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Nonexplosive Approach to Fragment Subkilometer Asteroids with a Tether Centrifuge

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Introduction

ATHOUGH we have some clues about the mineralogy and surface properties of different families of asteroids and comets we still know very little about the structure and physical properties of their interior. Such information would be extremely precious to plan future missions to divert asteroids from their collision course with our planet or to shatter them in small dispersed fragments. Additionally, a better knowledge of asteroid internal composition, structure, and morphology can provide invaluable insight into the history and formation of our solar system and the development of life.

So far, the approaches proposed in the literature toward improving our knowledge of asteroids structure and interior have been based on indirect measurements through radar tomography [1] and seismology [2] and on direct measurements through subsurface sampling [3]. Although the former can only provide limited resolution measurements of the interior the latter are restricted to the outer layers of the celestial object.

This Note presents a new approach to study the internal structure and mechanical properties of small asteroids and comets by artificially increasing their spin rate up to a level where the stress induced by the centrifugal load triggers out a fragmentation process. It is shown that the spin-up process can be effectively carried out using a counter-rotating tether satellite anchored to the asteroid surface as a means to exchange energy and angular momentum with the celestial body. By monitoring the mechanical response of the asteroid to the increased centrifugal load scientific data about its strength and structure can be gathered. Most important though, once the fragmentation process is activated a direct access to the inner layers of the celestial body becomes possible providing unique scientific information for asteroid mitigation missions, planetary science, and astrobiology. In addition, once the complex fragmentation dynamics and asteroid mechanical properties are better understood, the concept could provide an alternative means for asteroid fragmentation as well as an important tool in asteroid mining technology.

It is worth mentioning that tethered satellite systems of up to 20 km in length have already been successfully deployed during low-cost space missions [4]. Besides, tethered sling systems attached to asteroids have been studied in the past as reusable propellantless transportation systems for planetary missions [5–7] or for recovering asteroid resources to be used as construction material for solar power satellites or space habitats [8]. Although such proposed tether applications differ considerably from the present one, these references have addressed the basic dynamic issues of asteroid-based tether slings. In particular, Puig-Suari et al. [5] discussed the need for a tapered-cross-section tether to minimize the required tether mass and derived a formula for the optimum taper profile, whereas Kuchnicki et al. [6] investigates the spin-up and deployment dynamics of the sling accounting for the inertial characteristics of the tapered tether.

Asteroid Centrifuge

To make an asteroid spin-up maneuver technologically feasible using reasonable time and mass resources it is essential to devise an efficient method to impart continuous and relatively high torques to the asteroid throughout the mission duration. Simple calculations show that employing chemical or electrical thrusters attached to the asteroid periphery is both inefficient (as only small torques can be transmitted due to the limited lever arm) and risky (a thruster attached to the outermost parts of the asteroid may be flung off by centrifugal forces).

A much more efficient solution is to anchor a spacecraft to the asteroid surface in proximity of its rotation axis and to radially deploy a pair of tethered subsatellites with the help of an electric motor exchanging angular momentum with the tether system and the asteroid (Fig. 1). The tether is deployed by the action of the centrifugal force and is controlled in such a way that its angular rate and tension remain sufficiently high to guarantee stability. When the fully deployed length is reached the tether rotation rate can be increased until it becomes critical for the tether strength and/or for the operation of the subsatellites' actuators and sensors. At this point (if the asteroid has not yet been fractured) a pair of electrical thrusters is activated to maintain the tether angular rate constant providing a torque equal and opposite to the one given by the electric motor (which will not be switched off), while the angular rate of the asteroid will keep growing under the effect of the torque provided by the motor itself. From this point on, the spin-up process can be carried on until fragmentation begins as long as a sufficient amount of propellant is available.

The spin-up process can be monitored with sensors on the hub spacecraft as well as on the tethered spacecraft pair. However, once the fragmentation process has started the central hub could be possibly inactivated or detached from the asteroid in which case the monitoring would be left entirely to the tethered spacecraft. The latter, which will operate from a safe distance of a few kilometers from the asteroid, will not only be able to image the fragmentation process but could be promptly released from their tether links and attempt a rendezvous with the asteroid fragments to probe the asteroid inner layers.

