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Stability and evolution of orbits around the binary asteroid 175706 (1996 FG3): Implications for the *MarcoPolo-R* mission

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ABSTRACT

In support of the *MarcoPolo-R* mission, we have carried out numerical simulations of spacecraft trajectories about the binary asteroid 175706 (1996 FG3) under the influence of solar radiation pressure. We study the effects of (1) the asteroid's mass, shape, and rotational parameters, (2) the secondary's mass, shape, and orbit parameters, (3) the spacecraft's mass, surface area, and reflectivity, and (4) the time of arrival, and therefore the relative position to the sun and planets. We have considered distance regimes between 5 and 20 km, the typical range for a detailed characterization of the asteroids – primary and secondary – with imaging systems, spectrometers and by laser altimetry.

With solar radiation pressure and gravity forces of the small asteroid competing, orbits are found to be unstable, in general. However, limited orbital stability can be found in the so-called Self-Stabilized Terminator Orbits (SSTO), where initial orbits are circular, orbital planes are oriented approximately perpendicular to the solar radiation pressure, and where the orbital plane of the spacecraft is shifted slightly (between 0.2 and 1 km) from the asteroid in the direction away from the sun. Under the effect of radiation pressure, the vector perpendicular to the orbit plane is observed to follow the sun direction. Shape and rotation parameters of the asteroid as well as gravitational perturbations by the secondary (not to mention sun and planets) were found not to affect the results.

Such stable orbits may be suited for long radio tracking runs, which will allow for studying the gravity field. As the effect of the solar radiation pressure depends on the spacecraft mass, shape, and albedo, good knowledge of the spacecraft model and persistent monitoring of the spacecraft orientation are required.

1. Introduction

Near-Earth Asteroids (NEAs), approaching the Earth orbit, are readily accessible by spacecraft (e.g., Christou, 2003). Up to now, two successful missions have been flown to NEAs: (1) NASA's *NEAR* mission to asteroid 433 *Eros* that accomplished a successful touch-down on the asteroid's surface in 2000 (Veverka et al., 2001) and (2) the JAXA mission *Hayabusa* to asteroid 25143 *Itokawa* (Fujiwara et al., 2006; Yano et al., 2006). *Hayabusa* collected a sample of particles from the asteroid that was successfully brought back to Earth in 2010 (Nakamura et al., 2011).

The *MarcoPolo-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 and 2024, and to rendezvous with an NEA after a cruise-phase of about 4 years. Its main objective is to return a sample to Earth (Barucci et al., 2012). In the current mission scenario the return of the sample is expected for 2029. In addition to samples the characterization of asteroids in orbit yield essential information about interior structures, origins and evolution of these small solar system objects. To accomplish this task, in situ studies of morphology and dynamics are an essential part during *MarcoPolo-R* operations in orbit.

For this study the cameras, the optional laser altimeter, and the radio science experiment are of interest. The purpose of the Wide Angle Camera is to produce a global map which allows us to study multispectral properties and morphology of the asteroid surface as well as to search for suitable landing sites. The Radio Science Experiment will be used for spacecraft orbit determination and modeling of the asteroids' gravity field parameters. An optional laser altimeter will determine the global shape, regional and local topography and the rotation parameters

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(see also Zuber et al., 2000; Mukai et al., 2007, in application to *Eros* and *Itokawa*, respectively). Furthermore, the laser pulses will be used to measure the surface reflectivity (at the laser wavelength of 1064 nm), the surface roughness at the scale of the laser spot on the surface, and the local slopes of the terrain (e.g., Barnouin-Jha et al., 2008 in application to *Itokawa*). Laser altimetry could also assist in spacecraft navigation.

Based on scientific aspects as well as engineering constraints several target asteroids have been proposed for *MarcoPolo-R* among the variety of NEAs (Barucci et al., 2012). Earth-based observation campaigns have revealed basic knowledge on size, shape and rotational parameters of the main target, the binary asteroid 175706 (1996 FG3) (Mottola and Lahulla, 2000; Pravec et al., 2000; Scheirich and Pravec, 2009; Wolters et al., 2011) *MarcoPolo-R* would be the first mission to investigate an asteroid binary system in situ.

While shape and rotation models can be obtained in orbit by altimetry and stereo photogrammetric techniques, the gravity field of the asteroid can be obtained by ground-based tracking and analysis of the spacecraft's radio signal. However, orbits in the faint gravity fields of the small objects are subject to perturbations, and any surface monitoring programs must be carefully planned to maximize coverage and science return (see Yeomans et al., 2000; Abe et al., 2006, in application to *Eros* and *Itokawa*, respectively). The odd shape of the object in combination with its rotation, and the solar pressure may dominate over effects from motion of the spacecraft in the asteroid's gravity field (Scheeres, 1994; Scheeres et al., 1998; Scheeres, 2012). Perturbations from the secondary asteroid introduce a further complexity.

