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Rotational excitation and damping as probes of interior structures of asteroids and comets

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Abstract–Rotational excitation and damping are discussed in the context of inferring structural properties of asteroids and comets. Opportunities for carrying out deterministic experiments are outlined and basic concepts involving space missions are discussed. Spacecraft carrying an impactor or explosives together with an orbiter are suggested as effective probes of the interiors of asteroid and comets. The feasibility of such missions, especially to near-Earth objects (NEOs), is highlighted as NEOs provide an appropriate cost-effective path to explore interiors of asteroids and comets.

INTRODUCTION

From a practical point of view, the near-Earth object (NEO) population provides an excellent opportunity to investigate the interiors of both asteroids and comets. NEOs could be either of asteroidal or cometary origin and they may manifest themselves as asteroids or comets. While most of the NEOs that show characteristics representative of asteroids are indeed of asteroidal origin, a small fraction of them could be dormant or extinct comets masquerading as asteroids. Based on the dynamical properties of observed NEOs, Bottke et al. (2004) argue that the NEOs with a Jupiter-family comet origin constitute nearly 6% of the known NEO population. On the other hand, while the contribution to the NEO population due to long-period comets is likely to be comparatively small, the exact statistics are uncertain. On average, a random long-period comet nucleus is likely to be larger than a random near-Earth asteroid (NEA) and a collision of such a comet with Earth could be more catastrophic.

In addition to NEOs' asteroidal or cometary origin, their proximity to Earth means they are accessible by spacecraft with relatively lower costs than a mission to a distant asteroid or a comet. Furthermore, their close proximity to Earth makes them favored from an observational point of view. For example, the flux of the scattered solar radiation from NEOs varies as Δ^{-2} and the strength of the bounced radar signatures off NEOs for groundbased radar scales as Δ^{-4} where Δ is the geocentric distance to the NEO. All these arguments point to the suitability and the relative cost-effectiveness of the investigation of the NEO population to assess the interior structures of asteroids and comets.

The fact that the NEOs could be either of asteroidal or cometary origin, span a wide range of dynamical origins, physical sizes, and different degrees of evolution suggest the possibility that a range of interior structures could exist among different NEOs. The primary NEO structure deterministic techniques discussed in the literature involves reflection or refraction tomography using radio waves (e.g., Kofman and Safaeinili 2004) and seismic experiments involving explosives (e.g., Walker and Huebner 2004). Such experiments involve orbiting and/or lander spacecraft. An extensive knowledge of the structure of NEOs is essential for effective impact mitigation purposes, planned NEO resource mining in the future—either during human explorations of the solar system or as part of resource extraction for Earth-based utilizations, as well as to understand the environment of the early solar nebula during the formation epoch of the solar system.

As the rotational state of an NEO and its evolution depend on the interior structure, it is becoming increasing clear that the rotation could also be used as an effective and cheaper probe of the gross properties of the interior. Outgassing-caused orbital changes in comets have already been successfully used to estimate the bulk density and hence the bulk porosity of cometary nuclei (e.g., Rickman 1989; Farnham and Cochran 2002; Davidsson et al. 2007 and references therein), whereas assumed or otherwise empirically constrained bulk densities were used to calculate long-term changes to rotational states (e.g., Samarasinha et al. 2004 and references therein). In principle, one can invert the problem and use information on the characteristics of the activity and the observed changes in the rotational state to infer a bulk density. For example, extensive observing campaigns associated with the Deep Impact mission's target, comet 9P/Tempel 1, and the spacecraft observations of the comet itself make it feasible to characterize the activity and the spin state changes and to derive an independent bulk density for the nucleus. Therefore, a closer look into how rotational studies including rotational excitation and rotational damping provide an opportunity to investigate and probe the bulk interior properties of asteroids and comets is appropriate. Many observations on the spin states could be carried out from remote sensing from the Earth (e.g., Ostro et al. 2002; Pravec et al. 2002; Harmon et al. 2004; Samarasinha et al. 2004). However, in situ experiments by spacecraft or close long-term monitoring of spin evolution by orbiting space missions provide additional, yet more powerful, avenues to probe the bulk structural properties of these small bodies of the solar system.

In the next section, an introduction to rotational dynamics of comets and asteroids is presented, while the sections Rotational Excitation and Rotational Damping deal with rotational excitation and rotational damping. Experiments and Observations Involving Spacecraft discusses possible spacecraft experiments and follow-up observations which one may wish to carry out with the ultimate goal of determining or constraining interior structures of small bodies. As non-NEO asteroids and comets share structural similarities with NEOs, the subject matter in this paper is not restricted to NEOs alone but to other asteroids and comets too.

ROTATION OF SMALL BODIES

Observational evidence for asteroids and comets (e.g., Asphaug et al. 2002; Weissman et al. 2004 and references therein; Cheng 2004) provides compelling arguments that from the structural standpoint small bodies of the solar system cover a variety of scenarios (also see Richardson et al. 2002) all the way from objects that are weakly held together by gravity (e.g., "rubble-pile" asteroids and most likely the overwhelming majority of comets) to objects that are structurally much stronger (e.g., small "monolithic" asteroids, larger structurally consolidated but fractured asteroids such as Eros, and perhaps a minority of comets). However, even the strongest small body is likely to undergo internal deformations as a result of stresses and strains caused by rotation and possible changes to the spin state during its lifespan. Despite these deformations, rigid body dynamics will provide a framework to characterize the rotational properties of small bodies and ultimately to constrain or determine bulk structural parameters of the nucleus such as bulk density, bulk porosity, rigidity, and quality factor (Q-factor). The rigidity (i.e., shear modulus) is a measure of the force per unit area required for changing the shape of a material. The Q-factor quantifies the efficiency (or rather the inefficiency) of energy loss for a physical system and in the case of an excited rotator is simply the ratio between 2π times the total strain energy to the energy loss per cycle.