Breaking Limit for Homogeneous Asteroids

For the purpose of computing its breaking limit rotation rate let us assume our target asteroid has ellipsoidal shape with uniform bulk

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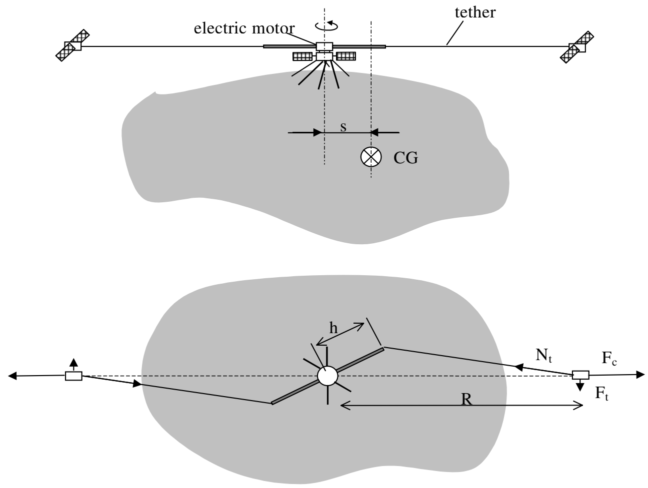

Fig. 1 Side and top views of the asteroid spin-up apparatus with represented force balance of each tethered satellite during the second phase of the spin-up process (F_t = thruster force, N_t = tether tension, F_c = centrifugal force). The center of gravity of the asteroid and its distance from the attachment axis are indicated as CG and s, respectively.

density and uniform material strength. Let ρ indicate the asteroid bulk density, m_a its mass, and I_a its maximum moment of inertia.

In [9] it is concluded that for the same material strength and total mass an ellipsoidal body is always more sensitive to rotational breakup than a spherical body. Hence, following a conservative approach in terms of required resources for artificial fragmentation, we introduce the equivalent diameter of a sphere having the same mass and density of our target asteroid:

$$d_{\rm eq} = \left(\frac{6}{\pi}\frac{m_a}{\rho}\right)^{\frac{1}{3}} \tag{1}$$

and we base our calculation on the stress field of a spherical body of diameter $d_{\rm eq}$ subject to centrifugal and self-gravitational load. Such stress field can be derived from Aggarwal [10], who considered a homogeneous, elastic spherical body subject to centrifugal, self-gravitational and tidal loads. When tidal effects are eliminated the stress tensor [10] retains the simple form:

$$\boldsymbol{\sigma} = \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix} \tag{2}$$

with

$$p = \left(\frac{2}{3}\pi G\rho - \frac{1}{3}\omega^2\right)\left(x^2 + y^2 + z^2 - \frac{d_{\rm eq}^2}{4}\right) \tag{3}$$

where G is the gravitational constant ($=6.67\times10^{-11}$ $\mathrm{m^3\cdot kg^{-1}\cdot s^{-2}}$), ω is the spin rate, and (x, y, z) are the Cartesian coordinates of a generic point with respect to the asteroid center of gravity.

Note that the point of maximum stress is *always* the center of the sphere with the compressive/tensional stress decreasing quadratically with the distance from the center and becoming zero at the surface. This is due to the fact that external (i.e., tidal) gravitational effects are not present here.

The critical rotation rate initiating the fragmentation process can be computed by equating the stress at the center of the asteroid [Eq. (3)] with the asteroid tensile strength σ_a and solving for ω:

$$\omega_{\rm break} = \sqrt{2\pi G\rho + \frac{12\sigma_a}{\rho d_{\rm eq}^2}} \tag{4}$$

In conclusion we can say that, in the hypothesis of homogeneous strength, a spun-up asteroid with rotation rate $\omega > \omega_{\rm break}$ will tend to fracture at the center with cracks propagating toward the surface and initiating the fragmentation process. Of course, for asteroids with nonzero internal strength but holding loosely bound regoliths at the surface (hence not qualifying as completely homogeneous bodies), one can expect some material to be initially ejected from the asteroid periphery. Nevertheless, it is unlikely that the body will undergo any kind of "erosion" from the surface inward as that would require a very heterogeneous material with strength decreasing considerably with the distance from the center.

Note also that Eq. (4) can be conservatively applied to the limit case of asteroids with zero strength and only held together by self-gravity. As explained by Weidenshilling [11], in this scenario the strengthless spherical body will undergo a change of shape to maintain hydrostatic equilibrium as the rotation rate grows. However the rotation rate cannot exceed the critical limit:

$$\omega_{\rm lim} = 0.53\sqrt{\frac{4\pi G\rho}{3}} \tag{5}$$

beyond which the body enters a mechanical instability region (Maclaurin–Jacobi transition) and undergoes fission into a binary asteroid [11].

