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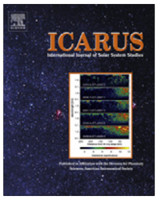

Instability zones for satellites of asteroids: The example of the (87) Sylvia system

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ABSTRACT

The stability of the (87) Sylvia system and of the neighborhood of its two satellites is investigated. We use numerical integrations considering the non-sphericity of Sylvia, as well as the mutual perturbation of the satellites and the solar perturbation. Two numerical models have been used, which describe respectively the short and long-term evolution of the system. We show that the actual system is in a deeply stable zone, but surrounded by both fast and secular chaotic regions due to mean-motion and evection resonances. We then investigate how tidal and BYORP effects modify the location of the system over time with respect to the instability zones. The conclusion is that the system will cross the evection resonance before 1 Gyr.

We generalize this study to other known triple systems, investigate possible evolutions of the systems under tidal and BYORP effects, and discuss their distance from instability regions. In particular, it is possible to show how systems in a joint opposing evolution can be destroyed depending on the masses of the satellites and their dissipative parameters.

1. Introduction

A large number of satellites of asteroids have been discovered since the discovery of the satellite Dactyl, thanks to the Galileo flyby of (243) Ida (Belton et al., 1996). As of today, there are 206 known systems (binary, triple and quintuple), following the Johnston's archive online database[1] (see also the online database[2] described by Pravec and Harris (2007) and Pravec et al. (2012)) and it is believed that small binaries could represent about 15% of the NEA population (Margot et al., 2002; Pravec et al., 2006). Triple systems are rare and only nine known systems have been reported up to now in the entire Solar System.

The dynamical evolution and formation mechanisms of these systems are highly dependent on the size ratio between the secondaries and the primary. If this ratio is very small, as in the case of the Main-Belt Asteroid (243) Ida, the systems are similar to the classical dynamical problem of a massless satellite orbiting a planet (see for example Kozai, 1959, 1962), this one being replaced by a possibly highly elongated ellipsoid (Chauvineau et al., 1993; Scheeres, 1994; Scheeres et al., 1996; Compère et al., 2012a). On the other hand, systems with similar size components, as the Near-Earth Asteroid (66391) 1999 KW4, have to be described taking into account both their shapes and their rotations. A lot of studies have been realized on the expression of the full two-body problem and the study of its aspects (Maciejewski, 1995; Scheeres, 2002; Fahnestock and Scheeres, 2008; Boué and Laskar, 2009). Similarly, emphasis has been given during the past decade on the description of dissipative effects on binary systems, like tidal effects (Mathis and Le Poncin-Lafitte, 2009; Goldreich and Sari, 2009; Taylor and Margot, 2010, 2011) and the Binary Yarkovsky–O'Keefe–Radzievskii–Paddack (BYORP) effect (Ćuk and Burns, 2005; Ćuk and Nesvorný, 2010; McMahon and Scheeres, 2010; Steinberg and Sari, 2011), or on effects acting specifically on the rotation rate of asteroids, like the classical YORP effect (Rubincam, 2000; Vokrouhlický et al., 2003; Nesvorný and Vokrouhlický, 2007; Rossi et al., 2009).

We studied in this paper the dynamics and stability of the (87) Sylvia system, which was the first triple asteroid system discovered (Marchis et al., 2005a). Sylvia, discovered in 1866, is a low eccentricity and midly inclined asteroid located in the outer Main Belt. Its long-term evolution has been investigated through the AstDys project (Milani and Knežević, 1998; Knežević and Milani, 2003) giving its proper orbital elements ($\bar{a} = 3.486$ AU, $\bar{e} = 0.0537$, $\bar{i} = 9.85^\circ$) and its secular fundamental frequencies ($n = 55.297^\circ/\mathrm{yr}$, $g = 134.798''/\mathrm{yr}$, $s = -130.782''/\mathrm{yr}$). In addition, its orbit has been found to be slightly chaotic, exhibiting a Lyapunov time of $\sim$1.4 Myr.

The two satellites of Sylvia present near-circular and near-equatorial orbits, and have mass ratios of about 10^{-4} and 10^{-5} with

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[1] http://www.johnstonsarchive.net/astro/asteroidmoons.html.

[2] http://www.asu.cas.cz/asteroid/binastdata.htm.

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Sylvia, which place the system in the first class described above. The outer satellite, Romulus, is approximately ten times more massive than the inner one, Remus, for a semi-major axis twice as large. The orbital elements of the satellites and the physical parameters of the system are presented in Table 1. The uncertainties (when known) are also given, and the references are precised in Section 2.

Winter et al. (2009) studied the system and found that the satellites could be highly unstable when the oblateness of Sylvia (even a small fraction of its determined value) is not taken into account. Indeed, the oblateness of the asteroid, as well as the short distance of the satellites from its surface (∼5 and 10 radius of Sylvia), critically increase the precession frequencies and prevent them from commensurabilities with frequencies arising from other gravitational perturbations.

Our aim is the understanding of the dynamical mechanisms present in the system and in its neighborhood. We then generalize some of the results to the other triple systems, and, in a general way, to the systems similar to (87) Sylvia, e.g. with a small size ratio and a primary diameter of the order of ∼100 km.

