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Note

Obliquities of "top-shaped" asteroids may not imply reshaping by YORP spin-up

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ABSTRACT

The timescales over which the YORP effect alters the rotation period and the obliquity of a small asteroid can be very different, because the corresponding torques couple to different aspects of the object's shape. For nearly axisymmetric, "top-shaped" near-Earth asteroids such as 101955 Bennu, spin timescales are an order of magnitude or more longer than obliquity timescales, which are $\sim 10^5$ to 10^6 yr. The observed low obliquities (near 0° or 180°) of top-shaped asteroids do not constitute evidence that they acquired their present shapes and spins through YORP spin-up, because low obliquities are expected regardless of the spin-up or reshaping mechanism.

1. Introduction

High-resolution radar observations of near-Earth asteroids (NEAs) have produced a wealth of information about their surface properties, rotation rates, and 3-dimensional shapes (Ostro et al., 2002). One intriguing result from these studies is the recurring emergence of shapes reminiscent of a child's top—nearly axisymmetric, slightly to moderately oblate, with an elevated ridge around the equator. The dozen or so top-shaped objects identified to date tend to have rapid rotation and axial obliquities near 0° or 180° (collectively referred to here as "low obliquity"), and several have satellites (Ostro et al., 2006; Busch et al., 2007, 2011; Nolan et al., 2013; Brozović et al., 2011).

One possible explanation for the formation of top-shapes, both with and without companions, was offered by Walsh et al. (2008, 2012b). These authors simulated the dynamical evolution of idealized rubble piles composed of spheres that interact through dissipative two-body collisions. They subjected the rubble piles to a steady increase in angular momentum, ostensibly arising from radiation recoil torques (the YORP effect; Paddack, 1969; Rubincam, 2000). They found that some of the objects evolved, through centrifugally driven movement of surface material, to top shapes. By continuing to add angular momentum, they could force the tops to shed mass, which reaccumulated in orbit to make satellites. Walsh et al. (2008) highlighted the strong similarity of their best results to the well-studied object 1999 KW_4, establishing YORP spin-up as a likely candidate mechanism.

These simulations are so visually compelling that YORP is now commonly invoked as *the only* mechanism responsible for top-shapes. Keller et al. (2010) state that the shape of the main-belt asteroid 2687 Steins is "probably the result of reshaping due to [YORP] spin-up"; Busch et al. (2011) describe 1999 KW_4's equatorial ridge and satellite as "believed to have formed due to YORP spin-up…"; and Walsh et al. (2012a) cite YORP-induced "bulk reshaping" as "the cause for the ubiquitous 'top-shape' and equatorial ridge".

Given the current state of knowledge, however, uncritical acceptance of the YORP spin-up mechanism as the only option for the formation of top shapes is logically unwise, for the following reasons:

1. Not all spin-accelerated rubble piles become tops, and it is not yet determined whether the properties of those that do correspond to the properties of real objects. Walsh et al. (2012b) found that objects with low initial angles of friction ϕ evolved, not to tops, but to highly triaxial or prolate bodies (see also Holsapple, 2010; Jacobson and Scheeres, 2011; Tanga et al., 2014; Cotto-Figueroa et al., 2014). Terrestrial materials like gravel or sand have larger values of ϕ ($\gtrsim 20°$), but it is by no means established that asteroidal materials will behave similarly. The high-ϕ objects of Walsh et al. (2008), which did become tops, were initialized in hexagonal-close-pack configuration, which provides extra rigidity by making motion of material below the surface impossible unless the object expands and the bulk density decreases. Furthermore, light curve observations show an abundance of rapidly rotating objects in the few-km size range that are significantly non-axisymmetric (Pravec and Harris, 2000; Warner et al., 2009).
2. YORP is not a limitless source of angular momentum. YORP spin-up will weaken as an object being reshaped becomes more symmetric. For objects having reflection symmetry (including axisymmetric oblate or prolate spheroids as well as triaxial ellipsoids) and rotating about a principal axis, the secular YORP effect on spin is identically zero.[1] Small deviations from symmetry are equally likely to produce positive or negative spin torques; hence gradual reshaping may lead to a stochastic random walk in spin rate (Statler, 2009) and/or to YORP self-limitation (Cotto-Figueroa et al., 2014), either of which could arrest reshaping and prevent mass shedding or fission. This scenario differs qualitatively from the continual spin-up assumed in the simulations.

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[1] The arguments in Sections 1 and 2 of this paper make use of the standard assumption that the recoil force from thermal photons is normal to the radiating surface. The consequences of loosening this assumption are discussed in Section 3.

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3. Other mechanisms that may also reshape and/or accelerate the spins of rubble piles have not been ruled out. Leading contenders are disruptive impacts (Leinhardt et al., 2000; Korycansky and Asphaug, 2006) and catastrophic disruptions followed by reaccumulation (Michel and Richardson, 2013). Tidal torques in close planetary encounters may also contribute but are expected to play a lesser role (Walsh and Richardson, 2006, 2008).