Details on rigid body rotation can be found in standard textbooks on dynamics (e.g., Ames and Murnaghan 1929; Landau and Lifshitz 1976). In addition, rigid body dynamics has been treated from a small body perspective in a number of publications (e.g., Belton 1991; Samarasinha and A'Hearn 1991; Hudson and Ostro 1995; Black et al. 1999; Samarasinha et al. 2004; Samarasinha 2007). Therefore, a detailed description of rigid body dynamics is not warranted here. However, an introduction to fundamentals is needed and will be presented in this paper, as the next sections will be discussing how rotational excitation and damping could be used as a probe of the interior.

A rigid body, by definition, represents an idealistic object and such a body will not deform due to applied forces. Rotation of a rigid body will be in either of the two rotation modes called short axis mode (SAM) and long axis mode (LAM) (Julian 1987) based on whether the rotational angular momentum vector precesses around the short axis or the long axis of the object in the body frame. As shown in Fig. 1a, typical SAM and LAM rotations can be expressed in terms of three component rotations (e.g., rotation around the long axis, precession of the long axis around the angular momentum vector, and a nodding motion of the long axis) in the inertial frame. However, two of these component rotations are coupled, thus leaving only two independent periods. The short axis and long axis here refer to the principal "short" and "long" axes that one may define by referring to the principal moments of inertia. For example, the principal short axis is the axis with the maximum moment of inertia.

SAM and LAM contain both principal axis (PA) rotations as well as non-principal-axis (NPA) rotations. The least energetic rotation (for a given rotational angular momentum) is a simple rotation around the principal short axis. On the other hand, the most energetic rotation (again for a given rotational angular momentum) is a simple rotation around the principal long axis. These two PA rotations are respective limiting cases for SAM and LAM rotations. Figure 1b shows the SAM and LAM rotations as a function of rotational energy.

Observations of asteroids and comets show evidence that the vast majority of them are in the least energetic "ground state" spin states. Generally, ground-based observations or flyby spacecraft observations, in contrast to rendezvous spacecraft observations, are incapable of pinpointing minute excitations from the ground state, as the signatures for such subtle excitations are difficult to identify. As indicated in Fig. 1b, a small excitation from the ground state corresponds only to a minute oscillation around the long axis (as well as to an extremely small nodding motion of the long axis) requiring unrealistically high S/N observations (for example, well-sampled extremely high S/N lightcurves). Model lightcurves (e.g., Kaasalainen 2001; Mueller et al. 2002) can be used to assess the photometric accuracy that one requires to determine such mild excitations. Therefore, the possibility exists that at

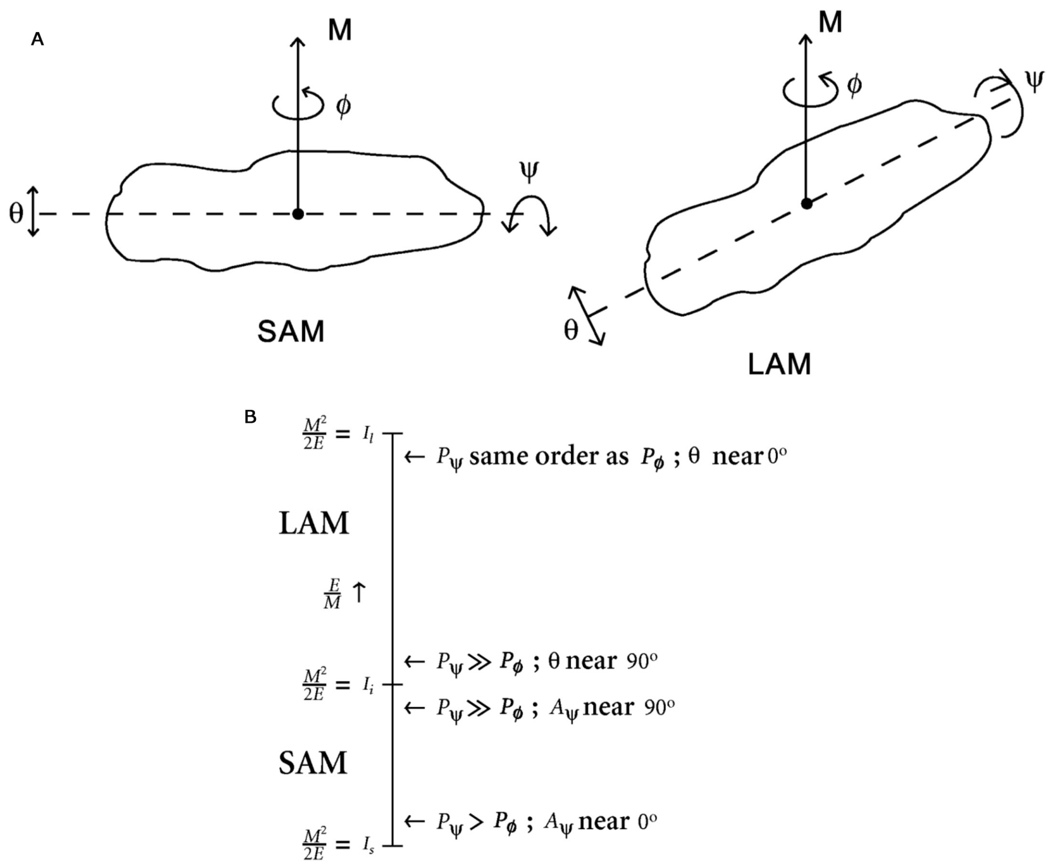

Fig. 1. a) Component rotations of SAM and LAM are depicted in relation to the long axis and Euler angles ψ, θ, and ϕ. These Euler angles denote rotation/oscillation around the long axis, nodding/nutation of the long axis, and precession of the long axis respectively. **M** is the rotational angular momentum vector and is fixed in the inertial frame. b) Characteristics of different spin states as the energy of rotation for a given rotational angular momentum increases from the least energetic state, corresponding to $M^2/2E = I_s$, to the most energetic state, corresponding to $M^2/2E = I_l$ (M, E, and I represent rotational angular momentum, rotational kinetic energy, and moment of inertia respectively while l, i, and s denote components along long, intermediate, and short principal axes). Behavior of the component periods, P_ψ and P_ϕ, are indicated for NPA spin states that differ slightly from PA states. For SAM spin states, the amplitude of the oscillatory motion of the long axis, A_ψ (as well as the nodding amplitude of the long axis, A_θ) increases as the spin state becomes more energetic. For LAM states, the mean value of the angle θ (as well as the amplitude of the nodding motion of the long axis, A_θ) decreases as the kinetic energy of the rotational state increases. Figure is from Samarasinha et al. (2004).