As $\omega_{\rm lim}$ is always smaller than $\omega_{\rm crit}$, Eq. (4) 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 the 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 [12] 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 [13,14] consider a Weibull exponential distribution of flaws with increasing volume from which the tensile strength can be written as

$$\sigma_a = \sigma_m V^{-\frac{1}{\phi}} \tag{6}$$

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 [14] can be set to approximately 6.

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

$$\omega_{\rm break} = \sqrt{2\pi G\rho + \frac{12\sigma_m}{\rho d_{\rm eq}^2}\left(\frac{\pi}{6}d_{\rm eq}^3\right)^{-\frac{1}{6}}} \tag{7}$$

Asteroid Spin-Up Dynamics

The asteroid spin-up process is carried out in two phases: a first phase in which the tether is spun up and deployed at the same time with constant tension and with no thrust applied, and a second phase where a pair of thrusters at the end of the fully deployed tether are activated to compensate for the increasing torque transmitted from the motor to the tether and hence avoid excessive tension buildup along the tether.

The model used in this preliminary analysis of the asteroid centrifuge concept is schematized in Fig. 1. A variable-length rigid dumbbell is attached to the asteroid at a convenient point which allows the tether to rotate around an axis parallel to the asteroid pole without intersecting the surface. This will in general mean that the rotation axis of the dumbbell will lay at some distance s from the asteroid center of gravity. Note that this fact does not prevent the system from exerting a torque on the asteroid.

The dumbbell system exchanges angular momentum with the asteroid through an electric motor mounted at the asteroid–dumbbell interface. The asteroid is modeled as a rigid body while the dumbbell is composed of two point masses m connected to the electric motor through two tether arms whose mass is neglected. The gravitational action of the asteroid on the dumbbell is also neglected.

The maximum moment of inertia I_a of the asteroid can be related to its equivalent diameter by introducing the inertia shape parameter k:

$$k = \frac{10 I_a}{m_a d_{\mathrm{eq}}^2} = \frac{60}{\pi} \frac{I_a}{\rho d_{\mathrm{eq}}^5} \tag{8}$$

which is defined as the ratio between the actual asteroid moment of inertia I_a and the moment of inertia of an homogeneous sphere having the same mass and density of the asteroid. Because I_a is the maximum moment of inertia, k is always equal or greater than one with unity corresponding to the case of asteroids having a spherical inertia tensor.

The asteroid moment of inertia can now be written in terms of its equivalent diameter as

$$I_a = \frac{\pi}{60} k \rho d_{\mathrm{eq}}^5 \tag{9}$$

After calling N_t the tether tension, the tether angular velocity ω_t is related to its radius R by a simple force balance and reads

$$\omega_t = \sqrt{\frac{N_t}{mR}} \tag{10}$$

Assuming zero initial angular velocity for the asteroid, that is, in the worse case scenario in terms of required resources for the spin-up process, the conservation of angular momentum yields

$$I_a \omega_a + 2mR^2 \omega_t = 0 \tag{11}$$

where ω_a is the angular rate of the asteroid. From Eqs. (10) and (11) the latter can be written as

$$\omega_a = -\frac{2mR^2}{I_a} \sqrt{\frac{N_t}{mR}} = -\frac{120}{\pi} \frac{mR^2}{k \rho d_{\mathrm{eq}}^5} \sqrt{\frac{N_t}{mR}} \tag{12}$$

So the asteroid kinetic energy variation for varying tether radius yields

$$\Delta E_a = \frac{1}{2} I_a \omega_a^2 = \frac{120}{\pi} \frac{mR^3 N_t}{k \rho d_{\mathrm{eq}}^5} \tag{13}$$

Conversely the kinetic energy variation of the two tethered masses is

$$\Delta E_t = 2 \frac{m \omega_t^2 R^2}{2} = N_t R$$

And the overall energy increase of the system after full deployment ($R = R_{\max}$) yields

$$\Delta E_{\mathrm{tot}} = \frac{120}{\pi} \frac{m R_{\max}^3 N_t}{k \rho d_{\mathrm{eq}}^5} + N_t R_{\max} \tag{15}$$

Given the average power $\bar{P}$ provided by the electric motor during the maneuver and neglecting dissipation effects it is easy to compute the maneuver time as

$$t_{\mathrm{depl}} = \frac{\Delta E_{\mathrm{tot}}}{\bar{P}} = \frac{120}{\pi} \frac{m R_{\max}^3 N_t}{\bar{P} k \rho d_{\mathrm{eq}}^5} + \frac{N_t R_{\max}}{\bar{P}} \tag{16}$$

Also it is important to compute the torque transmitted by the electric motor between the tether and the asteroid. The latter reads

$$\tau_m = \frac{P}{(\omega_t - \omega_a)} = P \sqrt{\frac{mR}{N_t}} \left(1 + \frac{120}{\pi} \frac{mR^2}{k \rho d_{\mathrm{eq}}^5} \right)^{-1} \tag{17}$$

where P is now the instantaneous power provided by the electric motor.

