Stability and Evolution of Orbits around Binary Asteroids: Applications to the Marco Polo-R Mission Scenario

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Introduction

In support of the *Marco-Polo-R* mission, we have carried out numerical simulations of spacecraft trajectories about the binary asteroid 175706 (1996 FG3) under the influence of various perturbations. We studied the effects of 5 different parameter groups:

1) the starting conditions (6 orbital elements)
2) the primary's mass, shape, and rotational parameters
3) the secondary's mass, shape, and orbit parameters
4) the spacecraft's mass, surface area, and reflectivity
5) the time of arrival, and therefore the relative position to the sun and planets.

These perturbations lead to a total amount of 17 independent parameters which we evaluated with regard to their influence on the orbit stability.

Marco-Polo-R Mission

The Marco-Polo-R mission is currently in assessment phase in the framework of ESA's Cosmic Vision M3 Program. The mission is planned to be launched between 2020 to 2024, and to rendezvous with a NEA after a cruise-phase of about 4 years. Its main objective is to return a sample to Earth. In addition to samples the characterization of asteroids in orbit yields essential information about interior structures, origins and evolution of these small Solar System objects [1].

The Asteroid

1996 FG3 is a binary Near-Earth Asteroid (NEA). It is orbiting the Sun at a mean distance of 1.054 AU with an eccentricity of 0.350 and an inclination 1.990.

In our simulation we assumed a tri-axial ellipsoid with axes (0.84×0.77×0.56) km and $GM = 1.42 * 10^{-7}\ km^3/s^2$ for the primary and a homogenous sphere with a $GM = 3.1 * 10^{-9}\ km^3/s^2$ for the secondary [2].

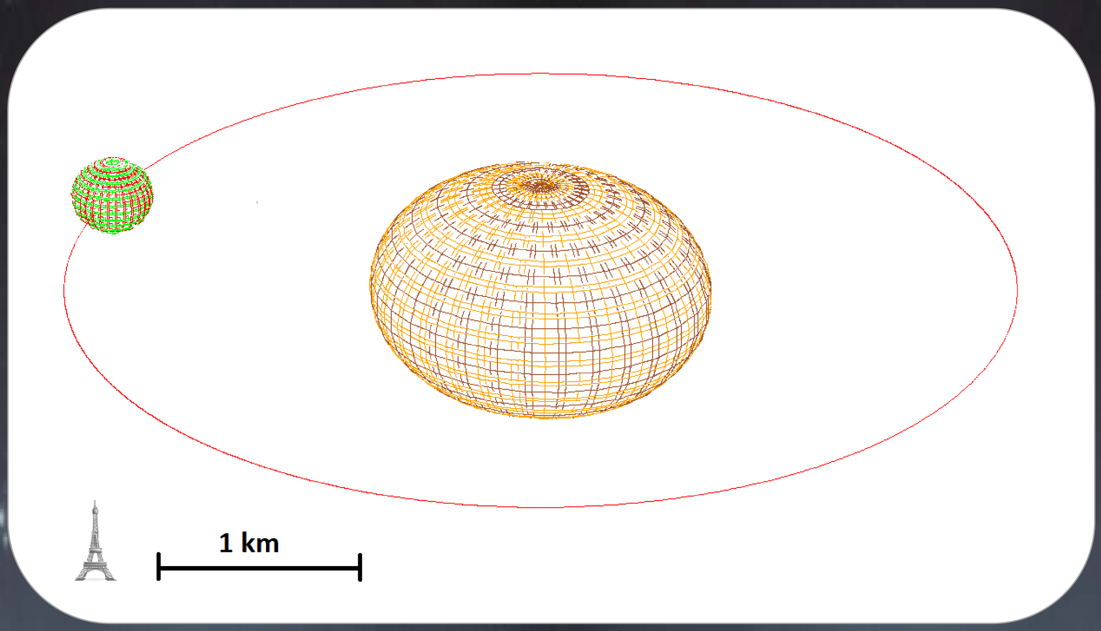


Fig.1: Scaled model of the binary asteroid 1996 FG3. The central body (primary) has a diameter of 1.4 km. Its companion (secondary) has a diameter of 0.28 km which is approximately 50 meters shorter than the height of the Eiffel Tower. The semi-major axis of the orbit is 2.3 km. [2]