least some small body rotational states that have been characterized as ground state spin states are actually mildly excited states from the ground state. On the other hand, highly excited rotators are comparatively easier to identify though they still require a well-sampled data set. Nevertheless, even obtaining such data sets is a task that is not accomplished very often due to observing limitations (e.g., lack of required temporal coverage and/or signal-to-noise issues) or difficulties associated with getting massive allocations of telescope time. Therefore, it is reasonable to assume that although most of the measured small bodies are in ground state PA spin states, the known fraction of NPA rotators among the small body population is only a lower limit. Comet 1P/Halley (e.g., Belton et al. 1991; Samarasinha and Belton 1991) and asteroid 4179 Toutatis (Hudson and Ostro 1995) are the first comet and asteroid to be conclusively identified as excited rotators.

Various physical processes over time can cause changes in the spin state. The changes to the spin state are caused either by external torques (e.g., collisions and YORP torques in the case of asteroids and outgassing torques in the case of comets) or variations to the moment of inertia (e.g., collisions in the case of asteroids and mass loss due to splitting events or outgassing in the case of comets). Simultaneous integration of the Euler's equations of motion (see below) allows one to monitor spin changes caused especially by relatively weak but long-acting torques (e.g., see Samarasinha et al. 2004 and references therein for details).

$$I_l\dot{\Omega}_l = (I_i - I_s)\Omega_i\Omega_s + N_l$$

$$I_i\dot{\Omega}_i = (I_s - I_l)\Omega_s\Omega_l + N_i$$

and

$$I_s\dot{\Omega}_s = (I_l - I_i)\Omega_l\Omega_i + N_s \quad (1)$$

where I, Ω, and N refer to moment of inertia, angular velocity, and the external torque, respectively, and the subscripts, l, i, and s denote the components along long, intermediate, and short principal axes.

ROTATIONAL EXCITATION

Under the assumption of a rigid body, an estimate can be made of the time scale for rotational excitation under external torques. As the amount of rotational excitation is characterized by the quantity $M^2/2E$ (e.g., see bottom panel of Fig. 1), where M and E are the rotational angular momentum and the rotational kinetic energy, respectively, one may express the excitation time scale as

$$\tau_{\mathrm{excite}} = \frac{M^2/2E}{-\frac{d(M^2/2E)}{dt}} = \left(\frac{\dot{E}}{E} - \frac{2\dot{M}}{M}\right)^{-1} \quad (2)$$

where $\dot{E}$ and $\dot{M}$ are the respective rates of changes for E and M.

It should be pointed out that this excitation time scale is different from the time scale for changing the spin period (is same as the time scale for changing the angular momentum) for an object that is always in a PA spin state. The time scale for spin period change for a PA rotator is given by (e.g., Samarasinha et al. 1986)

$$\tau_{\mathrm{spin}} = \frac{P}{\dot{P}} = \frac{\Omega}{\dot{\Omega}} = \frac{M}{\dot{M}} = \frac{I\Omega}{N} \quad (3)$$

where $\dot{P}$, $\dot{\Omega}$, and $\dot{M}$ denote rate of changes of P, Ω, and M respectively while I, Ω, and N will be I_s, Ω_s, and N_s in the case of PA rotation around the short principal axis. Despite the wider usage of τ_{spin} for τ_{excite}, it should be noted that τ_{spin} only provides a lower limit to the actual excitation time scale τ_{excite}. It has been noted in the literature that prolates for example are easier to excite than triaxial ellipsoids or irregulars (e.g., Gutierrez et al. 2003 and references therein). In addition, Gutierrez et al. (2003) derives the necessary condition governing the ratio between the component torques and moments of inertia for rotational excitation. For further discussions on the process of rotational excitation and the excitation time scale, the reader is referred to Samarasinha and Belton (1995), Neishtadt et al. (2002), and Gutierrez et al. (2003).

Rotational excitation could be either gradual (e.g., due to YORP torques on an asteroid or outgassing torques on a comet) or sudden and impulsive (e.g., due to a collision with another object). As mentioned earlier, Euler's equations of motion allows one to monitor changes in the spin state (e.g., Wilhelm 1987; Peale and Lissauer 1989; Samarasinha and Belton 1995; Gutierrez et al. 2005). Everything else being equal, for almost all conceivable processes of rotational excitation due to external torques (in contrast to rotational excitation caused primarily by moment of inertia altering events), the external torque can be expressed as being proportional to r^n (where r is the effective radius of the object and the exponent n is typically greater than zero). A closer inspection of Equation 2 reveals that similar to τ_{spin}, the excitation time scale τ_{excite} is also proportional to the relevant component moments of inertia whereas it is inversely proportional to the relevant component torques. Therefore, the excitation time scale scales as r^{5-n}. For example, as the outgassing forces in the case of comets and Yarkovsky forces in the case of asteroids (for a restricted range of radii) scales as the surface area (i.e., r^2), the respective outgassing torques and YORP toques scale as r^3 and the excitation time scale scales as r^2. For rotational excitations due to close planetary approaches (e.g., Scheeres et al. 2000), the tidal torques scale as r^2 and therefore the excitation time scale scales as r^3. When such processes dominate the rotational excitation, on average, one should expect smaller objects to exhibit rotational excitations at shorter time scales. There is an important caveat. The fast rotators, due to their high kinetic energies are difficult to excite. However, from a statistical point of view, one may argue that on average for nearly 50% of the situations, the spin rate changes due to external torques on a PA rotator may act in such a way as to decrease the net kinetic energy of the rotator thus facilitating the eventual rotational excitation of the object; i.e., an upper limit of 50% can be placed on the likelihood of rotational excitation due to sufficiently large external torques. Based on the above discussions, one may state that on average, small slow rotators are easier to excite than large fast rotators. However, all slow rotating small NEOs are not easily excitable as rotational excitation also depends on ratios among component torques and component moments of inertia as mentioned in the previous paragraph.

