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Artificial Spin-up and Fragmentation of Sub-kilometre Asteroids

Claudio Bombardelli
Advanced Concepts Team, European Space Agency, ESTEC, The Netherlands
claudio.bombardelli@esa.int

ABSTRACT

The article demonstrate the feasibility of artificially increase the spin rate of asteroids about 200 m in diameter beyond the limit in which they begin to disrupt. In the proposed concept a tethered satellite of less than a few tens of kilometers length anchored to the asteroid surface is employed as a mean to exchange angular momentum with the celestial body and increase its spin rate. Simple calculations based on angular momentum and energy conservation show that a 200 m diameter asteroid can be spun up to critical rotation speed in less than one year with current technology.
The scheme can be utilized as a unique scientific tool to characterize the asteroid internal structure and composition.

1. INTRODUCTION

Understanding the internal structure and composition of asteroids is a top priority for the coming planetary exploration program of many international space agencies. Asteroids are often regarded as 'celestial fossils' whose interior could yield very important clues about the formation and evolution of our planetary system and possibly on the pre-biotic chemical evolution of life.
Up to date several approaches have been proposed in order to map the interior of asteroids including subsurface drilling and sampling as well as radio reflection tomography and seismology. The drawback of these techniques is their poor resolution in characterising the asteroid features at greater depth.

Recently a different approach to the problem has been considered for the case of asteroid 99942 Apophis, which will make a close earth fly-by in year 2029. As the mechanical properties of Apophis will be considerably affected by the interaction with the earth gravitational field it is attractive to monitor its mechanical response during the fly-by with a suite of scientific instruments deployed in-situ (e.g. a distributed net of seismometers) gaining unprecedented knowledge about the structural make-up of the inaccessible asteroid interior [1,2].

This study makes one step further in this direction by introducing the possibility of radically modifying the dynamical status of a celestial object with artificial means. It is shown that by employing a tethered centrifuge of less than a few tens of kilometres anchored to the surface of a sub-km asteroid the latter can be gradually spun-up until it breaks up. In this way not only it becomes possible to study the asteroid response during a 'heavy' spin-up process but also a direct access to the inner layers of the fractured celestial body becomes possible providing unique scientific information on its interior.

The outline of the article is the following. Firstly an introduction of asteroid strength is presented. Second a description is given of the asteroid spin-up apparatus and the spin-up strategy. Next, an analytical model is introduced to investigate the spin-up dynamics of the tether-asteroid system. Starting from the analytical model fuel, power and mission lifetime requirements are derived together with the technological feasibility of fragmenting sub-km asteroids with a relatively modest-size tether centrifuge.
Results show that, in the worse case scenario of expected material strength, asteroids of up to 200 meter diameter can be fractured in less than 5 years with a tether centrifuge of a few tens of km and employing less than 20 tons of overall system mass.

1. REQUIRED SPIN RATE

The spin rate required to bring an asteroid to disruption can be estimated using a simple model in which the asteroid is treated as a homogeneous sphere subject to centrifugal acceleration and self-gravity. Following Dobrovolskis [3], the maximum tensile stress on a spherical spinning asteroid is located at the centre of the sphere (although in the particular case of a cohesionless sphere the point of maximum stress, in that case zero, is not only the centre but the whole body) and reads:

$$\sigma_{\max}^{H} = \left(\frac{1}{3}\omega^2 - \frac{2}{3}\pi G\rho\right)\frac{d^2}{4} \quad (1)$$

Dobrovolskis considers the asteroid always in the elastic regime and makes the assumption that all shear stresses decay with time and the asteroid relaxes toward an equipotential figure (hydrostatic stress tensor).