We must point out that the torque τ_m must not exceed the maximum torque that can be transferred to the central hub through the tether attachment point, which obeys

$$\tau_{\mathrm{hub}} \leq N_t h \tag{18}$$

where h is the distance of the tether attachment point on the hub from the rotation axis of the motor. Note that if the latter inequality is not satisfied the tether will begin "wrapping around" the central hub.

Given an asteroid of 200 m diameter with bulk density $\rho = 2\ \mathrm{g/cm^3}$, if we consider a 50-km radius tether, 10,000 kg for each tethered end mass and 5000 N of constant tension, the corresponding tangential velocity of the end masses will be about 158 m/s (which can be managed with a Kevlar tapered tether weighting less than 250 kg [7]). According to Eqs. (6) and (7) providing a constant power supply of only 100 W the full deployment maneuver can be carried out in less than 75 days and with a maximum transmitted torque of less than 17 kNm. This will require attaching the tether at a distance of at least 1.7 m from the center hub. Note that the final spin frequency achieved for the asteroid at the end of the maneuver would be of about 0.05 rpm.

After the deployment phase is completed a change in strategy is needed to push the asteroid spin rate to a higher level where the stress load induced in the asteroid interior exceeds its breaking stress.

Ideally, one could think about increasing the spin rate of the tethered masses indefinitely until the counter-rotating asteroid reaches a desired spin rate. Unfortunately, as shown by Lorenzini [15], even by making use of an optimally tapered tether with the best material available when the velocity of the tethered masses approaches a critical velocity (which depends on the specific strength of the tether material) the mass of the tether required to counteract the resulting centrifugal load begins to grow exponentially exceeding the mass of the tethered elements. To circumvent this problem the torque imparted to the tether by the electric motor needs to be counteracted by firing a pair of thrusters placed on each tethered platform. This operation is analogous to a reaction wheel desaturation maneuver and does not affect the ability to continue to exert a torque on the asteroid.

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

$$F = \frac{2 \eta W}{I_{\mathrm{sp}} g} \tag{19}$$

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[†] a thrust of 0.512 N can be achieved with 1900 s of specific impulse and 8 kW of power.

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

$$\Delta \omega_{a1} = \frac{2 F R_{\max} t}{I_a} = \frac{120}{\pi} \frac{F R_{\max} t}{k d_{\mathrm{eq}}^5} \tag{20}$$

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

$$\tilde{\omega}_a = \frac{P_{\max}}{2 F R_{\max}} \tag{21}$$

which is reached at the critical time:

[†]"High Power Hall-Effect Thruster Systems," Busek catalogue, available at http://www.busek.com/downloads/HighPower.pdf [retrieved 17 April 2007].

$$t^* = \frac{\pi}{240} \frac{P_{\max} k \rho d_{\mathrm{eq}}^5}{F^2 R_{\max}^2} \tag{22}$$

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

$$I_a \omega_a \dot{\omega}_a = P_{\max} \tag{23}$$

which yields the variation of angular rate:

$$\Delta\omega_{a2} = \sqrt{\frac{120}{\pi} \frac{P_{\max}(t - t^*)}{k \rho d_{\mathrm{eq}}^5} + \frac{P_{\max}^2}{4F^2 R_{\max}^2}} \tag{24}$$

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

$$\Delta\omega_a = \begin{cases} \frac{120}{\pi} \frac{F R_{\max} t}{k d_{\mathrm{eq}}^5} & t \leq t^* \\ \sqrt{\frac{120}{\pi} \frac{P_{\max}(t-t^*)}{k \rho d_{\mathrm{eq}}^5} + \frac{P_{\max}^2}{4F^2 R_{\max}^2}} & t > t^* \end{cases} \tag{25}$$

from which the torque transmitted to the asteroid becomes

$$\tau(t) = I_a \dot{\omega}_a = \begin{cases} 2F R_{\max} & t \leq t^* \\ 2F R_{\max} \sqrt{\frac{t^*}{2t - t^*}} & t > t^* \end{cases} \tag{26}$$

and the overall propellant consumption:

$$m_p = \frac{1}{I_{\mathrm{sp}} g} \int_0^t \frac{\tau(t)}{R_{\max}} \, \mathrm{d}t = \begin{cases} 2 \frac{F}{I_{\mathrm{sp}} g} t & t \leq t^* \\ 2 \frac{F}{I_{\mathrm{sp}} g} \sqrt{t^*(2t - t^*)} & t > t^* \end{cases} \tag{27}$$

