing potential R due to the non-uniform distribution of the Haumea mass is defined by the spherical harmonic coefficients J_2 and J_4 (flattening) and C_{22} (equatorial ellipticity). The equations are written in the form (Carvalho, 2019):

$$R_{J2} = -\frac{1}{4}\frac{\epsilon}{(1-e^2)^{3/2}}n^2(3s^2-2) \tag{1}$$

$$R_{J4} = \frac{3}{128}\frac{\epsilon_2}{(1-e^2)^{7/2}a^2}n^2(140e^2s^4(\cos(g))^2 - 120e^2s^2(\cos(g))^2 - 175e^2s^4 + 180e^2s^2 - 70s^4 - 24e^2 + 80s^2 - 16) \tag{2}$$

$$R_{C_{22}} = -\frac{3}{2}\frac{\delta}{(1-e^2)^{3/2}}n^2(c^2-1)\cos(2h-2\rho t) \tag{3}$$

where R_H represents the Haumea reference radius, n is the mean motion of the particle, c and s correspond to the cosine and sine of the angular inclination, respectively, g is the pericenter argument, e is the eccentricity, a is the semi-major axis and Ω is the longitude of the ascending node. The perturbation due to solar radiation pressure is developed in the single averaging model with the Sun in an elliptical and inclined orbit, and the function is given by Tresaco, Elipe & Carvalho (2016):

$$R_{SRP} = -\beta[\mu_\odot \frac{r}{r_\odot^2}\cos\psi + \frac{\mu_\odot}{2r_\odot}\left(\frac{r}{r_\odot}\right)^2(3(\alpha\cos f + \gamma\sin f)^2 - 1)] \tag{4}$$

where β is the luminosity number, μ is the gravitational parameter of the planet, $\mu_\odot$ is the gravitational parameter of the Sun, r is the distance from the particle to the planet, $r_\odot$ is the vector of the Sun's position in relation to the planet, f is the true anomaly and ψ is the angle between the vector radius r and $r_\odot$. The coefficients α and γ are obtained from the longitude of the ascending node and inclination of the particle and the third body, as well as the argument from the particle periapse and the true anomaly of the third body. The disturbing potential due to the third body is given by Murray & Dermott (1999):

$$R_p = \frac{\gamma G(m_0 + m_p)}{\sqrt{r^2 + r_p^2 - 2rr_p\cos(S)}} \tag{5}$$

where $\gamma = m_p/(m_0+m_p)$, with the masses of the central (m_0) and perturbed (m_p) bodies, r and r_p are the radius vectors of the m_0 and m_p bodies, respectively, and G is the constant of universal gravitation. S is the angle between the line connecting the massive central body to the disturbed body and the line connecting the massive central body to the disturbing body (the third body). The disturbing potential due to the moon Namaka and Sun are named R_{2MS_N} and $R_{2MS_{Sun}}$, respectively. Finally, the disturbing potential is written in the form: $R = R_{J_2} + R_{J_4} + R_{C_{22}} + R_{SRP}$

