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Numerical analysis of orbital motion around a contact binary asteroid system

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Abstract

The general orbital motion around a contact binary asteroid system is investigated in this study. System 1996 HW1 is explored in detail, as it is the mostly bifurcated asteroid known to date. The location of its equilibrium points (EPs) is obtained and their linear stability is studied. Families of Lyapunov, Halo and vertical periodic orbits (POs) in the vicinity of these EPs as well as their stability are found and examined, respectively. The influence of the relative size of each lobe and the shape of the ellipsoidal lobe and the rotation rate of the asteroid on the location and stability of the EPs are studied. Additionally, two families of equatorial orbits are obtained at a wide range of distances: from far away to nearby. Their stability is examined against the distance to the asteroid and the rotation rate of the asteroid, to uncover the influence of highly non-spherical gravitational field and the rotation of the asteroid on the orbital motion. Finally, resonant orbits in N commensurability with the rotation of the asteroid are found and their stability is discussed. The fast rotation of the asteroid has a stabilizing effect on the equatorial orbital motion.

Keywords: Contact binary asteroid; Equilibrium points; Periodic orbits; Resonant orbits; Linear stability

1. Introduction

Up to now, several space missions destined for small solar system bodies, e.g. asteroids and comets, have been launched. Close proximity operations are challenging for these missions, due to perturbations caused by the irregular gravitational field of these bodies. Comet 67P/Churyumov–Gerasimenko, the target of ESA's Rosetta mission, was found to be a contact body of two lobes with different origin (probably indicating different densities) recently (Sierks et al., 2015). NASA's New Horizons mission discovered that Kerberos, one of Pluto's tiny moons, is also a double-lobed body. From radar and optical observations, many near-Earth asteroids (NEAs), main-belt and Trojan asteroids, and even comets are found to be contact binaries; they are estimated to constitute 10–20% of all small solar system bodies (Harmon et al., 2010). This study focuses on investigating the general properties of orbital motion in the strongly perturbed environment induced by these highly bifurcated bodies.

Traditionally, the shape of an asteroid was approximated by a triaxial or oblate ellipsoid. With this model and the closed-form ellipsoidal potential, Chauvineau et al. (1993) investigated planar orbits by numerical integration and identified chaotic and regular orbits by varying the mass distribution and rotation rate of the body. Scheeres (1994) performed systematic studies about the EPs and POs in its vicinity, from which an asteroid was classified as type I if the non-collinear EPs are stable and

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type II if they are unstable. Werner (1994) developed the polyhedron method to approximate the shape and gravitational field of asteroids by means of thousands of polyhedra. This is the most accurate model, especially for studying motion extremely close to and on the surface of an asteroid. It has been widely applied for identifying the dynamical environment, e.g. EPs, POs and particle motions, around asteroids with detailed shape models (Scheeres et al., 1996, 1998, 2000). A closely related model is the so-called 'mascons' model that represents the asteroid with a collection of point masses, which was first used to estimate the lunar gravitational potential (Muller and Sjogren, 1968). However, it is less accurate on the surface of the body, compared to the polyhedron model (Werner and Scheeres, 1997). The spherical harmonics model was also widely applied for general analytical and averaging studies of orbital motion around asteroids. From this model, the C_{20}, C_{30} and C_{40} terms were found to introduce secular rates of the argument of periapsis, the ascending node, mean anomaly and eccentricity for orbits close to the asteroid. The C_{22} term was identified to change orbital energy and angular momentum (Scheeres, 2012). Even with higher degree and order spherical harmonics, frozen orbits were obtained (Ceccaroni and Biggs, 2013). In addition, the geometrical shapes of a cube, a straight segment, and two orthogonal segments were also applied (Bartczak and Breiter, 2003; Liu et al., 2011; Riaguas et al., 1999). Families of POs were generated in their vicinity and the stability of the orbits was investigated. The three-dimensional region for stable orbital motion around an asteroid represented by an ellipsoid was identified in (Lara and Scheeres, 2002).

For our exploration of the dynamical environment around contact binary bodies, a shape model consisting of two lobes (an ellipsoidal component and a spherical component) that are in physical contact, is applied. Based on it, the effects of system configuration (varying the relative size of each lobe and the shape of the ellipsoidal lobe) and the rotation rate of the asteroid on the orbital motion can be studied in a systematic way. For this kind of shape, Scheeres (2007) discussed formation mechanisms and studied the relationship between the relative configuration and the rotational angular momentum. The motion of an orbiting spacecraft or a particle in its vicinity will be investigated in this study. Here, the ellipsoid and the sphere are combined in one body, which breaks the symmetry along one axis of the system. This is different from the previous models that approximate the contact body by two connected spheres (German and Friedlander, 1991) and two mass dipoles (Prieto-Llanos and Gomez-Tierno, 1994), which have complete symmetry in three axes.

Following the definition in Magri et al. (2011), bifurcation is defined as a penalty function that identifies the body's deepest neck. It reflects the concavity of the shape and the narrow extent of the neck region. Contact binary system 1996 HW1 was found to be the mostly bifurcated asteroid until recently, as shown in Fig. 1. However, comet

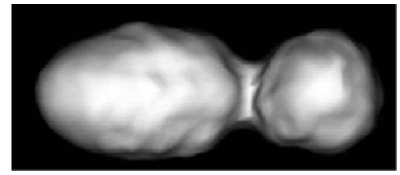

Fig. 1. The shape model of 1996 HW1 (Magri et al., 2011).

67P observed by the Rosetta mission might be more bifurcated since it has a deep neck region. Therefore, it serves as the basic model of a contact binary asteroid and its physical parameters are applied in our simulations. Although there are several methods to represent the gravitational field of this highly bifurcated shape, e.g. the spherical harmonics expansion and the polyhedron approximation as mentioned, in this study the potential from the combination of an ellipsoidal potential and a spherical potential is directly applied. Since the orbital motion in the vicinity of a highly perturbed gravitational field is the focus, other perturbations, e.g. solar radiation pressure and third-body gravitation, are not considered here.

For this kind of shape model, there are two free system parameters: the mass ratio μ that reflects the mass distribution between the two components, and the gravitational-centripetal acceleration ratio δ that indicates the rotation rate (fast or slow) of the asteroid. Therefore, this study is arranged as follows. First, based on the physical parameters of system 1996 HW1, the EPs and their linear stability are identified. Second, the influence of μ and δ on the location and stability of the EPs is investigated. Third, with approximated analytical initial conditions and the differential correction (DC) method and continuation process, families of Lyapunov, Halo and vertical POs are generated, and their stability is studied. In addition, equatorial POs around the entire system and their linear stability are investigated, and the effect of the parameter δ on their stability is examined. Finally, resonant orbits that are in N commensurability with the rotation of the asteroid, are obtained for different δ, and their stability is discussed.

2. Dynamical model

The geometry of the ellipsoid-sphere configuration is illustrated in Fig. 2. The parameters that characterize this configuration are: the three semi-axes of the ellipsoid α, β, γ, the radius of the sphere R and the uniform rotation rate ω, which is aligned with the axis of the maximum moment of inertia. The system is assumed to be homogeneous, with a constant density ρ. The vector between the centers of mass of the two components is defined to be $\vec{d}$ (from ellipsoid to sphere), where $|\vec{d}| = \alpha + R$, and the mass ratio μ is equal to $m_s/(m_s + m_e) = R^3/(R^3 + \alpha\beta\gamma)$ (m_s and m_e being the mass of the sphere and the ellipsoid, respectively). In the body-fixed frame (XYZ -frame in Fig. 2), the gravitational potential is invariant, and the equations of motion

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