From the point of view of constraining the gross internal structure of small bodies, lack of rotational excitation (caused by a rapid damping of rotational kinetic energy) despite the presence of adequate external torques will allow one to assess the structural deviations from a rigid body. In general, the natural processes for rotational excitation of comets (e.g., outgassing, splitting events) are more efficient than those for the asteroids. For example, numerical integrations of spin state changes due to outgassing torques for periodic comets indicate that detectable changes do occur at time scales of an orbit or less (e.g., Samarasinha et al. 2004 and references therein). Figure 2 shown below adapted from Gutierrez et al. (2005) indicates a variety of scenarios for the spin state changes for comet 67P/Churyumov-Gerasimenko during the rendezvous phase of the Rosetta spacecraft. Observations from Rosetta will be able to quantify the spin state changes and these observed changes can be compared with what is expected based on modeling of non-gravitational torques caused by outgassing. An accurate shape model of the nucleus, the mass and mass distribution of the nucleus, and the distribution of detailed activity on the nuclear surface from a multitude of observations by Rosetta, makes this comparison the most sophisticated experiment planned on determining the structural parameters of a small body. This will complement tomographic imaging of the nucleus by Rosetta (e.g., Kofman and Safaeinili 2004). However, as pointed out in the Introduction, until and unless a range of cometary nuclei (or for that matter asteroids) is investigated, one cannot make a secure assessment as to the structural diversity among the interiors of cometary nuclei (or asteroids).

A rapidly disintegrating comet with multiple fragments such as comet 73P/Schwassmann-Wachmann 3 (hereafter SW3) provides an excellent opportunity to investigate rotational excitation. Rapid mass losses from individual fragments result in changes to the spin states and if the initial spin states were ground states, subsequent mass losses will cause rotational excitations. Comet SW3, which was observed to undergo breakups in 1995 (e.g., Crovisier et al. 1996), had a close approach to Earth (~0.08 AU) in May 2006 and thus provided a rare opportunity to investigate the multiple fragments of this comet (Fig. 3). During the 2006 apparition, additional breakups were observed by both ground- and space-based observatories. Currently a number of groups are carrying out detailed analyses of observational data with the goal of uniquely identifying the spin states of individual fragments of SW3. A dedicated space mission would have made a significant contribution to this effort. Unfortunately, even the flyby spacecraft CONTOUR that was scheduled to visit SW3 did not materialize due to the destruction of the spacecraft in-flight.

Another suitable cometary candidate for studies of spin excitation is 96P/Machholz. As this comet has a comparatively small perihelion distance (~0.12 AU), the level of outgassing activity near perihelion will be nearly two orders of magnitude larger than a similar comet at 1 AU from the Sun. This level of activity could cause appreciable changes to the spin state from outgassing torques alone in shorter time scales.

ROTATIONAL DAMPING

Any asteroid or comet at the time of its formation is presumably be in an excited spin state (cf. Giblin and Farinella 1997). Such a body that is in an excited spin state, in the absence of a continuous process to maintain that excited spin state, will damp itself to the corresponding ground state PA spin state (e.g., Pravec et al. 2005 and references therein). Subsequent physical processes (e.g., collisions, breakups, etc.) could again excite the object followed by gradual relaxation to the ground state. Whether a particular object is in an excited spin state at a given moment is determined by the epoch of the excitation event, the extent of the excitation, and the damping time scale for that object. The damping occurs when rotational energy is lost by internal mechanical friction and heating as a result of stresses and strains (due to accelerations and decelerations) associated with the NPA spin states. Figure 4 schematically depicts this behavior of the loss of rotational energy and the resultant damping of the excited spin. The damping is most efficient when the accelerations and decelerations associated with component rotations of the NPA spin state are most extreme. This corresponds to NPA spin states which are well away from the PA spin states (e.g., see Appendix in Samarasinha and A'Hearn 1991). In other words, the damping time scale τ_{damp} is a function of the degree of excitation ε ($0 \leq \varepsilon \leq 1$) where $\varepsilon = (I_s - M^2/2E)/(I_s - I_l)$ as schematically illustrated in Fig. 4 (also see Sharma et al. 2005).

The damping time scale of a rotationally excited object due to mechanical energy loss can be expressed by (e.g., Burns and Safronov 1973)

$$\tau_{damp} = \frac{K_1 \mu Q}{\rho r^2 \Omega^3} \tag{4}$$

where K_1 is a non-dimensional scaling coefficient, μ is the rigidity (shear modulus), Q is the Quality factor, ρ is the bulk density, r is the radius, and Ω is the angular velocity. K_1 depends on the shape of the object and it also incorporates the damping time scales' dependency on the degree of excitation. Efroimsky (e.g., Efroimsky 2001 and references therein) argued that K_1 is approximately two orders of magnitude smaller than the initial estimates by Burns and Safronov thus implying shorter damping time scales. However, a reanalysis of the problem by Burns and colleagues (Sharma et al. 2005) indicates that the previous assessment for K_1 is consistent. Sharma et al. (2005) propose values around hundred to few hundreds for K_1 (which is redefined as the parameter D in their paper). However, one should be cautioned that these derivations for K_1 (or rather D) are for a symmetric rotator and the calculations for irregular bodies are yet to be carried out.

