Icarus 267 (2016) 267–295

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus

Binary asteroid population. 3. Secondary rotations and elongations

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ARTICLE INFO

Article history:
Received 2 October 2015
Revised 8 December 2015
Accepted 13 December 2015
Available online 19 December 2015

Keywords:
Asteroids, rotation
Asteroids, dynamics

ABSTRACT

We collected data on rotations and elongations of 46 secondaries of binary and triple systems among near-Earth, Mars-crossing and small main belt asteroids. 24 were found or are strongly suspected to be synchronous (in 1:1 spin–orbit resonance), and the other 22, generally on more distant and/or eccentric orbits, were found or are suggested to have asynchronous rotations. For 18 of the synchronous secondaries, we constrained their librational angles, finding that their long axes pointed to within 20° of the primary on most epochs. The observed anti-correlation of secondary synchroneity with orbital eccentricity and the limited librational angles agree with the theories by Ćuk and Nesvorný (Ćuk, M., Nesvorný, D. [2010]. Icarus 207, 732–743) and Naidu and Margot (Naidu, S.P., Margot, J.-L. [2015]. Astron. J. 149, 80). A

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http://dx.doi.org/10.1016/j.icarus.2015.12.019

Near-Earth objects
Photometry

reason for the asynchronous secondaries being on wider orbits than synchronous ones may be longer tidal circularization time scales at larger semi-major axes. The asynchronous secondaries show relatively fast spins; their rotation periods are typically < 10 h. An intriguing observation is a paucity of chaotic secondary rotations; with an exception of (35107) 1991 VH, the secondary rotations are single-periodic with no signs of chaotic rotation and their periods are constant on timescales from weeks to years. The secondary equatorial elongations show an upper limit of $a_2/b_2 \sim 1.5$. The lack of synchronous secondaries with greater elongations appears consistent, considering uncertainties of the axis ratio estimates, with the theory by Ćuk and Nesvorný that predicts large regions of chaotic rotation in the phase space for $a_2/b_2 \gtrsim \sqrt{2}$. Alternatively, secondaries may not form or stay very elongated in gravitational (tidal) field of the primary. It could be due to the secondary fission mechanism suggested by Jacobson and Scheeres (Jacobson, S.A., Scheeres, D.J. [2011]. Icarus 214, 161–178), as its efficiency is correlated with the secondary elongation. Sharma (Sharma, I. [2014]. Icarus 229, 278–294) found that rubble-pile satellites with $a_2/b_2 \lesssim 1.5$ are more stable to finite structural perturbations than more elongated ones. It appears that more elongated secondaries, if they originally formed in spin fission of parent asteroid, are less likely to survive intact and they more frequently fail or fission.

1. Introduction

Binary and multiple systems are frequent among asteroids smaller than about 15 km in (primary) diameter. The binary fraction in the population of near-Earth asteroids larger than 0.3 km was derived to be $15 \pm 4\%$ (Pravec et al., 2006; a similar number was obtained by Margot et al., 2002, from a smaller sample), and our photometric survey for main belt asteroid binaries suggests a similar binary fraction among $D < 15$ km asteroids in the inner main belt. Our current knowledge of properties of asteroid binaries and theories of their formation and evolution are summarized in the review by Margot et al. (2015).

One of the key mechanisms determining evolution of binary asteroid systems is spin–orbit dynamics. It has been theoretically studied by several researchers, most recently by Naidu and Margot (2015). However, this and previous studies were limited by the scarcity of observational data on secondaries of asteroid binaries. In this paper, we have collected observational data on 46 secondaries of near-Earth, Mars-crossing and small main-belt asteroid systems. We have derived or constrained their spin rates and states and estimated their elongations. We have found certain trends in the secondary properties that provide constraints on the theories of evolution of the asteroid systems.

