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Ranges and options for non-Keplerian orbits of spacecraft around asteroids

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Abstract

The goal of our study is to explore a natural phenomenon in celestial mechanics – the motion of particles in periodic stable orbits governed by radiation pressure. These orbits are not limited to invariable orbits over the body's terminator and enable a spacecraft to observe the body under a variety of lighting conditions. We compare orbital stability and give size limits of terminator orbits for selected asteroid targets.

1. Introduction

Missions to asteroids and dwarf planets are an increasingly important part of space exploration. The non-Keplerian orbits occurring in the faint gravity fields of minor bodies may be of interest for spacecraft mission planners and planetary scientists alike. We will focus on small asteroid targets of recent or upcoming missions like: Hayabusa-2, OSIRIS Rex, Marco-Polo-R and Hera. We will study the stable motion of spacecraft in such orbits and how these orbits may be used for mapping of the asteroid targets.

2. Methods

We analyze the particle motion with three different models, two are analytical and one numeric.
I: Considering solar radiation pressure and the asteroids gravity, but ignoring the heliocentric movement for the time, the equation of movement can be solved in cylindrical coordinates (x, ρ, Φ) (Figure 1) and parabolic coordinates (ξ, η, Φ) [1].
II: Including the eccentric orbit of the asteroid around the sun the model is called Augmented Hill Three-Body Problem (AH3BP). Solutions of this problem can by approximated with averaging over the orbital movement of the spacecraft or dust particle [2].
III: Numeric simulations are applied to study the interactions of additional perturbing forces coming from a non-spherical gravity field or reflected light.

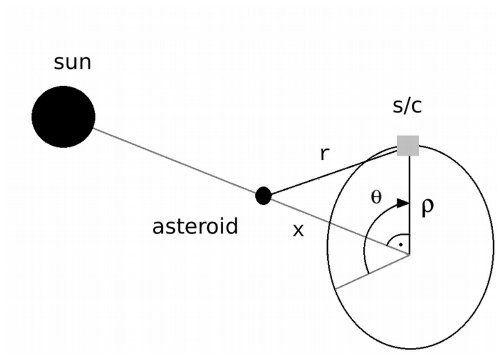

Figure 1: Schematic of non-Keplerian spacecraft orbit displaced in anti-sun direction; position relative to asteroid body ***r*** is often described in cylindrical coordinates (x, ρ, Φ)

3. Ranges for looping orbit design

Even though we ignore the heliocentric asteroid movement in the first model (*I*) analyzing the linear stability of a solution of (*I*) provides orbits resilient to small perturbations. For a circular terminator orbit for example linear stability is given for orbit radii up to a limit r_{max} shown in table 1. The limit and the displacement away from the sun depends on the effective acceleration due to solar radiation pressure and therefore on the size and mass of the test particle.

Every periodic orbit in model (*I*) solved in coordinates (ξ, η, Φ) is trapped between 4 parabolas where the momenta P_ξ and P_η vanish [1]. Vice versa a orbit can be designed to loop between two or four points (x, ρ) by choosing the parabolas accordingly. An application can be seen in figure 2. If the effective solar radiation pressure can not be modified (solar sailing), than one parabola can not be chosen freely.

body	perihel [AU]	r_{max} [km]
16 Psyche	2.536	8.55×10^4
Didymos	1.013	8.20×10^0
2001 SN263	1.037	4.42×10^1
Bennu	0.897	2.96×10^0
Ryugu	0.963	7.38×10^0
Phaethon	0.140	4.96×10^1
Ceres	2.558	5.49×10^5
1996 FG3	0.685	1.38×10^1

Table 1: Size limits for circular terminator orbits according to linear stability; medium s/c: 410 kg, 12 m² cross-section, 0.3 reflectivity

4. Occurrence of SSTO's

A particle in terminator orbit will realign its orbital plane to face the sun while the asteroid follows its heliocentric orbit. The orbit eccentricity and alignment oscillate periodically depending on effective SRP acceleration. This phenomenon is called a self sustaining terminator orbit (SSTO). In fact every averaged solution of the Augmented Hill Three-Body Problem is periodic and linear stable. Unstable orbits will only occur if either the eccentricity becomes to high or the averaging method is not applicable. For a given asteroid and test particle (spacecraft or dust) there is an upper limit for the particle semi-mayor axis so the averaging is valid and the orbit is periodic and stable. For orbits with higher semi-mayor axis one revolution takes more time relative to the periodic changes of the orbit so the averaging method becomes less accurate and unstable orbits ever more likely.

5. Summary and Conclusions

We have some degree of freedom when choosing a spacecraft obit at a target asteroid, venturing out on the day and night side without the need of regular usage of thrusters. Orbit transfers and short mapping phases can be planned using the limiting parabolas. For timescales above one heliocentric revolution the averaging method can be used to predict the stability and the periodic orbital changes.

The analytical models predict unstable orbits usually for high distances from the asteroid. We determine upper size limits of linear stable orbits for selected asteroids. For close approaches numeric validations are ever more important as the effects of the odd shaped asteroid gravity field becomes more prominent.

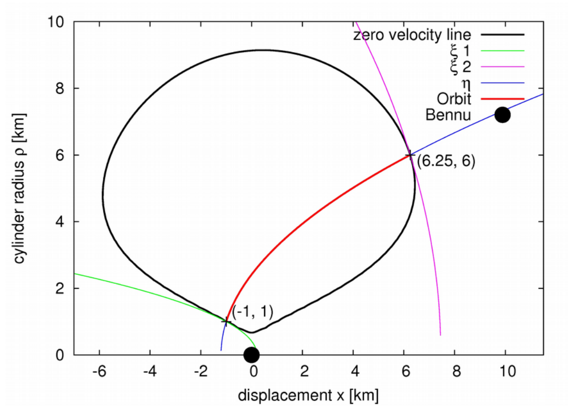

Figure 2: Orbit around Bennu designed to be attached to one parabola and confined to ρ ∈ [1:6]; SRP acceleration must be 3.016×10^{-9} m/s²

References

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