Equation 4 can be used to estimate the product μQ. Harris (1994) proposed a value of 5×10^{12} dyne cm^{-2} for μQ (with a likely uncertainty of a factor 10 and an extreme uncertainty of not more than factor 100) for small bodies based on the μ and Q of other solar system objects. However, this assessment requires confirmation considering the range of structural diversity that one can expect among the NEOs (as well as among different asteroids and comets). For future determinations of structural parameters, one needs to apply the most appropriate value of K_1 (or D) depending on the shape of

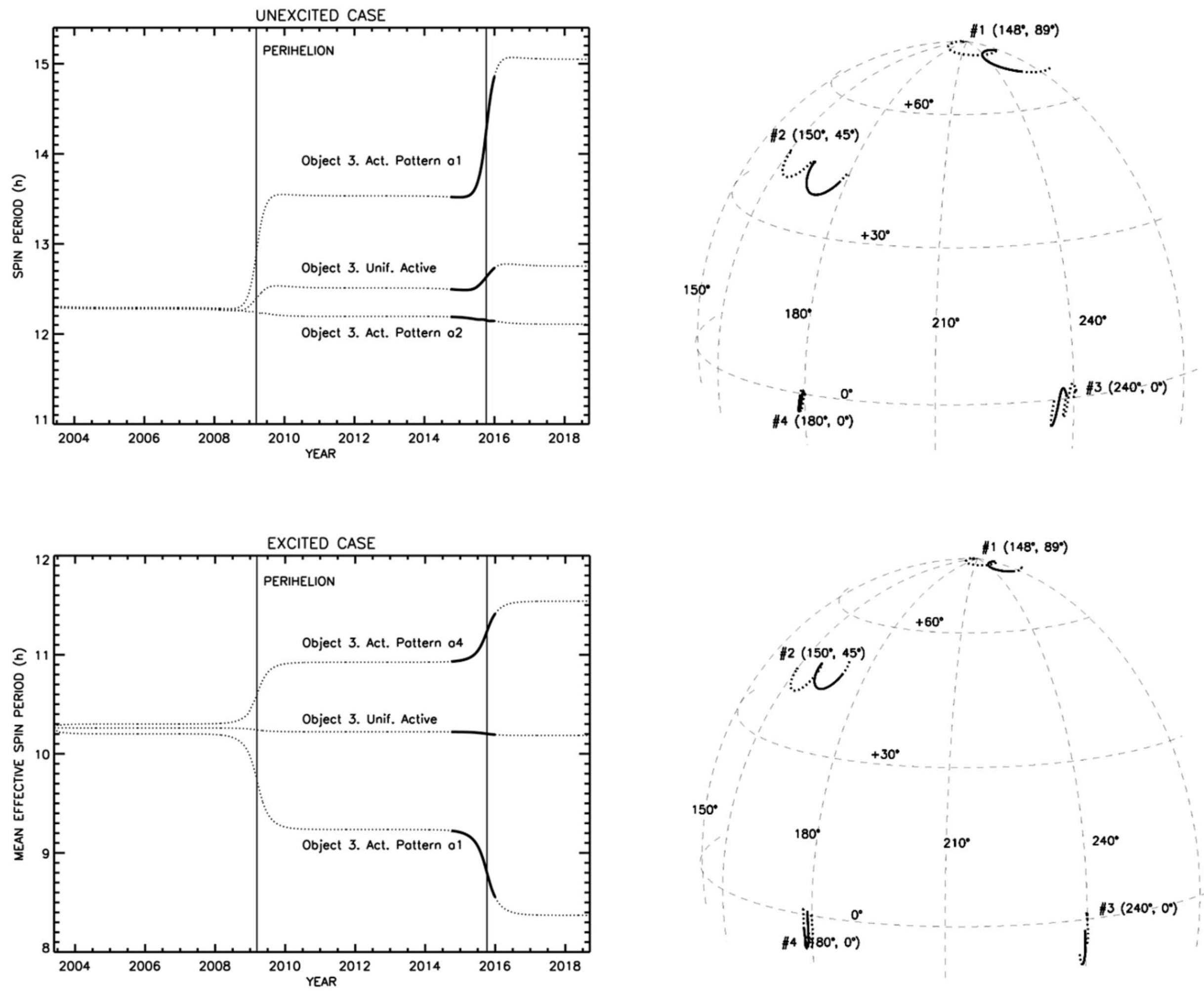

Fig. 2. Left: These panels depict the evolution of the spin period of comet 67P/Churyumov-Gerasimenko as a function of time for a variety of scenarios (nuclear shapes, outgassing patterns, and initial conditions). The top panel shows the cases corresponding to initial unexcited spin states, while the bottom panel depicts excited spin states. The solid portions of the evolutionary paths correspond to the time interval that Rosetta plans to carry out nucleus observations of the comet. Right: These panels show displacement of the direction of the rotational angular momentum vector in an inertial coordinate system for a range of scenarios. The top panel corresponds to cases where the initial spin state is unexcited whereas the bottom panel demonstrates the behavior for excited spin states. Again the solid portions of the paths correspond to the time interval that Rosetta will carry out nucleus observations. See Gutierrez et al. (2005) for further details.

the particular object and the initial and final degrees of rotational excitations over which the rotational damping is assessed.

An abrupt change to principal moments of inertia of an asteroid or a comet due to a collision or a splitting event will throw the asteroid or the comet into an excited spin state. For example, one should expect the fragments due to a cometary splitting event to be in excited spin states (as should have been the case for fragments of comet SW3 as discussed under Rotational Excitation). In addition, if the mass loss is sufficiently large, even the primary nucleus should be thrown into an observably identifiable excited spin state. Absence of rotational excitation in such cases can be used to place strict upper limits on the damping time scale and hence on the product μQ.

EXPERIMENTS AND OBSERVATIONS INVOLVING SPACECRAFT

For illustration purposes, one may use $\tau_{damp} = 0.24P^3/r^2$ as suggested for asteroids by Sharma et al. (2005) where τ_{damp} is in million years while P and r are expressed in h and km, respectively. It should be noted that this expression was derived using D = 200, $\mu Q = 5 \times 10^{12}$ dyne cm^{-2}, and ρ = 2.5 gram cm^{-3}. Ideally, for a rendezvous spacecraft mission to detect rotational damping, τ_{damp} should be small (of the order of 10^3 years or less). This means, even for a relatively fast rotator (P ~1 h) with a radius of ~1 km, one may conclude that the damping process is too slow to be observed. However, there are at least two arguments that suggest this is not necessarily the case for all asteroids and comets.