A tempting argument to invoke in support of the YORP spin-up model uses the tendency for tops and binaries to have obliquities ϵ close to 0° or 180°, which have been identified with stable end states of the YORP cycle (Čapek and Vokrouhlický, 2004). The argument is that, since tops are found near these end states, YORP must have been in operation for longer than the characteristic YORP timescale, over which time YORP must have significantly modified the spins. Pravec (2014) applies this argument to the general population of binary asteroids; Polishook (2014) employs a form of it in his discussion of asteroid pairs.

The point of this *Note* is to show that, at least for the top-shaped asteroids, the argument is fallacious. This is because the timescale for YORP to change the orientation of an object may have nothing to do with the timescale over which it changes the spin rate; and for nearly symmetric objects the latter timescale can be an order of magnitude or more longer than the former. The low obliquities of tops do not imply that they acquired their present shapes and spins through YORP spin-up, because low obliquities are expected regardless of the spin-up or reshaping mechanism.

2. YORP evolution of symmetric and nearly symmetric asteroids

The essential property of YORP in this discussion is that the torque component that changes the spin rate and the components that change the axis orientation couple, at leading order, to different attributes of the surface. The spin torque couples to chirality—the difference between eastward and westward facing slopes—while the other components couple merely to asphericity. (Mathematically, this concerns the symmetric and antisymmetric terms in the Fourier expansion of the topography: the spin torque couples only to the antisymmetric terms, the orientation component to the symmetric terms.) Thus, even axisymmetric spheroids, which have zero spin torque, will have their axes reoriented by YORP, and will have their obliquities changed if they have finite thermal inertia Γ. These results have been derived analytically by Breiter et al. (2007), Breiter and Michalska (2008), and Kaasalainen and Nortunen (2013), but seem to have been underappreciated, perhaps owing to the highly mathematical presentations in those papers.

Fig. 1 illustrates the origin of the axis-reorienting torque components on an axisymmetric oblate spheroid, for which the spin torque is identically zero at all times. Fig. 1a shows the case of a body with $\Gamma = 0$, at its northern summer solstice, illuminated by sunlight from the left. A warm spot is generated, centered around the sub-solar point, from which thermal re-radiation produces a recoil force normal to the surface. As the force is not directed toward the center of mass, the result is a twist in the direction indicated, corresponding to a torque directed out of the page. Half an orbit later, with the illumination from the right, the recoil twist is in the same sense, adding to the secular effect. For $\Gamma = 0$, this is the only non-zero component of torque, and it drives a precession of the rotation axis about the orbit normal. Fig. 1b shows a Sun's-eye view of the same body, now with $\Gamma > 0$. As a result of heat conduction and rotation (counterclockwise looking down on the north pole, as indicated), the warm spot is carried eastward, approximately along a parallel of latitude. The recoil force now has a component pointing downward in the diagram. The downward push on the right side of the body results in a clockwise twist and a torque directed into the page. Half an orbit later, illumination from behind creates an upward push on the left side of the body and a torque in the same direction. This contribution to the secular torque acts to lower the obliquity of a direct rotator toward $\epsilon = 0°$, and raise the obliquity of a retrograde rotator toward $\epsilon = 180°$.

As a measure of the characteristic timescale for this axis-righting process, I define $\tau_{\rm obl}$ as the time for the obliquity of a direct rotator to evolve from 60° (the median value for rotation poles distributed randomly over one hemisphere) to 5° (a typical observational uncertainty for well-determined rotation poles). Fig. 1c shows this timescale for three fiducial oblate spheroids over a range of thermal inertias, computed using the thermophysical code TACO (Statler, 2009). These fiducial objects are black (zero Bond albedo A and unit blackbody radiative efficiency $\epsilon_{\rm bb}$), with a uniform density of $\rho = 1000\ {\rm kg\,m^{-3}}$ and volumes equal to that of a sphere $D = 1$ km in diameter, differing only in their polar-to-equatorial axis ratio. They are assumed to be on circular ($e = 0$) orbits of semi-major axis $a = 1$ AU, rotating about their short axes with period $P = 2$ h. Thermal inertias range from small values ($\sim 10\ {\rm J\,m^{-1}\,s^{-1/2}\,K^{-1}}$) characteristic of fine regolith, through intermediate values ($\sim 10^2\ {\rm J\,m^{-1}\,s^{-1/2}\,K^{-1}}$) characteristic of fractured rock, to high values ($> 10^3\ {\rm J\,m^{-1}\,s^{-1/2}\,K^{-1}}$) typical of monolithic rock. The figure shows that righting times are short: $\tau_{\rm obl} < 1$ Myr for all likely values of Γ, even for objects that are only 10% aspherical, and are in the realm of 0.1 Myr for moderate flattenings and thermal inertias characteristic of fractured rock. Axis-righting occurs at constant spin rate, since the spin component of torque is zero and the timescale for YORP spin-up or spin-down is infinite. Any rotating oblate spheroid will evolve toward 0° or 180° obliquity, regardless of what made it oblate. (The results can be scaled to other objects and orbits using the relation $\tau_{\rm obl} \propto \rho D^2 a^2 (1 - e^2)^{1/2} P^{-1}$ and rescaling Γ so that $\Gamma P^{-1/2} = $ constant. For Lambertian reflection and emission, to leading order $\tau_{\rm obl} \propto [\epsilon_{\rm bb}(1 - A)]^{-1}$).

