document title/ titre du document

A Non-Explosive Approach To Artificially Fragment Earth-Threatening Asteroids Using Centrifugal Acceleration

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reference/*réference*
issue/*édition* 1
Revision/*révision* 03
date of issue/*date d'édition* 16 August 2006
status/*état*
Document type/*type de document* Internal Report ACT-RPT-CBO-4100-AFT02
Distribution/*distribution*

ABSTRACT

Asteroid fragmentation has been considered as a possible countermeasure to mitigate the threat of asteroids in collision course with our planet. The only reasonable fragmentation scheme proposed up to date involves the use of nuclear charges buried sufficiently deep under the asteroid surface.

The present document describes a concept to increase the spin rate of asteroids of up to 200m in diameter beyond the limit in which they begin to disrupt with no need for explosive devices. In the proposed concept a tethered satellite 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, in the worse case scenario, a 200 m diameter asteroid can be spun up to critical rotation speed in less than five years with current technology and that when smaller asteroids are considered (50-150 m in diameter) the cost to fragment them decreases considerably. The corresponding internal energy accumulated by the asteroid throughout the spin-up process, which can reach tens of megatons, would be orders of magnitude greater than the energy needed to break the chemical bonds of a 200 m well-consolidated asteroid and shatter it in fragments less than 10 m in size.

Other than adding a new capability in the field of asteroid threat mitigation the new fragmentation scheme may provide a unique scientific tool to characterise the asteroid internal structure and composition as well as its mechanical strength with unprecedented accuracy and may open up new possibilities for asteroid mining and resource utilisation.

1. BACKGROUND AND MOTIVATIONS

1.1 Asteroid Impact Threat Mitigation

It is well known and widely accepted that asteroids of different sizes have collided with the Earth with catastrophic consequences in the past and will continue to do so. According to recent studies [1], the impact from a 2-km diameter asteroid has 1 in 10000 chance to occur within the next century and would cause the death of a large fraction of our civilization. On the other hand the impact of smaller asteroids, ~50-100m diameter, may occur as frequently as once every 300 years or less and can destroy a city as large as Rome or Berlin. These figures call for the need of a considerable research and technological development in the direction of asteroid impact mitigation techniques.

Among the different countermeasures against asteroid impact threat, the concept of asteroid fragmentation and dispersal has received considerable attention in the literature and constitutes one of the preferred options in dealing with impacts having relatively short warning times, in which case deflection methods tend to be less effective. Unfortunately, its implementation is complicated by the need for nuclear charges which have to be detonated sufficiently deep under the asteroid surface [1]. This requires in situ drilling of several metres which is difficult on a low gravity object. Furthermore nuclear explosions in space are currently banned by the International Outer Space Treaty.

A new approach to the problem, which promises to overcome these limitations, is to employ energy and fuel resources to increase the spin rate of the asteroid up to a level where the stress induced by the centrifugal load triggers out a fragmentation process with no need for nuclear or chemical explosive.

This report shows that for asteroid of about 200 m diameter this process can be made technologically feasible by exploiting the large moment of inertia and lever-arm effect provided by a counter-rotating tethered satellite properly attached to the asteroid surface which allows transmitting continuous and relatively high-torques on the asteroid increasing its rotational state until fragmentation occurs.

1.2 Asteroid Science

Asteroids can provide invaluable insight into the history and formation of our solar system. For instance, the internal layers of C-type asteroids may host organic molecules playing a vital role on the development of life in its earlier stages [2]. The proposed fragmentation concept allows to literally 'crack-open' a celestial body to gain direct access to its internal structure which can be analysed by a suite of measurement instruments and imaging devices. Up to date there are no other means of achieving such result unless explosive charges are employed. In addition, the concept provides a direct mechanical test to characterise the strength of small monolithic asteroids and their fragmentation dynamics.

Finally, other than serving scientific purposes the collected data will be useful to plan future asteroid mitigation missions and asteroid resource utilisation

1.3 Asteroid Mining and Resource Utilisation

The idea of retrieving precious asteroidal resources to be sent back on Earth or to be utilised for space construction and propellant has been around for several years. Advances on asteroid detection, spectral characterisation techniques and solar system evolution models support the evidence that these celestial bodies may contain considerable amount of precious metals such as platinum and gold, as well as other important resources like water and methane.