Table 1
Orbital elements, physical parameters and corresponding uncertainties of the bodies.

Sylvia	
Radius R	130.47 km ($\sigma = 6.65$)
Mass M	1.478×10^{19} kg
Rotation period	5.184 h
Ecliptic coordinates of the pole	$\alpha = 100°$, $\delta = 62°$
Remus	
Semi-major axis	706 ± 5 km
Eccentricity	0.016 ± 0.011
Inclination	2° ± 1°
Mean anomaly	96.087°
Argument of pericenter	314°
Longitude of node	97°
Mass	2.154×10^{14} kg
Diameter	7 ± 2 km
Romulus	
Semi-major axis	1356 ± 5 km
Eccentricity	0.001 ± 0.001
Inclination	1.7° ± 1°
Mean anomaly	324.308°
Argument of pericenter	273°
Longitude of node	101°
Mass	3.6625×10^{15} kg
Diameter	18 ± 4 km

2. Study of the (87) Sylvia system

The gravitational potential of Sylvia is modeled by a spherical harmonics expansion (e.g. Kaula, 1966):

$$U(r,\lambda,\phi) = -\frac{\mu}{r}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R_p}{r}\right)^n P_{n,m}(\sin\phi)[C_{n,m}\cos(m\lambda) + S_{n,m}\sin(m\lambda)], \quad (1)$$

where μ is the gravitational constant of the central body, R_p is its radius, (r,λ,ϕ) are the spherical coordinates of the satellite, $C_{n,m}$ and $S_{n,m}$ are physical constants depending on the shape of the main body and named coefficients of the expansion (n is the degree and m is the order of the coefficients), and $P_{n,m}$ are the associated Legendre polynomials.

The coefficients of this expansion are computed using the freely available software archive SHTOOLS[3] developed by Mark Wieczorek and using the convex shape model of Sylvia (Kaasalainen et al., 2002; Marchis et al., 2006) available on DAMIT[4] (Database of Asteroid Models from Inversion Techniques). The asteroid shape models are represented by polyhedrons with triangular surface facets as shown in Fig. 1. The model used here is inferred from a convex inversion method based on photometric data (Kaasalainen et al., 2002). Unfortunately, this kind of data does not contain informations on shape details, so concavities are not always detected and the density is usually underestimated. In Kaasalainen et al. (2002), the authors maintain that a nonconvex shape does not fit better the data than the convex one presented. Furthermore, Marchis et al. (2006) showed that this convex model is also consistent with their Keck adaptative optics observations. This lead us to trust the model even if some shortcomings are possible (see for example Magri et al., 2011 for contact binaries).

When a non-convex shape model for Sylvia based also on radar data will be available, it would be interesting to recalculate the spherical harmonics coefficients and do again these analyses with the new data. However, we are convinced that the results will be quite similar and that the conclusions of this paper will stay valid.

Using this shape model as an input of a home-made code (which call the functions SHExpandLSQ, MakeGridDH and CilmPlus of SHTOOLS), we computed the spherical harmonics coefficients of Sylvia up to the tenth degree and order. After having run test integrations, we conclude that a 4th order and degree harmonics development is sufficient to precisely approximate the perturbation due to the shape of Sylvia. The coefficients up to that degree and order are presented in Table 2. More details on how they have been computed can be found in Compère et al. (2012b). Notice that the value found for $J_2(=-C_{2,0})$ is consistent with the estimated value of Marchis et al. (2005a): 0.175 ± 0.050 and the one of Winter et al. (2009): 0.12.

The orbital elements and the physical parameters used for the integrations are presented in Table 1. The orbital elements and diameters of the satellites have been taken from Marchis et al. (2005a) and their masses from Winter et al. (2009). The orbital elements of the two satellites from Marchis et al. (2005a) correspond to different epochs of reference, so we took as a unique reference epoch the mid-time between these epochs (JD 2453248) and move the mean anomalies of the satellites to this date, by considering fixed mean motions. The heliocentric orbital elements of Sylvia at this epoch, as well as its radius and rotation period, have been taken from the JPL Horizon service. The mass of Sylvia was obtained from Marchis et al. (2005a) and the ecliptic coordinates of its pole from Drummond and Christou (2008).

Based on this shape model, we used two dynamical models to investigate the dynamics of the system. One was used for short-term and precise numerical integrations, while the second one was used to study the secular evolution of the system.

2.1. Short-term numerical integrations

Our first set of integrations was based on the complete equations of the orbital motion of the satellites Remus and Romulus. These simulations were computed with the software NIMASTEP, presented in Delsate and Compère (2012), which is a home-made numerical software. It allows to integrate the osculating motion (using Cartesian coordinates) of an object considered as a point mass and orbiting a homogeneous central body which rotates constantly around its principal moments of inertia. It has been successfully tested and used in many papers, as for example Delsate et al. (2010), Lemaître et al. (2009), Valk et al. (2009a), Delsate (2011), Compère et al. (2012a). To the aim of this work, the software has been improved in order to integrate the motion of two interacting satellites.

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[3] Available at http://www.ipgp.fr/wieczor/SHTOOLS/SHTOOLS.html.

[4] This database is available at http://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php (see Durech et al., 2010 for more details).