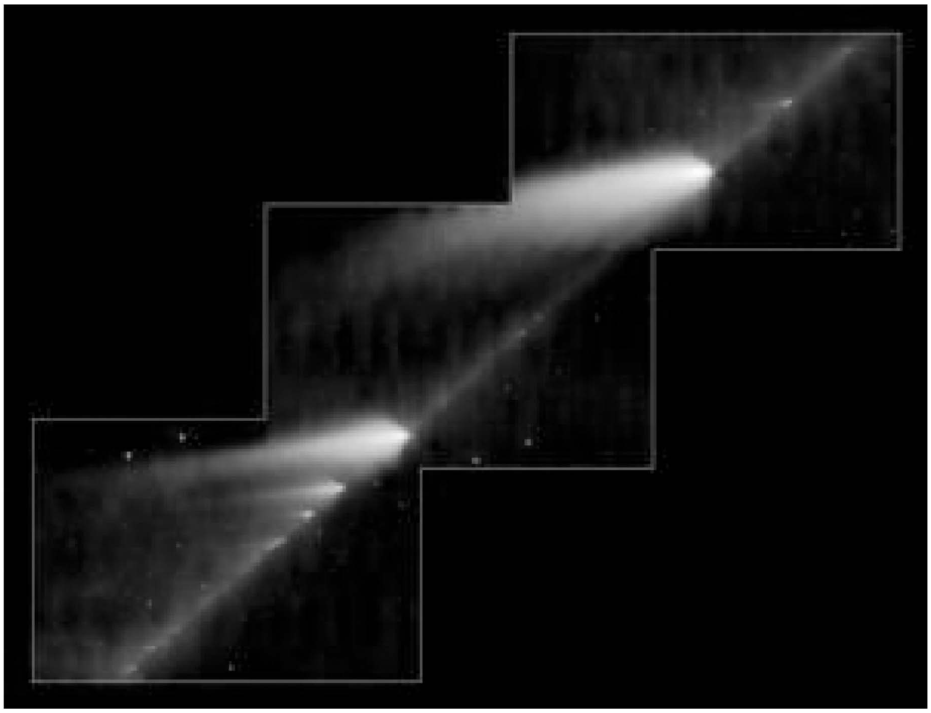

Fig. 3. A mosaic of comet 73P/Schwassmann-Wachmann 3 showing its many fragments (mini comets) based on Spitzer Space Telescope images taken in 2006. The nominally brightest (and hence likely to be the largest) fragment, component C, is at the upper right whereas the second brightest (and the brightest during the larger outbursts) fragment, component B, is slightly below and left to the center of the image. Image courtesy of William Reach and collaborators, NASA/JPL-Caltech.

1. There is mounting evidence that at least some asteroids and comets are rubble pile or fragile loosely bound aggregates of material (e.g., Richardson et al. 2002 and references therein). If indeed that is the case, μQ has to be much smaller than was assumed earlier and therefore the damping time scales are much smaller. Spacecraft monitoring of damping would yield conclusive evidence for such a structural configuration as well as the corresponding values for the structural parameters.
2. Simple comparisons between time scales for rotational excitation and damping for short period comets show evidence that nearly all short-period comets should be in excited spin states (Fig. 2 of Jewitt 1999). (Note: Jewitt used τ_{spin} for τ_{excite}; however, even with a longer time scale for the rotational excitation, his argument holds true at least for nuclei smaller than few tens of km—i.e., for the overwhelming majority of short period comets.) On the other hand, observations suggest most comets are not in excited spin states. The suggested values for μQ in the literature are of the order of 10^{12} dyne cm^{-2}, Peale and Lissauer 1989; also see arguments presented in Harris 1994). However, if the actual μQ is indeed smaller than these suggested values, the damping time scales must be shorter and many comets must be in relaxed spin states (Samarasinha et al. 2004).

Figure 5 depicts the behavior of $\mu Q/\tau_{\text{damp}}$ as a function of the rotational period and the radius of the NEOs. It is clear that large fast rotators will have small damping time scales for a given value of μQ. Alternatively, small μQs would result in smaller damping time scales. Indeed, if the value of μQ is sufficiently small, even relatively small rotators (e.g., representative of sub-km size NEOs) with rotation periods of several hours may exhibit detectable damping time scales. So, for asteroids and comets—many of which may simply be gravitationally bound aggregates, how small can μQ be? Nobody knows for sure. However, observational and experimental evidence are suggestive of extremely small values for μQ. Based on the tidal evolution of the binary NEO 2000 DP107, Margot et al. (2002) derive a value for μQ as low as 10^9 dyne cm^{-2} (also see work of Scheeres et al. 2006 on the binary NEO 1999 KW4). Complicating the issue further is the lack of knowledge on the “effective μQ” for a gravitationally bound aggregate. One may suspect Q for such an aggregate is likely to be less than what is typically adopted (~100) for solid rocky material. Experimental work by He and Aherens (1994) on shock-damaged rocks indicates drastic reductions in the Young’s modulus (which is a measure of the elasticity) with the increasing rock damage (their Equation 1 and Fig. 2 indicate a Young’s modulus essentially approaching zero for extremely damaged rocks!). As the Young’s modulus and the shear modulus are of the same order, one may infer that the shear modulus too decreases with increased