Some studies [3] [4] foresee the advent of future asteroid mining enterprises where precious minerals are extracted from the nearest asteroids and sent back to Earth as raw material or after being processed in-situ. Besides, future large-scale space based activity will likely exploit raw material obtained from in-situ resources rather than from Earth to overcome the high lunch costs.

The proposed concept may play an important role in the mining process as it provides access to the core of the celestial body which is believed to contain the most precious metals accumulated by melting collisions [5].

Future studies can be focused on enhancing the cooperation between the fragmentation system and the material extraction and separation subsystems.

2. CONCEPT DESCRIPTION AND FEASIBILITY ASSESSMENT

2.1 An Asteroid Centrifuge

In order to make an asteroid spin-up manoeuvre technologically feasible using reasonable time resources (say less than 5 years) 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 the high centrifugal force). A much more efficient solution is to anchor a spacecraft to the asteroid surface along its rotation axis and to radially deploy a pair of sub-satellites connected through two tether arms as in Fig. 1. Tethered satellite systems of up to 20 km in length have already been successfully deployed during low-cost space missions [6].

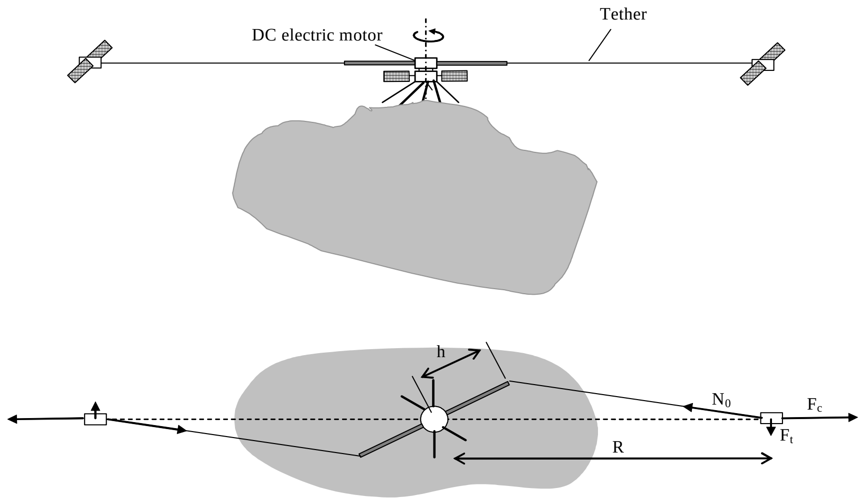

Fig.1 Side and top view of the asteroid spin-up apparatus with represented force balance of each tethered satellite during the second phase of the spin-up process (F_t= thruster force, N_0= tether tension, F_c= centrifugal force)

The tether fast rotation rate necessary to provide the system with sufficient tension and stability during the deployment phase is given by an electric motor exchanging angular momentum with the asteroid. In this way the tether system acts as a giant counter-rotating reaction wheel which, thanks to its very high moment of inertia, is able to modify the angular rate of the asteroid itself. Note that the transmission of kN level torques to the asteroid can be accomplished without creating excessive stress on the attachment point by increasing the contact area and its distance from the asteroid rotation axis hence distributing the torque on a relatively wide footprint. When the fully deployed length is reached the tether is gradually spun-up by the action of the electric motor until it reaches a rotation rate critical for the tether strength and/or for the operation of the subsatellite 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. Note *that for this second phase the role of the tether is to provide the necessary lever arm to magnify the torque transmitted from the propulsion system to the asteroid.*

2.2 Characteristics of the Target Asteroids

As it will be more evident in the following the concept of the asteroid centrifuge is best suited to relatively small asteroids (say less than 200 m in diameter) as the need for power, fuel and time resources is directly proportional to the asteroid rotational moment of inertia.

In fact, one can argue that relatively small asteroids are the most interesting for several reasons:

1- Roughly speaking the distribution of NEOs is inversely proportional to the square of the diameter (for example Rabinowitz [7] proposes a power-law dependence with exponent 2.5) due to the fact that the process of accretion and collision are both strongly related to the target cross section.
2- Following the previous statement the probability of an asteroid impacting the Earth tends also to be inversly proportional to the square of its diameter (see also Chapman and Morrison [1]). Small asteroids are much more likely to strike our planet.
3- Since self-gravity is very weak for small asteroids, most of the fragments will tend to be dispersed due to the asteroid rotation rather than being reaccumulated by gravity. This will obviously make the mitigation strategy more effective.
4- Being more frequent small asteroids are also likely to be more accessible. Some studies (see for example ref. [3]) refer to the ‘Arjuna’ asteroid family as a group of small objects in very Earth-like and accessible orbits. These objects require considerably less delta-V to be reached from Earth and are hence interesting for exploration and sample return missions as well as mining and resource utilisation missions. As national space agencies plan to widen the census of NEOs by funding high resolution observation campaign, smaller and more accessible objects will discovered in the future.