Method

Based on ephemeris data generated with JPL's HORIZONS tool (http://ssd.jpl.nasa.gov) we have constructed SPICE ephemeris kernels for the target asteroid. As a second order approximation we assume tri-axial ellipsoids for the asteroids' shapes which are consistent with the mean radius, mass and reasonable density values. Shapes, orientations of the rotational poles, rotation rates, and GM-values are implemented as planetary constants in SPICE kernels.

To calculate the spacecraft trajectories around an asteroid, we have used a numerical integrator which solves the equation of motion of the spacecraft. Taking into account the relevant forces that are acting on the spacecraft we solve the following general equation:

$$\ddot{\vec{r}} = \underbrace{-\frac{GM}{r^3}\vec{r}}_{\text{main body}} + \underbrace{\ddot{\vec{r}}_{HT}(\vec{r},t)}_{\text{higher terms}} + \underbrace{\sum_{SB}\ddot{\vec{r}}_{SB}(\vec{r},t)}_{\text{sec. bodies}} + \underbrace{\ddot{\vec{r}}_{SRP}(\vec{r},t)}_{\text{solar rad. press.}}$$

Fig.2: General integrator equation

Main Results

The Asteroid Mass

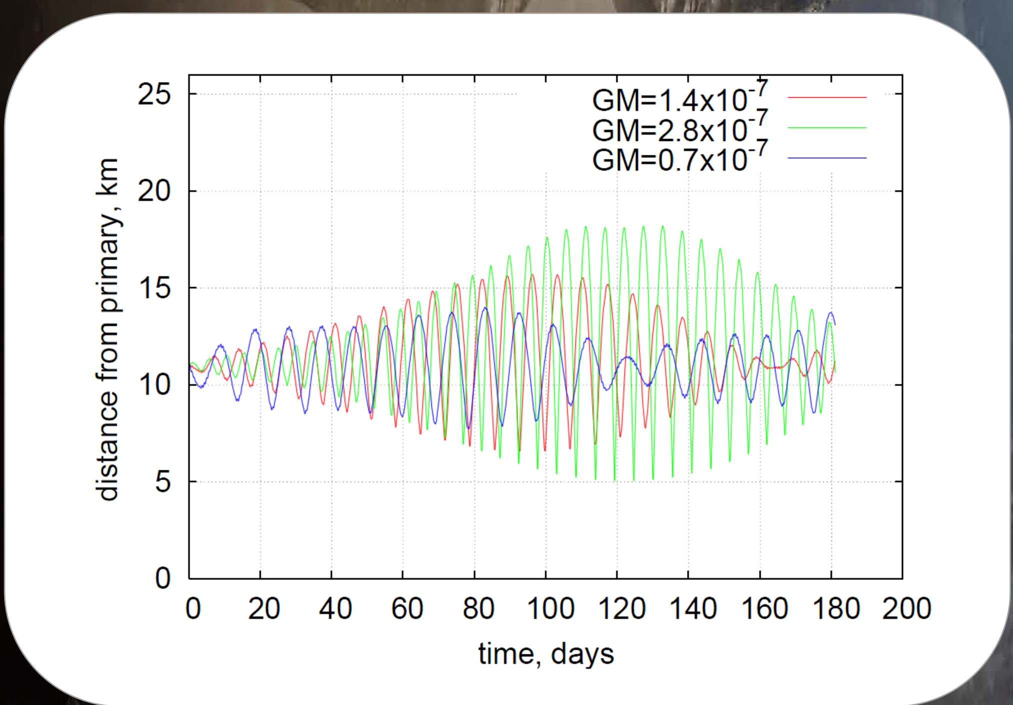


Fig.3: Influence of 1996 FG3's GM-value on spacecraft trajectories. The red curve represents the reference value. The green and blue curves show the evolution taking into account uncertainties in GM-determination.