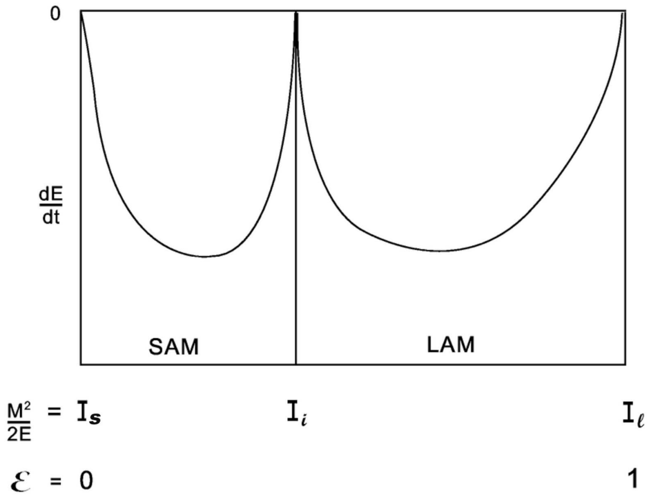

Fig. 4. A schematic diagram to demonstrate how the rate of change of rotational kinetic energy due to mechanical friction may depend on $M^2/2E$ as well as on the degree of rotational excitation ε ($0 \leq \varepsilon \leq 1$) where $\varepsilon = (I_s - M^2/2E)/(I_s - I_l)$. For NPA spin states near PA states, the rate of change of rotational energy, dE/dt , approaches zero.

rock damage. The inferred mass movements and the surface features on the rubble-pile NEO (25143) Itokawa (Fujiwara et al. 2006) are additional pointers that structural parameters such as shear modulus must be extremely low for rubble-pile or highly fractured objects. The shear modulus is smaller for objects with significant porosity when compared with that of solid objects (e.g., Lambe and Whitman 1979; Pal 2005 and references therein). Furthermore, a number of commonly found soil categories have relatively low shear moduli (e.g., very soft clay and silt as low as 7×10^6 dyne cm^{-2} and silty sand as low as 2×10^7 dyne cm^{-2}; Bowles 1988) whereas for a material such as rubber it could be as low as 2×10^6 dyne cm^{-2} (Gere and Timoshenko 1997) suggesting that for a gravitationally bound rubble pile structure, the "effective μQ" is extremely small. Therefore, despite lack of direct measurements, one may argue that the evidence presented above, when taken together, points to small body μQs as low as 10^7 dyne cm^{-2} (if not lower). This value of μQ corresponds to a $\mu Q/\tau_{damp}$ as low as 10^4 dyne cm^{-2} year $^{-1}$ when τ_{damp} is around 10^3 years. Therefore, in Fig. 5, the regime above the $\lambda = 4$ line (where $\lambda = \log_{10}(\mu Q/\tau_{damp})$ with $\mu Q/\tau_{damp}$ expressed in units of dyne cm^{-2} year $^{-1}$) represents the NEOs of whose rotational damping may be measured with an orbiting spacecraft.

Space missions equipped with an impactor (or lander) and an orbiter can rotationally excite an NEO and then monitor its spin state evolution. I.e., an impactor such as what was used in the case of NASA Deep Impact mission to comet 9P/Tempel 1 (A'Hearn et al. 2005) can be used to impart an impulse. Alternatively, a lander could be used to place explosives in strategic locations on the surface of an NEO (explosion itself can be near-surface or by using buried explosives) such that the maximum possible impulse can be transferred to the NEO. For rotational excitation purposes, the surface location of application of the impulse will critically determine the degree to which the NEO will be rotationally excited. In that sense, usage of explosives has an advantage over impactors unless the impactor can be delivered to a specific surface location at high relative velocity (~10 km/s). On the other hand, as discussed below, standard explosives may require a heavier payload than an impactor resulting in an expensive mission. Spacecraft experiments involving impactors or explosives could provide clues to the interior structure in two ways: first during the process of impact/explosion by measuring the structural damage to the NEO and by observing the rotational excitation and then later on by monitoring the rotational damping using the orbiter spacecraft. These observations can be complemented by groundbased observations although groundbased observations are not a replacement for the high-resolution measurements from the orbiter.

The change in angular velocity, $\Delta\Omega$, due to an impactor is given by

$$I\Delta\Omega \approx md\ \Delta V \tag{5}$$

where I is the moment of inertia about the axis of rotation, m is the mass of the impactor, d is the impact parameter, and ΔV is the relative velocity of the impact. By approximating d to the radius of the NEO, r, the Equation 5 can be rewritten as

$$\Delta\Omega \approx \frac{m\ \Delta V}{\rho r^4} \tag{6}$$

where ρ is the bulk density of the NEO. For a 10^3 kg (i.e., one ton) impactor moving at 10 km/s and hitting a 100 m radius NEO having a density of 2 g cm^{-3}, $\Delta\Omega$ could be a significant fraction of the original spin. Therefore, by assuming that a 100 m radius NEO with a period of 10^4 s can be rotationally excited by this impact (i.e., assuming that the other necessary conditions for rotational excitation discussed under Rotational Excitation are satisfied), one may determine all NEOs that can be excited by the above impactor. For this purpose, one needs to evaluate the radius and the period dependency of the excitation time scale. By an exercise similar to that under Rotational Excitation, it can be seen that the torque is proportional to the radius of the target (since the impactor mass and the impact velocity are the same) and therefore the excitation time scale varies as r^4/P. The dashed line and the regime below it in Fig. 5 represents the radius, r, and the rotation period, P, for such NEOs. It should be noted that this dashed line represents only a crude approximation. Therefore, for example, for the proposed ESA NEO mission Don Quijote (despite that the target asteroid could be somewhat larger), one may still see observable changes in its spin state. As the kinetic energy of rotation is given by $E = I\ \Omega^2/2$ where I is the moment of inertia around the axis of