On the other hand Holsapple [4] computes the maximum stress including the shear component obtaining, for the elastic regime:

$$\sigma_{\max}^{E} = \left(\frac{3+2\nu}{7+5\nu}\omega^2 - \frac{2}{3}\pi G\rho\right)\frac{d^2}{4} \quad (2)$$

where ν is the material Poisson ratio. Regardless of the small influence of ν the value of $\sigma_{\max}^{E}$ is always larger than $\sigma_{\max}^{H}$ so the latter can be used conservatively as reference for deriving the limit spin rate for fragmentation which is obtained by equating $\sigma_{\max}^{H}$ with the asteroid tensile strength σ_a to yield:

$$\omega_{break} = \sqrt{2\pi G\rho + \frac{12\sigma_a}{\rho d^2}} \quad (3)$$

If one assumes plastic failure for the asteroid the analysis gets more involved and although the point of maximum stress is still the center of the sphere the failure zone, associated with the onset of unconstrained plastic flow, is generally located on a non-central cross section of the body [4]. At any rate, considering plastic failure goes beyond the scope of this article.
Note that Eq. (3) can be conservatively applied to the limit case of asteroids with zero strength, zero friction and only held together by self-gravity. As explained by Weidenshilling [5], in this scenario the strengthless spherical body will undergo a change of shape in order to maintain hydrostatic equilibrium as the rotation rate grows. However the rotation rate cannot exceed the critical limit:

$$\omega_{\lim} = 0.53\sqrt{\frac{4\pi G\rho}{3}} \quad (4)$$

beyond which the body enters a mechanical instability region (Maclaurin-Jacobi transition) and undergoes fission into a binary asteroid [5].

As ω_{lim} is always smaller than ω_{crit}, Eq.(3) can be conservatively used also for the case of strengthless asteroids.
As far as the asteroid tensile strength is concerned, while it is agreed that asteroid can range from weak rubble-pile aggregates to rocky formations with material strength, the observation data at our disposal are still not sufficient to provide statistically significant information on this topic.
As the aim of the present analysis is to estimate the required mass and power resources to spin-up a generic asteroid until fragmentation a worse case scenario in terms of material strength has to be considered. For this purpose one can refer to the tensile strength of very strong terrestrial rocks such as strong basalt as a reasonable upper limit. The strength of an intact (i.e. free of cracks) basalt sample can be estimated from [6] to be about 10 MPa. Besides, a size dependent decrease in tensile strength has to be taken into account due to the increasing concentration of flaws in larger rocks. Housen and Holsapple [7] consider a Weibull exponential distribution of flaws with increasing volume from which the tensile strength can be written as:

$$\sigma_a = \sigma_m V^{-\frac{1}{\phi}} \qquad (5)$$

where σ_m is the material tensile strength of the intact rock sample, V is the rock volume and ϕ is the Weibull exponent which based on terrestrial rocks data can be set to ~6.

From Eq.s (4) and (6) we finally obtain a reference fragmentation spin rate for later use:

$$\omega_{break} = \sqrt{2\pi G\rho + \frac{12\sigma_m}{\rho d^2}\left(\frac{\pi}{6}d^3\right)^{-\frac{1}{6}}} \qquad (6)$$

2. CREATING THE SPIN-UP TORQUE

Practically speaking the proposed spin-up apparatus utilised for asteroids is based on the same working principles of reaction-wheel-based attitude control systems of artificial satellites. Given an artificial satellite with certain inertia characteristics a reaction unit having sufficiently high moment of inertia is designed in order to exchange angular momentum with it. The angular momentum is transferred by spinning the wheel around the same axis the satellite is to be rotated but in the opposite direction.
The reaction wheel inertial characteristics depend on the amount of angular momentum to be exchanged with the body they are mounted on which is proportional to the body inertia and desired spin rate. On the other hand reaction wheels are often designed to compensate for only a fraction of the total required angular momentum estimated for a given mission. In fact, each time a reaction wheel has reached the maximum amount of angular momentum it can bear, depending on mechanical and system constraints, it is de-saturated by employing a mass reaction system (usually thrusters) in order to apply a net torque on the whole spacecraft and re-establish the proper angular momentum balance. This practice permits to optimise the masses and sizes involved and to simplify the overall system design.
As asteroids moments of inertia are huge compared with artificial satellites a reaction wheel of very large inertia is needed together with an efficient strategy to de-saturate it. A tethered dumbbell satellite of less than a few tens of kilometres anchored on the asteroid surface (Fig.1) can serve both purposes as it offer a very high inertia/mass ratio and a large lever arm for the application of a torque with a pair of thrusters mounted on the dumbbell ends.