2. Predictions from theories of satellite rotation

A satellite formed in a general rotational state can be captured into spin–orbit resonance by the process of tidal despinning. Murray and Dermott (1999, Section 5), gave an overview of analytical theories of satellite rotation. They showed that an irregular satellite with the permanent quadrupole moment, i.e., permanent bulges or departures from sphericity, can be in a spin–orbit resonance with p equal to an integer multiple of +1/2, with the rational p defined by

$$\gamma = \theta - pM, \tag{1}$$

where θ is an angle between the long axis of the satellite and a reference axis that lies in the orbit of the satellite around the primary and that is fixed in inertial frame (and which is chosen to be the line of apsides for a Keplerian orbit), and M is the mean anomaly of the satellite orbiting the primary. The physical meaning of γ is that it describes the orientation of the long axis of the satellite on passage of the satellite through pericenter, i.e., it is a *stroboscopic angle* that is evaluated when $M = 0$. (The geometry is shown in Fig. 1.) They obtained the *strength criterion*

$$\frac{|\langle N_S \rangle|}{\mathcal{C}} < \frac{1}{2}\omega_0^2, \tag{2}$$

where $|\langle N_S \rangle|$ is the mean tidal torque acting to change the spin of the satellite averaged over one orbital period, $\mathcal{C}$ is the satellite's moment of inertia around the spin axis, and ω_0 is the libration frequency. It is

$$\omega_0 = n\left[3\left(\frac{\mathcal{B}-\mathcal{A}}{\mathcal{C}}\right)|H(p,e)|\right]^{\frac{1}{2}}, \tag{3}$$

where n is the mean motion, $\mathcal{A}$ and $\mathcal{B}$ are the satellite's moments of inertia around the long and the intermediate principal axes, and $H(p,e)$ are factors dependent on p and the satellite's orbital eccentricity e (see Murray and Dermott, 1999, Eqs. (5.74)–(5.82)).[1] If the strength criterion (Eq. (2)) is satisfied, then the mean torque due to the resonant interaction between the planet and the quadrupole moment of the satellite compensates for the mean tidal torque acting to change the spin of the satellite, $\langle\ddot{\gamma}\rangle = 0$, and γ librates about an equilibrium value γ_0. If the left term in Eq. (2) is much less than the right term, i.e., if the mean tidal torque is weak in comparison with the resonant torque, Murray and Dermott obtained that for $p = +1$ (i.e., 1:1 spin–orbit resonance) and $e < 0.687, \gamma_0 \approx 0$ or π and the long axis of the satellite points towards the primary on passage of the satellite through pericenter.

For a satellite trapped in 1:1 spin–orbit resonance, the rotational motion of the satellite has short-period librations about the equilibrium configuration. This is because the full equation of motion contains short-period terms. Murray and Dermott (1999) derived that the amplitude of forced librations is

$$\gamma_A = \frac{2\omega_0^2 e}{\omega_0^2 - n^2}. \tag{4}$$

If the forcing frequency n is less than the natural frequency ω_0, then the librations are in phase with the force. If $n > \omega_0$, then the librations and the force are 180° out of phase. The resonance with $\omega_0 = n$ occurs for $(\mathcal{B}-\mathcal{A})/\mathcal{C} \approx 1/3$, i.e., for the secondary equatorial axes ratio $a_2/b_2 \approx \sqrt{2}$. Near the resonance, the secondary libration amplitude is high even for low-eccentricity orbits.

Murray and Dermott (1999) also touched the problem of asynchronous satellite rotation. Analysing surfaces of section of the satellite's rotational motion, they showed that chaotic motion occurs for elongated satellites on eccentric orbits. However, the purely analytical theory reaches its limits with this problem.

Ćuk and Nesvorný (2010) constructed a semi-analytical model of secondary rotation that is applicable for asteroid satellites on close orbits with the semimajor axis $a \lesssim 10D_1$ (primary diameters).

[1] The $H(p,e)$ are factors in the averaged equation of motion of the satellite's libration, see Murray and Dermott (1999, Eq. (5.73)).