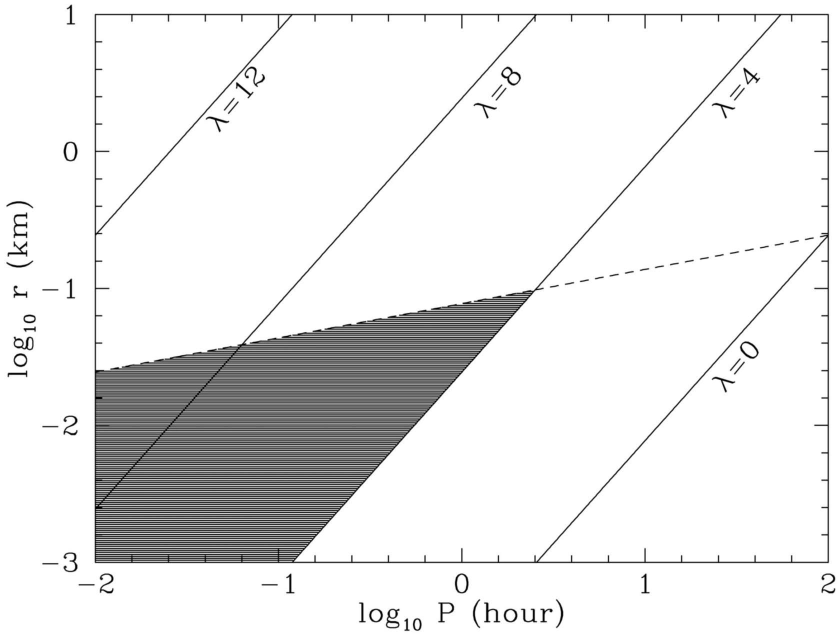

Fig. 5. A plot showing the behavior of λ (= $\log_{10}[\mu Q/\tau_{damp}]$) based on the damping time scale given in Equation 4. Here K_1 = 200 and ρ = 2 g cm^{-3} are assumed and $\mu Q/\tau_{damp}$ has units of dyne cm^{-2} year^{-1}. Even for many sub-km sized objects, if the interior structure resembles a rubble pile (or of highly fractured nature), the effective μQ may be sufficiently low to enable accurate measurement of τ_{damp} by orbiting space missions. To be determined by an orbiting spacecraft equipped with a small telescope (few tens of cm size aperture) with a rendezvous phase lasting several months to a year, the damping time scale should be of the order of 10^3 years or less. The λ = 4 line represents the r and P dependency of λ when $\mu Q = 10^7$ dyne cm^{-2} and $\tau_{damp} = 10^3$ years. Therefore, an orbiting spacecraft could monitor the rotational damping of the NEOs occupying the regime above the λ = 4 line. The regime below the dashed line represents the NEOs that can be rotationally excited by the impactor discussed in the text. Therefore, the shaded area represents the potential NEO candidates for which both the rotational excitation as well as the spacecraft monitoring of the damping process are feasible.

rotation and Ω is the angular velocity, $E \propto r^5/P^2$. Therefore, from the point of view of rotationally exciting the target NEO, a small (order of 100 m) and a slow rotator is favored. For comparison purposes, one may consider the Deep Impact experiment (A'Hearn et al. 2005). The spin period changes of 9P/Tempel 1 due to the impulse from the impactor of the Deep Impact mission was of the order of ten millisecond (Note: radius of 9P/Temple 1 is nearly 3 km and the impactor mass was around 370 kg). Even accounting the creation of the crater and the subsequent mass ejections and their effect on the spin period, still the changes to the spin period of 9P/Tempel 1 is well below one second.

A small slow rotator that is preferred from the point of view of the rotational excitation seems to be in conflict with what is preferred from the point of view of monitoring its rotational damping process with an orbiting spacecraft. A small telescope on-board (few tens of cm aperture) with a rendezvous phase lasting several months to a year can detect damping time scales of the order of 10^3 years. Therefore, as discussed earlier in this section, for an NEO with μQ as low as 10^7 dyne cm^{-2}, the corresponding $\mu Q/\tau_{damp}$ translates to 10^4 dyne cm^{-2} year^{-1}. In this case, it can be seen from Fig. 5 that NEOs in the shaded regime are the ideal objects from the point of view of both rotationally exciting as well as the subsequent monitoring of the damping process. As an example, a 100 m diameter size NEO with a rotation period near 1 h is a possible candidate. Indeed, an increased energy of impact (either using a massive impactor or a higher impact speed), a smaller μQ, or a larger τ_{damp}, will expand the shaded area, thus allowing a larger range of r and P for candidate NEO targets.

If one uses conventional explosives to impart the same spin rate change as the one-ton impactor discussed earlier, the corresponding explosive requirement will be more than 10 tons of TNT. Therefore, while explosives can be placed at precise location(s) on an NEO, the corresponding mission payload is likely to be larger than using an impactor. On the other hand, due to the structural characteristics of the NEO (e.g., rubble pile or highly fractured), if the explosives could easily cause the breakup of a significant mass of the NEO and alter the moments of inertia of the NEO, the strategically placed explosives could be efficient in rotationally exciting an even larger NEO.

Finally, if the object is already in an excited spin states (such as some known comets and asteroids), monitoring by a rendezvous spacecraft can be used to measure its damping time scale and infer μQ for that object. As discussed earlier, large and fast rotators will have smaller measurable damping time scales. For rubble pile or highly fractured objects, the range of radii and spin rates which allows determination of the damping time scale is larger than that for monolithic "rigid" objects (e.g., see Fig. 5).

SUMMARY

Basic principles behind rotational excitation and damping are discussed together with a range of examples of how excitation and damping of asteroids and comets can be used to infer bulk structural properties of these small bodies. Spin state changes can be used to infer or constrain structural properties such as bulk density, rigidity, and Quality factor (note: monitoring of the damping process will determine the product of μ and Q and not the individual parameters). These measurements can be used in conjunction with other imaging techniques such as radar tomography to obtain a comprehensive picture of the small body interiors as well as to assess the structural diversity among them.

Basic concepts for space missions are outlined where rotational excitation and damping play key roles in determining interior structures of NEOs. In particular, the role of the impactor missions and lander missions with explosives are discussed with relevant pros and cons. It is argued that spin state alteration of small NEOs and subsequent monitoring of spin state evolution are possible with the help of spacecraft missions.

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