Among the asteroids discovered so far the great majority of asteroids larger than 200m have rotation periods larger than about 2.2 revolution per hour, a value often referred as the rotation rate barrier for ‘rubble pile’ asteroids [8] while smaller asteroids tend to exhibit higher spin rates the more so the smaller the size. The fastest rotating asteroid known is 2000 DO_8 with an estimated rotation period of 78 seconds and an estimated diameter of 35 to 75 m. Based on Whiteley et al. [9] asteroids with known spin rate in the diameter range of 100 to 200 m have rotation rates spanning from less than 2 minutes to 1.5 hours and averaging around 48 minutes. This fact strongly supports the evidence that the great majority of smaller size asteroids are consolidated objects held together by their material strength. Based on the spin data provided by Whiteley et al.[9] it is quite interesting to compute the kinetic energy content of the sub-km size asteroids and to compare it with the energy that would be needed for an explosive buried inside the asteroid to fragment the latter in pieces less than 10 m in size [1]. The asteroids are here regarded as homogeneous spheres having bulk density of 2.0 g/cm^3. Notably, a considerable fraction of the sub-km size asteroids posses already an amount of internal energy greater than the energy required to shatter terrestrial rocks (Fig. 1). This fact opens up an interesting possibility: the internal structure and cohesiveness of the small fast rotating asteroids may be such that once a fragmentation process is initiated the high amount of energy transmitted by internal 5 stress waves will break the highly tensioned body in a multitude of small fragments rather than in a few relatively large chunks [10].

Future numerical and experimental analyses will be extremely useful to clarify this issue.

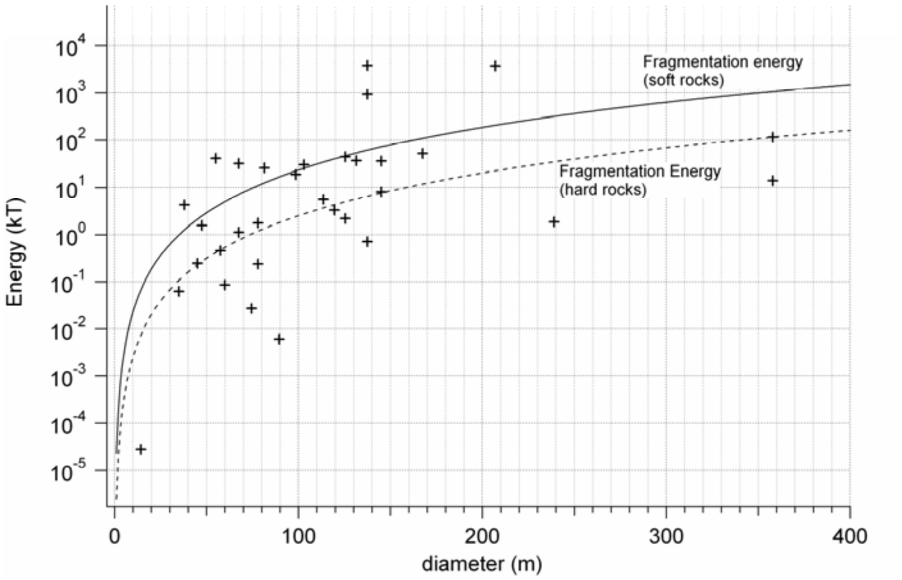

Fig.2 Energy content of small spinning asteroids compared to the energy required to fragment them in pieces of less than 10m diameter with a buried explosive charge

2.3 Braking Limit for Homogeneous Asteroids

Assuming the asteroid a homogeneous rigid sphere only subjected to centrifugal load, the critical rotation period that causes tensile fragmentation is [11]:

$$P_T = \frac{\pi}{\sqrt{\frac{\pi}{3}G\rho + \frac{4N_a}{\rho d^2}}} \qquad (1)$$

where G is the the gravitational constant (=6.67·10^{-11} m^3 kg^{-1} s^{-2}) is the asteroid bulk density, N_a the asteroid tensile strength and d its diameter.