Due to the irregular shape of the asteroid and its weak gravity field, orbits are typically found to be unstable (Hamilton and Burns, 1992). Many sets of initial conditions can result in immediate (on a time-scale of hours) escape from or collision with the main or secondary asteroid. Hence, such orbits would require careful monitoring and spacecraft station-keeping. One goal of this study is to search for orbits which are stable on the order of months to minimize the number of spacecraft operation maneuvers and to allow for long gravity field observations by Doppler tracking. As derived from previous studies (e.g., Scheeres et al., 1998), orbital stability is achieved in the case of near-circular orbits when the orbital plane is perpendicular to the asteroid-sun direction. While the asteroid revolves about the sun, the orbital plane of the spacecraft will be maintained in that orientation due to perturbations by solar radiation pressure.

Here we apply a numerical model to the case of the *MarcoPolo-R* mission scenario. We analyze spacecraft trajectories in the model gravity field of asteroid 175706 (1996 FG3) and its companion. Given the small mass of the asteroid, the solar radiation pressure contributes significantly to the characteristics of spacecraft orbital motion. We study the target asteroid properties and assess spacecraft trajectories in terms of stability and ground coverage that can be accomplished by altimetry and imaging. Furthermore, we will assess to what extent radio science can recover the mass of the main asteroid.

In Section 2 we describe the *MarcoPolo-R* target asteroids according to ground-based data. The numerical integration and the model assumptions are described in Section 3 followed by our results in Section 4. Implications and prospects for the *MarcoPolo-R* mission with respect to coverage and gravity field recovery of asteroid 175706 (1996 FG3) are shown in Section 5. Main conclusions are summarized in the final section.

2. The *MarcoPolo-R* target asteroids

Three candidate asteroids have been selected for the *MarcoPolo-R* mission at the present study phase (Barucci et al., 2012).

Table 1
Semi-major axis a, eccentricity e, and inclination I of the *Marco-Polo-R* candidate targets. For comparison the asteroids 25143 *Itokawa* and 433 *Eros* are also listed. Reference system: heliocentric, ecliptic J2000-System. Data is taken from the JPL small-body database http://ssd.jpl.nasa.gov (as of Aug 2011).

Asteroid	a (AU)	e	I (deg)
175706 (1996 FG3)	1.054	0.350	1.990
162173 (1999 JU3)	1.190	0.190	5.883
101955 (1999 RQ36)	1.126	0.204	6.035
25143 *Itokawa*	1.324	0.280	1.622
433 *Eros*	1.458	0.223	10.828

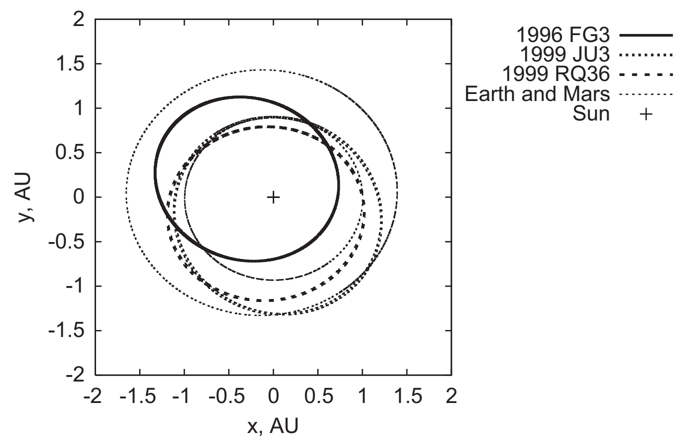

Fig. 1. Orbits of the three *MarcoPolo-R* candidate targets projected on the ecliptic plane. The baseline target is the binary asteroid 175706 (1996 FG3). For comparison the orbits of the Earth and Mars are also included.

Whereas 1999 RQ36 is the prime target for *OSIRIS-REx*, NASA's next New Frontiers mission,[1] 1999 JU3 is the main target for *Hayabusa-2* (e.g., Hasegawa et al., 2008). The three targets revolve about the sun with semi-major axes of about 1 AU, small inclinations, and moderate eccentricities (see Table 1 and Fig. 1). The *MarcoPolo-R* baseline target is the binary asteroid 175706 (1996 FG3). Basic characteristics of the binary system are given in Table 2. Asteroid 175706 (1996 FG3) is accompanied by a small secondary asteroid orbiting the primary at a distance of about 2.3 km (about three radii of the primary) with a period of about 16 h (Mottola and Lahulla, 2000).

Binary systems are common among all dynamical classes of asteroids (Pravec and Harris, 2007). As of Jan 2012 there are 37 confirmed or suspected Near Earth Asteroid multiple systems.[2] Two of them are triple systems. Gravitational perturbations by the asteroids on the spacecraft would be most complex if the mass ratio of the two asteroids is close to unity. As reported by Pravec and Harris (2007), there are various NEA binary systems for which the diameter ratio is close to unity. In addition several systems have diameter ratios similar to 0.3 the one of the 1996 FG3 system. The latter corresponds to a mass ratio of about 0.03 assuming equal densities. Since the stability of spacecraft orbits around these systems critically depends on the radiation pressure in relation to the asteroids' gravity, a detailed investigation of each phase-space would be needed. In this study we focus on the 1996 FG3 system.

[1] See www.nasa.gov/centers/goddard/news/releases/2011/11-037.html.
[2] See also http://www.johnstonsarchive.net/astro/asteroidmoons.html#1.