Planetary and Space Science 146 (2017) 1–9

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Spacecraft orbit lifetime within two binary near-Earth asteroid systems

Friedrich Damme[a,*], Hauke Hussmann[b], Jürgen Oberst[a,b]

[a] Technical University of Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
[b] DLR Institute of Planetary Research, Germany

ARTICLE INFO

Keywords:
Asteroid binaries
Spacecraft orbits
AIDA
Missions
Solar radiation pressure
Lagrangian points

ABSTRACT

We studied the motion of medium-sized and small spacecraft orbiting within the binary asteroid systems 175,706 (1996 FG3) and 65,803 Didymos (1996 GT). We have considered spacecraft motion within the binary systems distance regimes between 0.4 and 2.5 km for Didymos and 0.8–4 km for 1996 FG3. Orbital motion of spacecraft, beginning from 20,000 initial conditions lying in the orbital planes of the secondary, were simulated and evaluated for lifespan.

The simulations include the effects of (1) the asteroid's mass, shape, and rotational parameters, (2) the secondary's mass and orbit parameters, (3) the spacecraft mass, surface area, and reflectivity (representing large box-wing-shaped medium-sized spacecraft as well as small satellites), and (4) the time of the mission, and therefore the relative position of the system to the sun.

Stable orbital motion (i.e., not requiring thrusting maneuvers) was achieved using the Lagrange points L4/L5 and orbital resonances. This allows for long motion arcs, e.g. of 90 days (L4) and 35 days (resonance) in the Didymos system. The accuracy necessary to deploy a probe into L4, so it can remain there for 35 day, is evaluated by comparisons. Retrograde orbits were found assuring 90 days of low eccentric orbiting for a compact small satellite for a great variety of initial conditions.

The comparison of simulations at aphelion and perihelion as well as the different spacecraft show the critical impact of solar radiation pressure on orbital stability. 65,803 Didymos (1996 GT) is shown to be more suitable for orbit phases at the close distances we studied compared to 175,706 (1996 FG3). Two possible obliquities of the Didymos system were considered to study the effects of the inclination on perturbing forces at equinox and solstice, showing that cases of low obliquity or times of equinox are beneficial for spacecraft orbiting.

1. Introduction

NEOs (Near-Earth Objects) originate from various distant Solar System sources. While intercepting the orbits of the terrestrial planets they may potentially collide with Earth, and therefore pose a hazard to humankind (Cheng et al., 2015). NEOs also are known to contain precious resources and may have substantial economic value in the future (e.g., Abell et al., 2015). Binary NEOs (i.e., a pair of NEOs orbiting each other) are of particular interest. From observations of their mutual motion, basic dynamic parameters of the system (such as masses and interior structure parameters) can be derived. Hence, they may hold important records on the formation of the asteroid population (e. g., Walsh and Jacobson, 2015).

Another reason missions to NEOs have received high priority in space exploration is the comparably low expenditure necessary to carry out such a mission. As their orbits are typically similar to the Earth orbit, costs for a mission are comparably low. For example, the proposed AIDA mission to the asteroid 65,803 Didymos (1996 GT) requires a velocity increment less than that of going to the moon (Benner, 2017).

However, the operation of a spacecraft near an NEO comes with new challenges. Owing to the small sizes and odd shapes of these bodies, their gravity fields are faint, but complex. Non-gravitational forces such as the SRP (Solar Radiation Pressure) may potentially exceed the gravitational force of the NEO, thus making “orbital” motion difficult. In the general case, a spacecraft will tend to collide or escape from the neighborhood of the asteroid on a timescale of hours. Obvious navigation solutions include frequent propulsion maneuvers or simply moving at safe distance to the target. Alternatively, for carefully selected initial conditions, we may find motion trapped in so-called terminator orbits, where self-gravitation and radiation pressure are in balance (e.g., Hussmann et al., 2012; Scheeres et al., 1998).

Surprisingly, for binary systems, further options arise for spacecraft

---

[*] Corresponding author.
E-mail address: Friedrich.Damme@tu-berlin.de (F. Damme).

http://dx.doi.org/10.1016/j.pss.2017.07.018
Received 31 January 2017; Received in revised form 18 May 2017; Accepted 26 July 2017

Table 1
Main characteristics of asteroid Didymos. Only nominal values were used for the simulations.*From radio/photometric observation; **derived using assumptions about the density.

Asteroid	1996 GT	1996 GT b	3-σ error	References
Mass [kg] **	5.24×10^{11}	3.45×10^{9}	10%	Benner et al. (2010)
Mean Radius [km] **	0.385	0.075	10%	Scheirich and Pravec (2009)
Axes *a*,*b*,*c* [km] **	0.395,0.39,0.37			
$C_{2,0}$ un-normalized	−0.023	–		See section 2.1 text
$C_{2,2}$ un-normalized	−0.0013	–		See section 2.1 text
Spin period [h] *	2.26	–	±0.0001	Michel et al. (2016)
Mutual Orbit				
Orbital period [h] *		11.92	±0.005	Scheirich and Pravec (2009)
Mass ratio $\mu_2 = m/(M+m)$ **		0.0065		
Semi-major axis [km] **		1.178	+0.04/-0.02	Scheirich and Pravec (2009)
Eccentricity		0.05		
Orbital pole A (λ, β) [°] *		(300, −60)	(-,±20)	Scheirich and Pravec (2009)
Orbital pole B (λ, β) [°] *		(310, −84)	(-,±9)	Michel et al. (2016)

Table 2
Main characteristics of asteroid 175,706 (1996 FG3). Only nominal values were used for the simulations. * From radio/photometric observation; ** derived using assumptions about the density.