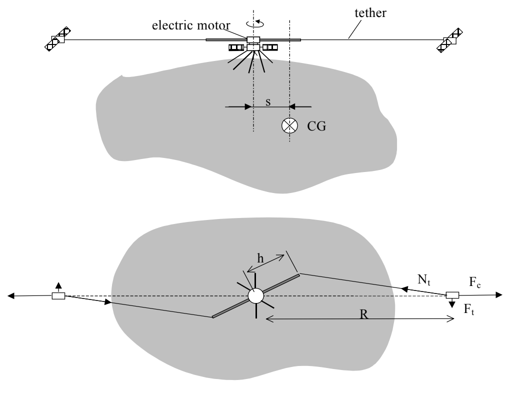

Fig.1. Side and top views of the asteroid spin-up apparatus.

It can be shown that in order to optimise the spacecraft mass resources it is best to spin-up and deploy the tether (through an electric motor in contact with the asteroid) in such a way that it will reach its maximum length R_{max} at a high enough angular rate to provide a nominal tension N_t. At that point, having a long lever-arm-tether stiffened by the centrifugal force it will be possible to transfer a high torque to the asteroid by firing a pair of thrusters at the tether ends.

Assuming for simplicity a spherical asteroid its moment of inertia yields:

$$I_a = \frac{\pi}{60} k\rho d^5 \qquad (7)$$

Starting from the condition of fully deployed tether with maximum nominal rotation rate ($R=R_{max}$, $\omega_t=\omega_t^{max}$) counter-spinning with respect to the asteroid and neglecting, conservatively, the initial angular rate of the asteroid, the asteroid spin-up strategy consists of having a torque between the spinning dumbbell and the asteroid which tends to spin-up both the asteroid and the dumbbell in opposite directions. On the dumbbell this torque is counteracted by the action of a pair of tangential thrusters mounted at the dumbbell ends in such a way that the angular rate of the tether is kept constant together with the maximum nominal tension N_t in the tether.

Assuming a pair of electrical thrusters is employed the thrust F depends on the characteristics of the electric propulsion system and on the power available as:

$$F = \frac{2\eta W}{I_{sp} g} \qquad (8)$$

Where I_{sp} is the specific impulse, W is the power available to the propulsion system, g is the see-level gravitational acceleration and η is the overall electrical thruster efficiency. Considering off-the-shelf Hall-effect thrusters [8] a thrust of 0.512N can be achieved with 1900s of specific impulse and 8 kW of power.

The increase in asteroid angular rate, given the maximum radius R_{max} of the deployed tether, obeys:

$$\Delta\omega_{a1} = \frac{2FR_{max}t}{I_a} = \frac{120}{\pi}\frac{FR_{max}t}{kd^5} \qquad (9)$$

Given the maximum power P_{max} available to the electric motor the asteroid can be spun up using full thrust until the limit:

$$\tilde{\omega}_a = \frac{P_{max}}{2FR_{max}} \qquad (10)$$

which is reached at the critical time:

$$t^* = \frac{\pi}{240}\frac{P_{max}k\rho d^5}{F^2 R_{max}{}^2} \qquad (11)$$

For $t>t^*$ the torque has to be reduced and the asteroid angular rate will obey:

$$I_a \omega_a \dot{\omega}_a = P_{max} \qquad (12)$$

which yield the variation of angular rate:

$$\Delta\omega_{a2} = \sqrt{\frac{120}{\pi}\frac{P_{max}\left(t-t^*\right)}{k\rho d^5} + \frac{P_{max}{}^2}{4F^2 R_{max}{}^2}} \qquad (13)$$