Finally the asteroid kinetic energy increase can be computed as

$$\Delta E_{\text{spin up}} = \frac{\pi}{120} \frac{\Delta\omega_a^2}{k \rho d_{\mathrm{eq}}^5} \tag{28}$$

System Requirements and Design Issues

The results from Eqs. (4) and (25–28) are plotted in Fig. 2 for a range of asteroid diameters. The asteroids are here modeled as homogenous spheres ($k = 1$) 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. 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 100 m asteroid that can be strong enough to reach a spin period of 0.5 min the corresponding increase in internal energy would be of the order of 10 Mtons.

As far as the design and engineering issues are concerned the most critical point is probably to properly anchor the hub to the asteroid and keep it securely attached to the asteroid during the whole spin-up process. The transmission of relatively high torques to the asteroid (up to 50 kNm in the most extreme case plotted in Fig. 2) will require increasing the attachment system contact area and its distance from the torque axis to distribute the torque on a sufficiently wide footprint. For weaker asteroids this will be particularly challenging and redundant systems (e.g., multiple attachments) will need to be devised to minimize the risk.

Another point to be taken into consideration is the possible internal structure shift that the asteroid could experience during the spin-up process. In the case of strong consolidated bodies seismic waves propagating toward the attachment point could rise as a result of internal structure reorganization. On the other hand, rubble-pile asteroids, for which seismic waves are more efficiently damped, will experience larger deformations. In both cases the hub anchoring system would be challenged in a significant way.

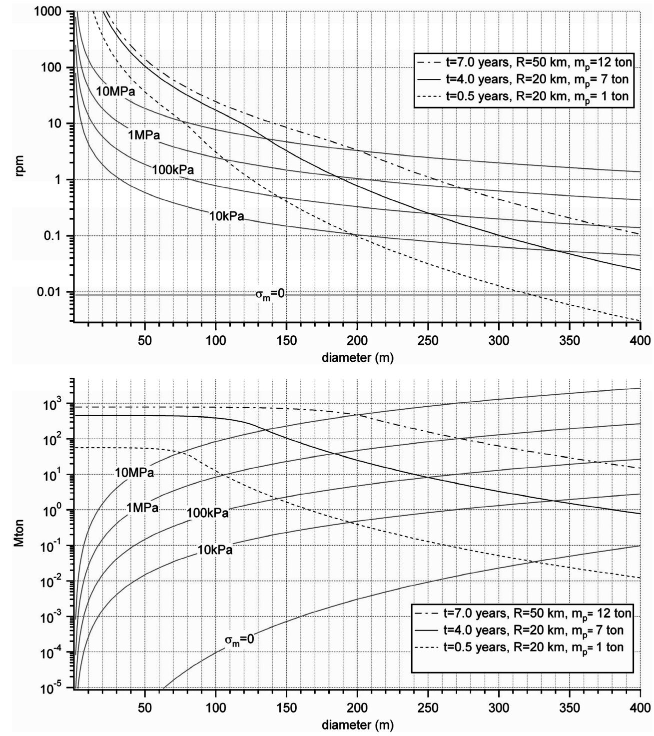

Fig. 2 Achievable asteroid spin rate and kinetic energy at the mission end for different tether radii *R*, mission duration *t*, and maximum fuel consumption m_p. Each end spacecraft is equipped with an ion propulsion thruster with 8 kW of power, 0.5 N of thrust, and 1900 s of specific impulse. The maximum power available for the hub motor is 15 kW. Asteroid inertia tensor is assumed spherical ($k = 1$). The curves representing the breakup limit [Eq. (7)] for rocks of different tensile strength are added for comparison.

Finally the tether deployment and spin-up phase will need to be controlled to make sure that the tether can freely rotate without intersecting the asteroid surface. For a generic asteroid this means that the hub will in general be attached at some distance s from the asteroid rotation axis (see Fig. 1). While this will not affect the capability of applying continuous torques to the asteroid, the hub will be subject to a centrifugal acceleration proportional to s and the attachment system will need to be designed accordingly.