The secondary

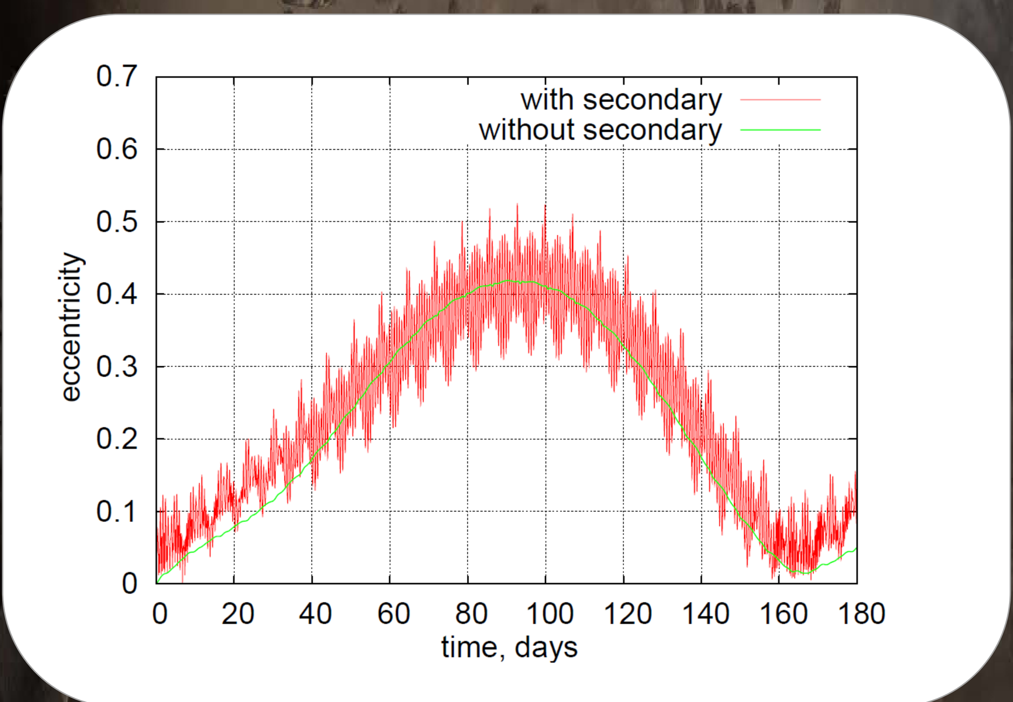


Fig.6: Orbital eccentricity of the spacecraft without (green) and with (red) gravitational perturbations by the secondary asteroid (solar radiation pressure included). The short period terms of the red curve appear due to orbital period of the secondary.