Ultimately the variation in angular rate for the propelled spin-up phase may be written as:

$$\Delta\omega_a = \begin{cases} \dfrac{120}{\pi}\dfrac{FR_{\max}t}{kd^5} & t \le t^* \\ \sqrt{\dfrac{120}{\pi}\dfrac{P_{\max}\left(t-t^*\right)}{k\rho d^5} + \dfrac{P_{\max}{}^2}{4F^2R_{\max}{}^2}} & t > t^* \end{cases} \quad (14)$$

from which the torque transmitted to the asteroid becomes:

$$\tau(t) = I_a\dot{\omega}_a = \begin{cases} 2\,FR_{\max} & t \le t^* \\ 2\,FR_{\max}\sqrt{\dfrac{t^*}{2t-t^*}} & t > t^* \end{cases} \quad (15)$$

and the overall propellant consumption:

$$m_p = \frac{1}{I_{sp}g}\int_0^t \frac{\tau(t)}{R_{\max}}dt = \begin{cases} 2\dfrac{F}{I_{sp}g}t & t \le t^* \\ 2\dfrac{F}{I_{sp}g}\sqrt{t^*(2t-t^*)} & t > t^* \end{cases} \quad (16)$$

Finally the asteroid kinetic energy increase can be computed as:

$$\Delta E_{spinup} = \frac{\pi}{120}\frac{\Delta\omega_a{}^2}{k\rho d^5} \quad (17)$$

The results from Eq. (3) and Eq.s (14-17) are plotted in Fig. 2 for a range of asteroid diameters. The asteroids are here modeled as homogenous spheres with bulk density of 2.0 g/cm^3 and different values of tensile strength. Asteroids up to 200 m diameter can be spun up to rotation periods of less than a minute using reasonable propellant and time resources. In order to survive this acceleration without breaking the asteroid would need to have an internal strength unreasonably high. Of course as the expected tensile strength decreases it becomes feasible to fragment even larger asteroids.

Remarkably, the energy that can be transferred to a given asteroid with available fuel resources can be extremely high. For example for the case of a 100m asteroid that can be strong enough to reach a spin period of 0.5 minutes the corresponding increase in internal energy would be of the order of 10 megatons.

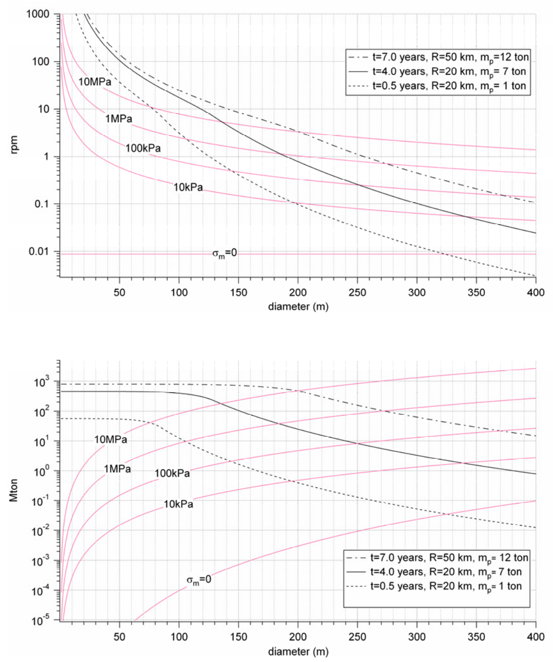

Fig.2 Achievable asteroid spin rate and kinetic energy at mission end for different tether radii (R), mission duration (t) and maximum fuel consumption (m_p) . Each end spacecraft is equipped with an ion propulsion thruster with 8 kW of power, 0.5N of thrust and 1900s of specific impulse. The maximum power available for the hub motor is 15 kW. The curves representing the break-up limit (Eq. 3) for materials of different tensile strength are added for comparison.