Breaking Itokawa

Asteroid 25143 Itokawa is presently the only subkilometer asteroid visited by a space mission and its shape and inertial properties are known with good accuracy. From [16,17] the estimated mass is about 3.5×10^{10} kg, and the estimated density is about 1.9 g/cm^3, while the estimated maximum moment of inertia is 7.7×10^{14} kg $\cdot$ m^2. By substituting these values into Eqs. (1) and (8) we obtain $k \cong 2$ and $d_{\mathrm{eq}} \cong 328$ m. As far as the material strength is concerned the data at our disposal support the evidence that Itokawa is a rubble-pile structure with very low or negligible strength [18] and made up of two distinct components resting on each other to form a so-called contact-binary asteroid [19]. Itokawa may have experienced considerable structural shifts in the past (on a time scale of a few hundred thousand years) as a consequence of YORP-effect-induced (Yarkovsky–O'Keefe–Radzievskii–Paddack) spin variations [20].

Based on this information it is interesting to estimate the required resources to increase its angular rate up to the breaking limit. Figure 3 shows the required time and tether radius to break Itokawa assuming different values of material tensile strength consistent with a very weak structure ($\sigma_m < 10$ kPa). The corresponding breaking periods are about 2 h for the zero strength case, 50 min for the 1 kPa case, and 17 min for the 10 kPa case.

The reader should bear in mind that the reference stress field employed for estimating the breaking limit is conservatively based

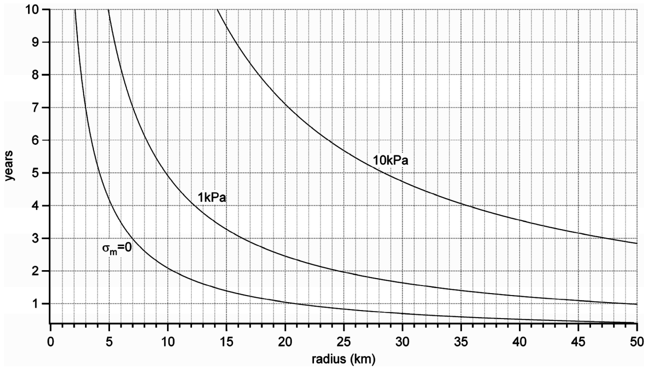

Fig. 3 Required resources in terms of tether radius and spin-up time to break asteroid 25143 Itokawa for different values of the material tensile strength. A spherical stress field is conservatively taken as a reference for the critical fragmentation limit.

on an equivalent spherical homogeneous asteroid with diameter $d = d_{eq} = 328$ m. For instance, the possible contact-binary structure of the asteroid is not taken into account in this analysis. As more refined models for the asteroid are considered one can expect fission to occur at an earlier stage. For example, according to Scheeres [20] the transition between contact and orbiting binary could occur already when the rotation period reaches 6.5 h.

In any case, if the rubble-pile hypothesis is confirmed, Itokawa could be fragmented at a relatively low cost. Besides, given its peculiar shape the hub could probably be attached in proximity of the northern pole, which has enough elevation to allow the tether to be deployed without intersecting the asteroid surface. Nevertheless the likely rubble-pile nature of this asteroid could pose a significant challenge to the design of a reliable attachment system.

Conclusions

The work demonstrates, for the first time, the possibility of spinning up subkilometer asteroids with artificial means beyond the limit at which fracturing and fragmentation begins.

The proposed solution exploits a very simple concept: the use of a large deployable spacecraft to channel solar and chemical energy into the rotational energy of an asteroid. Preliminary calculations show that monolithic asteroids of significant strength and diameter up to 200 m can be spun up to critical fragmentation speed with reasonable time and fuel resources while for the case of moderate or low strength asteroids (as 25143 Itokawa) it becomes feasible to fragment bodies having even larger diameter. Besides, because the requirements in terms of propellant mass decrease with the inverse of the asteroid moment of inertia, that is, with the fifth power of the asteroid diameter, it appears to be considerably less demanding to break an 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.

The most critical issue appears to be the attaching mechanism which has to cope with the transmission of relatively high torques to a possibly fragile asteroid and must also withstand local structural variations following the spin-up process. The design of such a mechanism is undoubtedly a serious technological challenge.

Further analysis should be focused on the mechanical behavior of the asteroid as its spin increases, with particular attention to internal structural shifts and possible seismic effects, and on the outcome of the centrifugal fragmentation process.

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