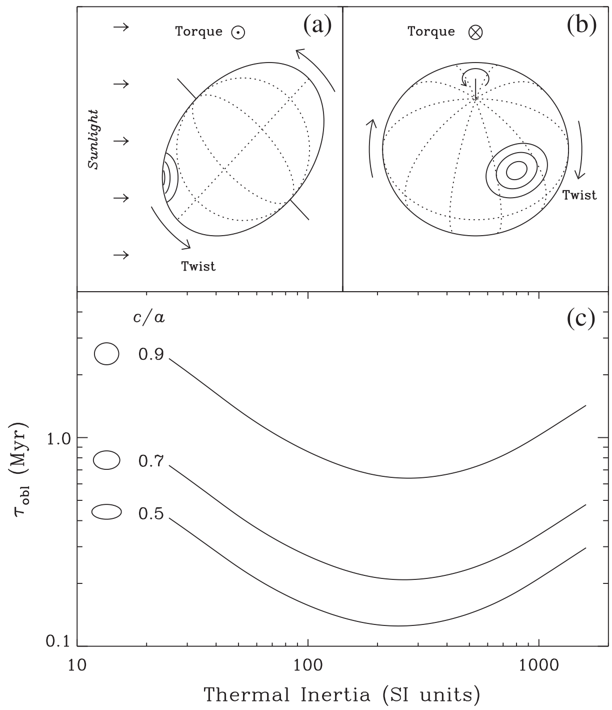

Fig. 1. YORP torque components on an axisymmetric oblate spheroid. (a) An object with zero thermal inertia is shown at its northern summer solstice. Re-radiation from the sub-solar warm spot (*contours*) produces a twist in the direction indicated, i.e., a torque directed out of the page that drives a precession of the rotation axis. (b) Sun's-eye view of the same body, with finite thermal inertia, rotating counter-clockwise. The warm spot is displaced eastward along a parallel of latitude. The recoil force has a downward component in the plane of the page, resulting in a clockwise twist and a torque into the page that lowers (raises) the obliquity of a direct (retrograde) rotator toward $\epsilon = 0°$ (180°). (c) Characteristic YORP timescale, $\tau_{\rm obl}$, for obliquity to evolve from 60° to 5°, *vs.* thermal inertia Γ for fiducial, black oblate spheroids of density $1000\ {\rm kg\,m^{-3}}$ and mass 5.346×10^{11} kg, with 2 h rotation periods and on circular orbits of radius 1 AU. Curves correspond to different values of short-to-long axis ratio (polar flattening) as indicated. Any rotating oblate spheroid with $\Gamma > 0$ will evolve toward $\epsilon = 0°$ or 180°, regardless of what made it oblate.

Real objects are not precisely symmetric, and will have nonzero spin torques owing to deviations from reflection symmetry. But for top-shaped objects the spin torque is still typically an order of magnitude smaller than the obliquity torque. To demonstrate, I calculate the YORP effect on four well-observed objects with high-resolution radar models: 101955 Bennu, (29075) 1950 DA, (341843) 2008 EV_5, and (66391) 1999 KW_4. The adopted parameters are given in Table 1. For 2008 EV_5, Γ has been estimated from thermal infrared observations (Alí-Lagoa et al., 2014). Its density is poorly constrained; Busch et al. (2011) give $3000\ {\rm kg\,m^{-3}}$ as an upper limit, which I adopt as a conservative estimate but which is higher than expected for a rubble pile. For Bennu and 1950 DA, observations of Yarkovsky drift (Chesley et al., 2014; Emery et al., 2014; Rozitis et al., 2014) permit constraints on ρ and Γ. For 1999 KW_4, no information on Γ is available, and so I simply adopt $100\ {\rm J\,m^{-1}\,s^{-1/2}\,K^{-1}}$ as an intermediate value. The torque calculation includes 1-dimensional heat conduction with the full nonlinear radiative boundary condition at the surface, as well as self-heating by reflected sunlight and thermal emission. Only the shallow diurnal thermal wave is calculated. The seasonal effect (which vanishes for zero obliquity) is neglected, as are surface roughness and beaming effects. I also assume for simplicity that the object remains in its present orbit for the length of the calculation.

For the following discussion, I adopt a working premise that is intentionally counter to the YORP spin-up concept: I assume that each of these objects attained its current shape through some unspecified process or event some time in the past, and has retained that shape until now. I integrate the coupled spin and obliquity evolution driven by YORP backward in time, from the present period and obliquity, and ask how long it should have taken for the object to reach its current spin state. The initial obliquity, at the time of the shape-setting event, is, of course, unknown.

Fig. 2a shows the times to reach the current spin states, as a function of initial obliquity. The black curve shows that Bennu could have reached its present obliquity in, at most, 0.2 Myr; the median time, assuming a statistical ensemble of random, isotropically oriented initial rotation poles, would be 0.1 Myr. For