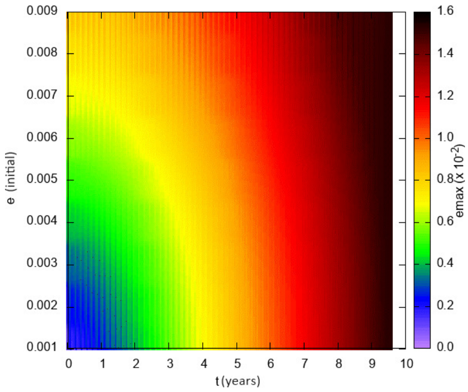

FIGURE 1. $R = R_{SRP}$

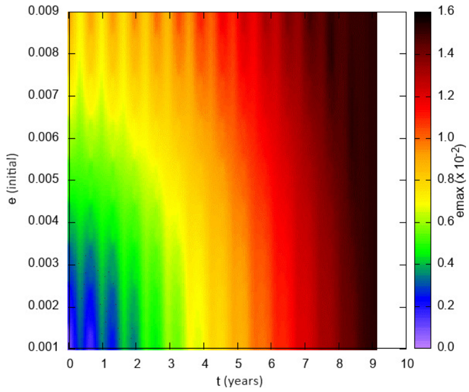

FIGURE 2. $R = R_{SRP} + R_{2MS_{Sun}} + R_{2MS_N}$

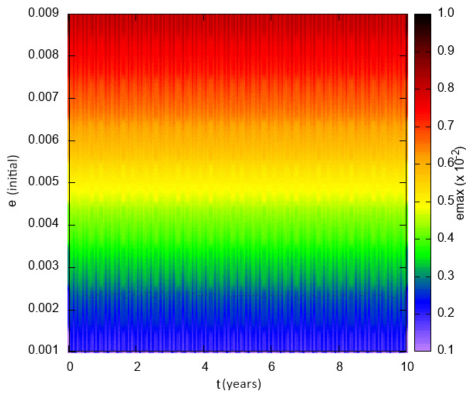

FIGURE 3. $R = R_{SRP} + R_{2MS_{Sun}} + R_{2MS_N} + R_{J_2} + R_{J_4}$

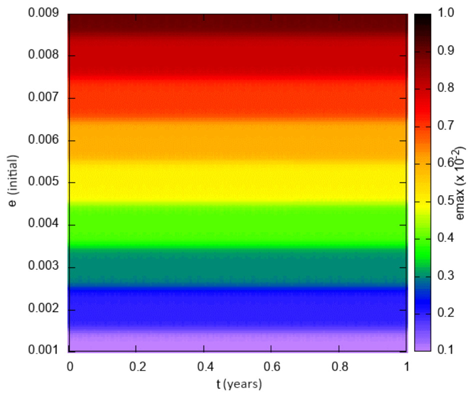

FIGURE 4. $R = R_{SRP} + R_{2MS_{Sun}} + R_{2MS_N} + R_{J_2} + R_{J_4} + R_{C22}$

$+ R_{2MS_{Sun}} + R_{2MS_N}$, being substituted in the Lagrange planetary equations and numerically integrated. Numerical simulations of the nonlinear differential equations system were developed via Maple Software.

3. Results

In this study, particles with a radial distribution of 1 μm were examined in almost circular orbits with an initial semi-major axis at a_0= 2,287 km, referring to the radius of the Haumea ring. The initial eccentricities adopted are: $0.001 - -0.009$. As for the orbital parameters, it is considered as initial conditions: $g = 0^o$, $h = 0^o$ and $i = 0.01^o$. From the results of numerical integrations, color maps were developed involving the initial eccentricity, maximum eccentricity and the integration time. The 1 μm particles have mass equal to $m_p = 3.8537\ 10^{-12}\ g$ and mass-area ratio $\sigma = 0.3067\ g/m^2$.

In Figure 1, considering only the perturbation due to solar radiation pressure, particles escape the ring system before 10 years. It is noticed cause small particles are sensitive to solar radiation due to the large proportion of their volume affected. In Figure 2, with the perturbations due to solar radiation pressure, Namaka and the Sun, the time particles remain within the ring system is around 9 years. This means that the gravitational influence of Namaka and the Sun on particles close to the ring location is not that significant. In Figure 3, with perturbations due to solar radiation pressure, the Sun, Namaka, J_2 and J_4, it is verified by the maps that the particles remain more stable in the system, with less eccentricity change than Figure 1 and 2 cases. An integration time of 10 years was adopted in this analysis to have a better visualization of the eccentricity change, but particles can remain in the ring system for more than 50 years. In simulations considering $R = R_{J_2} + R_{SRP} + R_{2MS_{Sun}} + R_{2MS_N}$, that is, without the J_4 term, the behavior is similar to the Figure 3 case, with no significant changes. In Figure 4, considering all the perturbations in the study, thus adding the effect of the C_{22} term on the dynamics, the particles remain totally stable in the system, with minimal eccentricity variations. The integration time adopted is 1 year, for better visualization, but the particles manage to remain in the system for more than 50 years. Therefore, it can be inferred that the C_{22} harmonic is dominant in the dynamics of the particles in the ring. It means that the fast rotation linked to the Haumea equatorial ellipticity and non-sphericity ensure that the particles stabilize in the region where the ring is located.

4. Conclusions

We verified that the solar radiation pressure effect strongly contributes to remove the particles from the ring, but when the Haumea equatorial ellipticity (C_{22}) is taken into account the particles remain in a stable region, because the eccentricity variation is minimal and within the limits of the ring radius.

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