3. TRANSFERRING THE TORQUE TO THE ASTEROID

As shown by previous calculations relatively high torques have to be continuously exerted on the asteroid.
Moreover the spin-up apparatus has to be kept in contact with the asteroid despite of its negligible surface gravity and withstand possible seismic reshaping of the asteroid following the increased centrifugal load.
These requirements make the attachment system likely to be the most technologically challenging part of the system.
In order to transfer a high torque to a possibly brittle material while minimising the risk of local fracturing of the asteroid is to increase the lever arm of the applied force and distribute the force on a wider footprint. This will limit the tension exerted on the asteroid surface. Fig.2 shows two possible implementation schemes of this concept. The first scheme involves penetrating the asteroid surface with cutting-disk appendages and is probably more effective for weakly consolidated asteroids like Itokawa. The second approach consists of wrapping the asteroid with high-strength belts to distribute the force on the asteroid external surface. Although available high strength/density materials are available to limit the mass of the km-size belt the complexity of the deployment operation is considerably high and may require the assistance of robotic units.

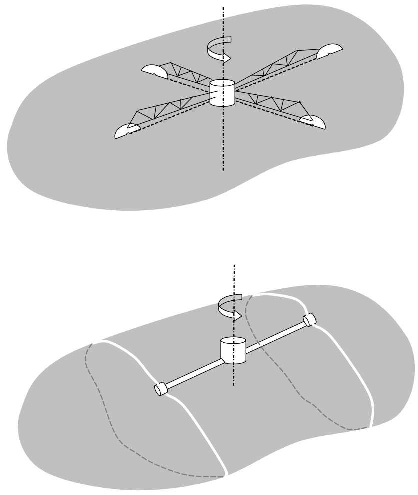

Fig.2. Possible attachment systems.

4. CONCLUSIONS

Sub-km asteroid up to 200 metres diameter and beyond can be artificially spun up to disruption with the use of a tether centrifuge attached to the asteroid surface.
Preliminary calculations accounting to the main physics of the problem show that asteroids of significant strength and diameter up to 200 m can be spun-up to critical fragmentation speed with reasonable time and fuel resources. Clearly, when material strength decreases it becomes feasible to fragment bodies having even larger diameter. Besides, since the requirements in terms of propellant mass decrease with the inverse of the asteroid moment of inertia, i.e. with the fifth power of the asteroid diameter, it appears to be considerably less demanding to break asteroid of 150 m diameter or less. The innovative concept could open up new technological capabilities in the areas of asteroid science and resources utilization and possibly in the field of asteroid threat mitigation.
What appears to be the most critical issue is the design of a reliable and robust system to attach the centrifuge to the asteroid and allowing the transmission of very high torques throughout the spin-up process. The system will need to cope with local or

global structural reshaping following the increased centrifugal load and possible seismic phenomena ('astro-quakes'). Also, as the characteristics of the asteroid surface are not known a priori the system will need to be flexible enough to cope with a given variability of surface strength and morphology.

REFERENCES

1. Scheeres, D.J., et al "Abrupt alteration of Asteroid 2004 MN4's spin state during its 2029 Earth flyby", *Icarus, Volume 178, 2005, pp. 281-283.*
2. Scheeres, D.J., et al. "Asteroid surface science with pods". Lunar Planet. Sci. 34. Abstract 1444. 2003.
3. Dobrovolskis, A.R., "Tidal Disruption of Solid Bodies", *Icarus, Volume 88, 1990, pp. 24-38*
4. Holsapple, K., "Spinning rods, elliptical disks and solid ellipsoidal bodies: elastic and plastic stresses and limit spins", *Journal of Applied Mechanics.,* accepted for publication (2007)
5. Weidenschilling, S.J., "How Fast Can an Asteroid Spin?", Icarus 46, pp.124-126. 1981.
6. Hoek and Brown, "Practical estimates of rock mass strength", International Journal of Rock Mechanics and Mining Sciences, Vol. 34, No 8, 1997, pages 1165-1186.
7. Housen, K. R. and Holsapple, K.A. "Scale Effects in Strength-Dominated Collisions of Rocky Asteroids", Icarus, 142, pp. 21-33. 1999.
8. "High power Hall-effect Thruster Systems". Busek catalogue. 2007. http://www.busek.com/downloads/HighPower.pdf