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Evolution of Small Near-Earth Asteroid Binaries

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Abstract

Stable small, binary asteroid systems will evolve according to three processes: the YORP effect, mutual body tides, and the binary YORP (BYORP) effect. The interplay of these effects on the dynamics of the system must result in the observed binary asteroid systems: asynchronous binaries, synchronous binaries, and doubly synchronous binaries.

1. Introduction

The YORP effect rotationally accelerates small bodies in the inner Solar System. Small asteroids are "rubble piles" that when spun fast enough can fission into two co-orbiting components. The subsequent dynamical evolution can stabilize the orbit, typically resulting in a rapidly spinning primary relative to the mutual orbit [1]. The secondary spin states are often also rapid and prograde, however a fraction are retrograde and another fraction are close to synchronous. Three non-conservative effects continue to evolve these systems on timescales shorter than the planetary and solar flyby lifetimes of these binaries: the YORP effect, mutual body tides, and the BYORP effect.

1.1. YORP Evolution

The YORP effect is the summation of radiative torques on a small body. The total torque can change the spin rate of the body over short timescales ($10^5 - 10^6$ years) [2]. To first order, the evolution of the spin rate of a body depends on a unitless YORP coefficient Y, which depends on the shape of the body and varies from $-0.025 \leq Y \leq 0.025$ [3]. The YORP effect will evolve the spin rate [3]:

$$\dot{\omega}_Y = \frac{Y H_\odot}{2\pi}\left(\frac{1}{\rho R^2}\right) \qquad (1)$$

where $H_\odot = F_\odot/(a_\odot^2\sqrt{1-e_\odot^2})$, $F_\odot$ is the solar radiation constant, $a_\odot$ and $e_\odot$ are the heliocentric semi-major axis and eccentricity, and ρ and R are the bodies' density and radius.

1.2. Tidal Evolution

Relative motion between components in a binary system dissipates energy and transfers angular momentum between spin and orbit states via tides. Assuming spherical, homogenous bodies with identical compositions and a mutual orbit with low eccentricity and low inclination, an asteroid's first order geophysics can be characterized by two parameters: the tidal Love number k and the tidal dissipation factor Q. The torque from tides evolves the spin state of a body [4]:

$$\dot{\omega}_T = -\text{sign}(\omega - n)\frac{15k\omega_d^2}{4Q}\left(\frac{R}{a}\right)^6 \qquad (2)$$

where a is the mutual orbit semi-major axis, n is the mean motion, and $\omega_d = (4\pi G\rho/3)^{1/2}$ is the surface disruption limit for a sphere. Tides raised on the secondary by the primary synchronize the spin of the secondary to the mutual orbit period, this is the fastest binary evolutionary process [5]. On longer timescales, tides also evolve the mutual orbit [4]:

$$\dot{a}_T = 3\frac{k_p}{Q}\left(\frac{R_p}{a}\right)^{\frac{11}{2}}\omega_d q\sqrt{1+q} \qquad (3)$$

$$\dot{e}_T = \frac{57k_p q^{\frac{1}{3}} - 84k_s}{8Q}\left(\frac{R_p}{a}\right)^{\frac{13}{2}}\omega_d e q^{\frac{2}{3}}\sqrt{1+q} \qquad (4)$$

where q is the mass ratio, e is the mutual eccentricity, and subscripts denote the primary p or secondary s.

1.3. BYORP Evolution

The BYORP effect is the summation of radiative effects on a synchronous component. Asymmetries in the shape of the synchronous body create torques on the mutual orbit, which secularly change both the semi-major axis and eccentricity [6]. To first order, the evolution of the semi-major axis and the eccentricity only depends upon the unitless BYORP coefficient B, which is the averaged, normalized acceleration in the direction parallel to the motion of the secondary and determined from the shape of the body. A symmetric body has a value of $B = 0$. and common values for asteroids are $B \sim 10^{-3}$. The BYORP effect can either expand or contract the semi-major axis, however the sign of the eccentricity evolution is always opposite that of the semi-major axis evolution [6]:

$$\dot{a}_B = \pm \frac{3H_\odot B}{2\pi\omega_d\rho}\left(\frac{a^{3/2}}{R_p^{7/2}}\right)\frac{\sqrt{1+q}}{q^{1/3}} \quad (5)$$

$$\dot{e}_B = \mp \frac{3H_\odot B}{8\pi\omega_d\rho}\left(\frac{a^{1/2}e}{R_p^{5/2}}\right)\frac{\sqrt{1+q}}{q^{1/3}} \quad (6)$$

2. Synchronous Binaries

Assuming an appropriate "rubble pile" interior model, analysis shows that the synchronous binary asteroid population may be in an equilibrium between mutual body tides and the BYORP effect [7]. Mutual body tides must be stronger than the YORP effect to synchronize the secondary. Afterwards, the mutual orbit evolves according to tides and the BYORP effect. For nominally 50% of these systems, the BYORP effect contracts the semi-major axis and this drives the system to an equilibrium state. Outside of this equilibrium, the BYORP effect dominates and the system semi-major axis contracts to the equilibrium, and inside of this equilibrium, mutual body tides are stronger and the system semi-major axis expands to the equilibrium. These systems resemble the observed synchronous binary population with a synchronous secondary, a rapidly rotating primary (the effect of the equilibrium is to slowly rotationally accelerate the primary) and this is a stable state explaining the abundance of these systems [7]. The other 50% of these systems, where the BYORP effect expands the orbit, are discussed in the asynchronous binary section.

3. Doubly Synchronous Binaries

At larger system mass ratios, the primary is tidally locked before the mutual orbit significantly evolves. These systems resemble the observed doubly synchronous population. Since the bodies are comparable in size the strength of the effect will be on the same order, however the BYORP effect on each body is independent and so for each direction of evolution (expansion or contraction) there is nominally a 50% probability for each body. For 25% of all doubly synchronous systems, the BYORP effect on both bodies will act to contract the semi-major axis potentially creating the contact binary population. For another 25%, the BYORP effect on both bodies will continue to expand their semi-major axes; their continued evolution is discussed further in the asynchronous binary section. The remaining 50% will have one member act to contract and the other act to expand. While the BYORP effect won't necessarily be of the same magnitude for each body, these combined effects will cancel to some extent and create a pseudo-stable doubly synchronous population.

4. Asynchronous Binaries

Both of the previous evolutions required that mutual body tides dominate the spin state evolution of a body over the YORP effect. The tidal torque responsible for synchronization has a very strong dependence on semi-major axis, but the YORP effect does not. If the YORP coefficient is not zero, then there exists for all systems a semi-major axis where the tidal torque is equivalent in strength to the YORP torque, and exterior to this semi-major axis the YORP torque will dominate and the body will rotationally accelerate. 50% of synchronous binaries and 25% of doubly synchronous binaries (another 25% at a reduced rate) are expanding in semi-major axis due to tides and the BYORP effect, which causes very rapid expansion in certain cases. Eventually, all either expand so far that they are easy prey to planetary and solar flybys disrupting the system and creating asteroid pairs, or reach the semi-major axis at which the YORP torque wrests control of the spin state of the secondary from the tidal torque and rotationally accelerates the body. These systems appear as the asynchronous binary population with semi-major axes that resemble synchronous and doubly synchronous binaries but secondaries that are rapidly rotating.

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