Asteroid	1996 FG3	1996 FG3 b	3-σ error	References
Mass [kg] **	4.26×10^{12}	9.41×10^{10}	13%	Barucci et al. (2012)
Mean Radius [km] **	0.69	0.19	13%	Hussmann et al. (2012)
Axes *a*,*b*,*c* [km] **	0.84, 0.77, 0.56			Hussmann et al. (2012)
$C_{2,0}$ un-normalized	−0.14	–		See section 2.1 text
$C_{2,2}$ un-normalized	0.012	–		See section 2.1 text
Spin period [h] *	3.5952	–	3×10^{-6}	Scheirich et al. (2015)
Mutual Orbit				
Orbital period [h] *		16.15	0.0002	Scheirich and Pravec (2009)
Mass ratio $\mu_2 = m/(M+m)$ **		0.0216		
Semi-major axis [km] **		2.3886	±0.4	Scheirich and Pravec (2009)
Eccentricity		0.07		Scheirich et al. (2015)
Orbital pole (λ, β) [°] *		(266, 83)	(±4,±4)	Scheirich et al. (2015)

orbiting. From theoretical studies of restricted three-body systems (e.g., Murray and Dermott, 1999), orbits with long lifetime are predicted to exist, which include periodic motion near the Langrangian points or orbits in resonance with the secondary of the asteroid pair.

In this paper, we study spacecraft motion, in search for stable orbits, in the orbital planes of two binary asteroid systems: 65,803 Didymos (1996 GT) and 175,706 (1996 FG3). They have recently been proposed as targets for space missions. We integrate spacecraft trajectories numerically using a manifold of initial conditions and study the lifetimes of these orbits by applying different stop-criteria. These criteria give us a practical definition of stability. We demonstrate the impact of seasonal effects, i.e., changing distance and direction of the sun relative to the orbit plane of the binary system. We also study orbit lifetimes for two different spacecraft types, medium size spacecraft as well as small CubeSats (which respond differently to Solar Radiation Pressure).

We suggest to venture into closer proximity to the asteroids to benefit from long lasting orbits for gravity field mapping and remote sensing.

1.1. *Proposed asteroid missions*

The AIDA (Asteroid Impact & Deflection Assessment) mission is proposed for launch in the 2020/2021 time frame to demonstrate the effects of an impacting spacecraft into a small asteroid moon and, hence, to study the feasibility of deflecting an asteroidal object from a collision course to Earth. The mission concept consists of two spacecraft, AIM (provided by ESA), which would orbit the asteroid and DART (provided by NASA), which would impact the moon. AIDA would target the binary asteroid system Didymos (1996 GT) (with its small satellite tentatively and unofficially termed “Didymoon”). The goal of AIM is to study the dynamics and physical characteristics, in particular the mutual orbits of the asteroid pair, their shape and gravity fields. Orbital tracking of the asteroid pair will reveal the masses and the specific densities of the asteroid pair (Michel et al., 2016). In addition, deployment of two 3-unit CubeSats is foreseen to investigate the dust environment or to land on Didymoon (Michel et al., 2016).

The Marco Polo mission was proposed initially for ESA's M4 mission call (Barucci et al., 2012). The mission was to return a sample from a Near-Earth asteroid and to carry out studies of the dynamics and surface characteristics by optical remote sensing and laser ranging. The mission was later re-proposed for M5 (“Marco-Polo-R”) for which a new target was selected – the binary Asteroid 1996 FG3. In addition to sample return and a mapping campaign, the deployment of a lander from L2 onto the moonlet was foreseen.

2. Asteroid and spacecraft models

2.1. *Target asteroids*

Both target asteroid systems have been thoroughly studied by Earth-based observing campaigns, and their physical and dynamical parameters are unusually well characterized.

From the asteroid shape parameters, spherical harmonic coefficients were determined using the algorithm from Balmino (1994) adopting the shape of a tri-axial ellipsoid and assuming homogeneous mass distribution, for use in our models. Due to the lack of other information we assume in both cases that the ellipsoidal *a* and *b* axes of the primary (with *c* being the rotation axis) are within its equatorial plane, and that the equatorial plane corresponds to the orbit plane of the secondary asteroid, respectively.

The ephemeris of perturbing planets and the Sun are provided by the DE421 SPICE-Kernel (Folkner et al., 2009). The ephemeris for the heliocentric orbit of both binary asteroids are obtained from the JPL Solar System Dynamics Web-Interface (https://ssd.jpl.nasa.gov/horizons.cgi; 2016). To include the ephemeris data in the software they were compiled into SPICE-Kernels.

Main characteristics of the binary asteroid Didymos (1996 GT) are summarized in Table 1. With an eccentricity of 0.384 the minimum distance to the sun is about 1.013 AU and the maximum distance is 2.276 AU. In the time interval of the AIDA mission, the perihelion pass is in Oct-21 2022 and the aphelion pass in Nov-10 2023 (http://ssd.jpl.nasa.gov).

As two pole axis solutions are available for the asteroid (models A/B, Table 1), we must consider differing seasonal effects (i.e, differing position of the Sun with respect to the orbit plane of the asteroid system) on spacecraft orbit perturbation. Note that with given orbit pole A, the asteroid system is near solstice at Jul-15-22, and near equinox at Oct-22-22, followed by a solstice on Feb-01-23. For pole axis B (near-perpendicular to the ecliptic) seasonal effects are smaller, the differences are discussed in section 5.5. For the eccentricity major parameter upgrades are available (Richardson et al., 2016) which are discussed in section 6.