Solar Radiation Pressure and Orbital Elements

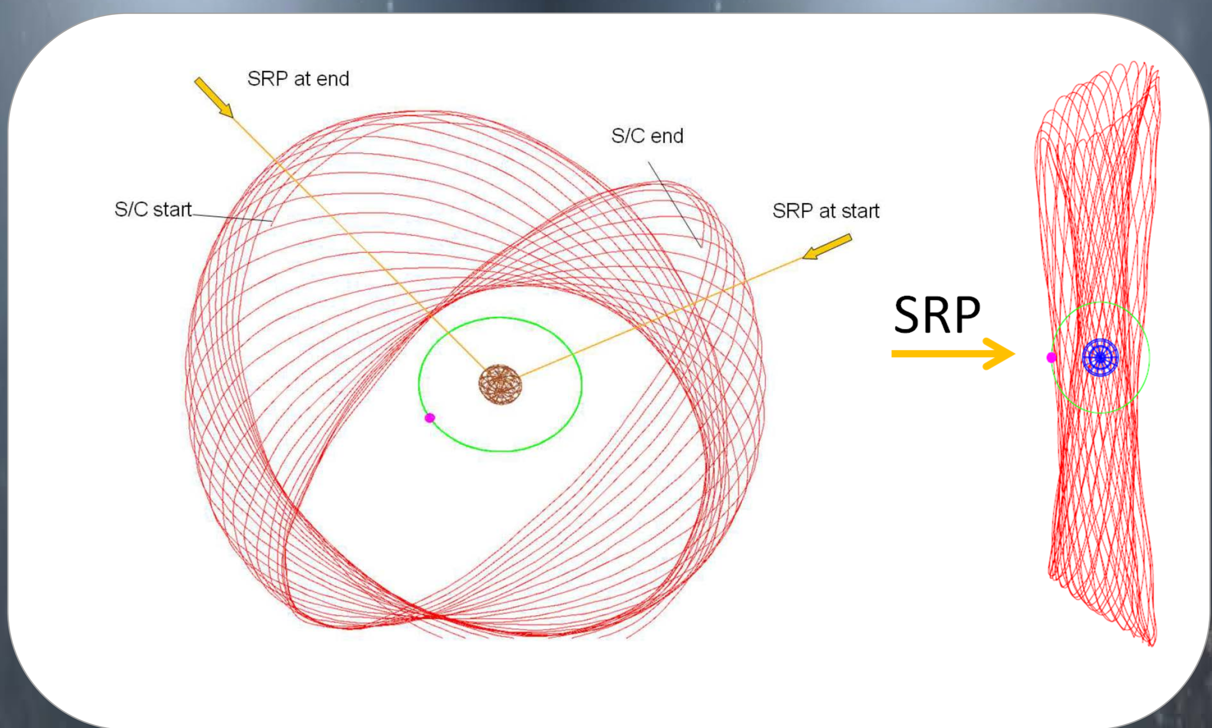


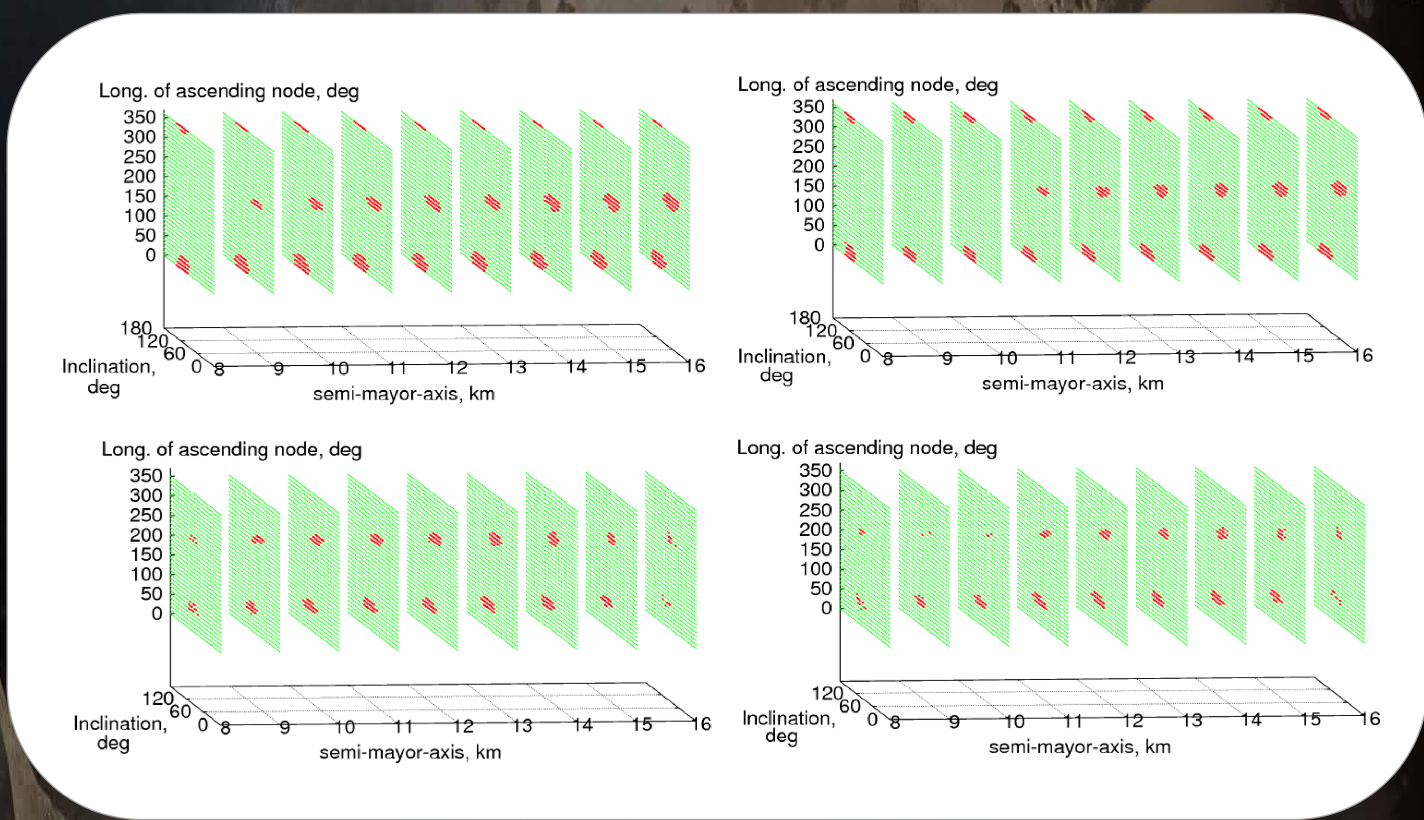
Fig.4: (left): Stable orbit of a spacecraft around the binary in J2000 mean earth equator system. The spacecraft orbit's orientation follows the sun by itself.

(right) Same orbit transferred into a heliocentric system rotating according to the asteroid revolution around the sun.

Due to the gravity of the asteroid a spacecraft in orbit around the binary is highly affected by external perturbations like other bodies or the solar radiation pressure (SRP).

The SRP has one of the highest influence on the orbits; the mass-to-surface ratio and the reflectivity of the surfaces are crucial for the orbital stability. If the initial conditions of the orbit are not chosen correctly the SRP causes the spacecraft either to crash on the Asteroid or to escape from its gravity. However, all stable ones lie in the same region of the parameter space. The two most important orbital elements are the inclination and the right ascension of ascending node as they define the orientation of the orbital plane relative to the sun. Stability can only be achieved if the orbital orientation is maintained such that the solar radiation pressure is (almost) always perpendicular to the sun.

Figure 5: Stability analysis of initial conditions (stable: red points; unstable: green points). Each point represents different starting conditions of the spacecraft.
x-axis: semi-major axis, y-axis: inclination, z-axis: Right ascension of ascending node.
Top-row: insertion date 01-Feb-2026; top-left: eccentricity e = 0; top-right: e = 0.1;
bottom row: insertion date 01-May-2026
bottom-left: e = 0; bottom-right: e = 0.1.
Angles are given in J2000 Earth equator system.



[1] Barucci, M.A. and 26 colleagues 2011. MarcoPolo-R : Near Earth Asteroid Sample Return Mission. *Exp. Astr.*, submitted 2011.

[2] Mottola, S. and F. Lahulla, 2000. Mutual Eclipse Events in Asteroidal Binary System 1996 FG3: Observations and a Numerical Model. *Icarus* 146, 556–567.