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The YORP Effect on Rubble Piles: How Centrifugal Reshaping of Small Aggregates Kills the YORP Cycle

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ABSTRACT

We simulate, for the first time, the self-consistent spin evolution of gravitational aggregate (rubble-pile) asteroids driven by the YORP effect. We follow the sequence of spin states through which they evolve as the changing spin alters their shape, and the changing shape alters the YORP torques. We find that aggregates undergo a spin evolution completely unlike that of rigid monoliths. Instead of following a semi-deterministic "YORP cycle" characterized by episodes of significant rotational acceleration followed by deceleration, aggregates tend to exhibit a stochastic spin evolution driven by recurring small changes in shape. Quasi-random walks in spin rate, obliquity, or both are common. The fact that rigid monoliths and rubble piles behave qualitatively differently under YORP suggests that detailed spin characterization of asteroid families may offer a statistical indicator of material properties and structure.

INTRODUCTION

The recoil due to the reflection and emission of photons from a Sun-irradiated surface is a major driver of dynamical evolution for small asteroids—especially the sorts that pose an impact hazard for Earth. The net recoil force (the Yarkovsky effect) drives evolution of the orbital elements, and can influence the trajectories of potentially hazardous objects through or past keyholes. The net recoil torque (the YORP effect) drives evolution of the spin rate and axis orientation, influencing the magnitude and direction of the Yarkovsky force. Both effects are sensitively dependent on the spin state; hence understanding how spins evolve under the influence of YORP is crucial for understanding how orbits evolve under the influence of Yarkovsky.

Previous work showed that monolithic, rigid asteroids should follow a largely deterministic "YORP cycle", characterized by long phases of rotational acceleration and deceleration accompanied by slow, monotonic changes in obliquity. This type of evolution arises because, for a rigid body, the spin component and obliquity component of the YORP torque are smooth functions of obliquity. But evidence from both light-curve observations and in situ mass measurements strongly suggests that most asteroids are probably not monolithic, but rather loosely-bound aggregates. We have shown (Statler 2009) that YORP is so hypersensitive to the detailed topography of the surface that even slight motions of loose material can qualitatively alter the torque and interrupt the YORP cycle; and we predicted that either self-limiting or stochastic behavior of YORP could be the result.

Here we present preliminary results from the first self-consistent simulations of the YORP effect on dynamically evolving aggregates, following the change in spin state caused by YORP, the change in shape caused by the evolving spin, and the change in YORP caused by the evolving shape.

METHODS

To self-consistently model the YORP effect on the spin states of dynamically evolving aggregates we combine two codes: TACO and pkdgrav. TACO models the surface of an asteroid using a triangular facet representation and can self-consistently compute the torques from the YORP effect (Statler 2009). The code pkdgrav is a cosmological N-body code modified to simulate the dynamical evolution of asteroids represented as idealized aggregates of spheres using gravity and collisions (Richardson et al. 2000).

We have developed several algorithms in order to allow the two codes to interact. One fits a triangular tiling over an object created for pkdgrav, composed of spheres, in order to be used with TACO to compute the YORP torques. Starting from the diagonalized inertia tensor, we obtain the axes of the equivalent ellipsoid. The object is rotated to the principal axis orientation and a tiling of the equivalent ellipsoid is generated. Then the vertices are adjusted inward or outward to fit the tiling tightly around the object.

For initial conditions we use the end-state objects from Tanga et. al (2009), who created ellipsoidal aggregates with fixed axis ratios and angular momenta and allowed them to evolve dynamically, allowing reshaping, until they reached a stable equilibrium. The objects have a natural disordered packing, are composed of ~1000 spheres and have a sphere density of 2.96 g/cc. The bulk density and the diameter of the objects are in the range of 1.5 to 1.7 g/cc and 1.3 to 2.6 km, respectively.

We use the hard-sphere discrete element method in pkdgrav and set the normal and tangential coefficients of restitution to 0.2 and 0.5 for all simulations. After obtaining the tiling and YORP torques for the original aggregate object, we evolve the obliquity and spin in time. Objects are evolved incrementally in spin rate with increments no larger than 0.5% and without exceeding the maximum and minimum allowed spin rates given by the expected rigid-body evolution. The object is run dynamically with pkdgrav at each new spin rate for several rotations; if there is a movement of material we let it evolve further until it settles down and reaches a new equilibrium. Then we transform the object to the orientation of the original object to obtain a new tiling minimally different from the previous one, transform the tiling to the actual orientation, and compute the new YORP torques. We follow the evolution of aggregate objects computing the sequence of spin states and YORP torques through which they evolve as the changing spin alters their shape, which subsequently changes the YORP torques. The obliquity and spin evolutions are obtained using a fourth-order Runge Kutta integrator with a 10^3 year step size.

RESULTS AND DISCUSSON

Here we present only illustrative preliminary results from the simulations. Full results and statistical analysis will be presented in a future publication.

We find, in general, that subtle recurring reconfigurations of the body under the changing centrifugal force continually interrupt the YORP cycle, resulting in a qualitatively different evolution that resembles a random walk in spin rate, obliquity, or both. Figure 1 shows the spin rate and obliquity as functions of time for one representative object. The spin evolution that the object would have followed had it been a rigid body is shown in white. (Note that even a rigid-body YORP calculation does not necessarily predict inexorable spin-up to arbitrarily high rates.) The actual evolution is shown in a color sequence; each change in color indicates a reconfiguration of the object that precipitated a re-calculation of the torques. Long after the initial object's rigid cousin would have completed its evolution through the YORP cycle, the aggregate is still spinning at nearly its initial rate, having gradually rotated to zero obliquity rather than the 90 degree obliquity initially expected.

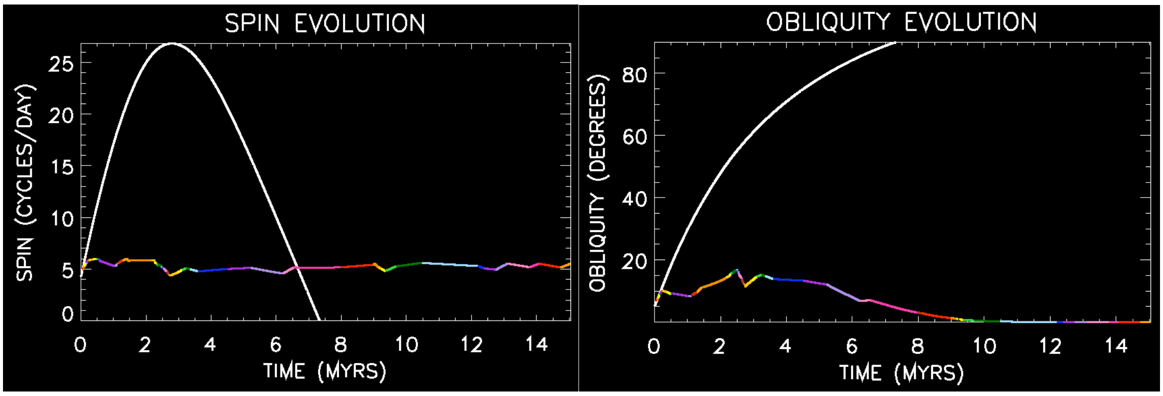

Figure 1. Evolution of an aggregate in spin rate (left) and obliquity (right). White curve shows the evolution that would have been followed had the initial object remained rigid; colored lines show the actual evolution. In this example YORP is self-limiting and the spin rate stays near its initial value.

The key result of our simulations is that rigid bodies and rubble piles behave qualitatively differently under the YORP effect. Neither the intermediate nor the asymptotic spin states predicted in the rigid-body approximation are attained by the aggregates. This difference will have significant implications for orbital evolution driven by the Yarkovsky effect, with potentially observable consequences for the spreading of collisional families. These results open the door for large-scale spin characterization of asteroid populations to become effective tools, complementing orbital spectroscopic characterization, for constraining the physical states and material properties of near-Earth objects.

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