Likewise the critical period that causes shear fracture reads:

$$P_S = \pi\sqrt{\frac{\rho}{8S_a}}d \qquad (2)$$

In the case of tensile fracture the planes of maximum stress are all the planes parallel to the spin velocity vector and intersecting the centre of the sphere. Conversely the planes with maximum shear stress are tilted by 45 degrees with respect to the sphere equatorial plane and again intersecting the centre.

The same article [11] shows that sub-km asteroids and comets are more likely to undergo tensile fracture than shear fracture, therefore we will consider Eq. (1) as a basis for our critical fragmentation period.

Note that the assumption of spherical shape is conservative in the sense that an ellipsoidal spinning body reaches the fragmentation limit at lower angular rate than a spherical body with the same size [12]. Spheres are much harder to break than ellipsoids.

As far as the asteroid tensile strength is concerned the only data at our disposal, i.e. estimated asteroid rotation rates vs. diameter, can only suggest that small fast rotating asteroid should have a cohesive strength of at least 0.1 MPa [13] but nothing is known about their maximum strength. As a conservative value one can use the tensile strength of strong terrestrial rocks which is 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] consider a Weibull exponential distribution of flaws with increasing volume from which the tensile strength can be written as:

$$N_a = \overline{N}_a V^{-\frac{1}{\phi}} \qquad (3)$$

where $\overline{N}_a$ is the material tensile strength at lab scale, V is the rock volume and ϕ is the Weibull exponent which based on terrestrial rocks data [13] can be set to ~6.
From Eq.s (2-3) we finally obtain a reference fragmentation period for later use:

$$P_T = \frac{3\pi}{\sqrt{3\pi G\rho + 36\frac{\overline{N}_a}{\rho d^2}\left(\frac{\pi}{6}d^3\right)^{-\frac{1}{\phi}}}} \qquad (4)$$

2.3 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, 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 build-up along the tether itself.
After calling N_0 the tether tension and considering the tether mass negligible when compared to each deployed end mass m the tether angular velocity ω_t is related to its radius by the following equation:

$$\omega_t = \sqrt{\frac{N_0}{mR}} \tag{5}$$

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

$$I_a \omega_a + 2mR^2 \omega_t = 0 \tag{6}$$

Where I_a and ω_a are the moment of inertia and angular rate of the asteroid. Frome Eq.s (5-6) the asteroid rotation rate can be written as:

$$\omega_a = -\frac{2mR^2}{I_a}\sqrt{\frac{N_0}{mR}} \tag{7}$$

So the energy of the asteroid for varying tether radius yields:

$$\Delta E_a = \frac{2mR^3 N_0}{I_a} \tag{8}$$

Conversely the kinetic energy of the two tethered masses is simply:

$$\Delta E_t = 2\frac{m\omega_t^{\,2} R^2}{2} = N_0 R \tag{9}$$

So the overall energy increase of the system after full deployment yields:

$$\Delta E_{tot} = \frac{2mR_{\max}^{\;3} N_0}{I_a} + N_0 R_{\max} \tag{10}$$

Given the average power P_{av} provided during the maneuver it is easy to compute the maneuver time as:

$$t_{depl} = \frac{\Delta E_{tot}}{P_{av}} = \frac{2mR_{\max}^{\;3} N_0 + I_a N_0 R_{\max}}{P_{av} I_a} \tag{11}$$

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

$$\tau_m = \frac{P}{|\omega_a| + |\omega_t|} = \frac{P\sqrt{\frac{mR}{N_0}}}{1 + \frac{2mR^2}{I_a}} \tag{12}$$

where P is the instantaneous power of the electrical 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:

$$\tau_{hub} \leq N_0 d \tag{13}$$

Where d 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. Note also that, in principle, the maximum torque that can be exchanged with the asteroid through the anchor point can be increased at will by increasing the overall contact area and its distance from the rotation axis.
Given an asteroid of 200 m diameter with bulk density ρ= 2 g/cm^3, if we consider 20-km radius tether, 7000 kg for each tethered end mass and 5000 N of tension, the corresponding tangential velocity of the end masses will be about 115 m/s (which can be managed with a Kevlar tapered tether weighting less than 100 kg [7]). According to Eq. (7-8) providing a power supply of only 100W the full deployment manoeuvre can be carried out in less than 15 days and with a maximum transmitted torque of less than 15 kNm. This will require attaching the tether at a distance of at least 1.5 m from the centre hub. Note that the final spin frequency achieved for the asteroid at the end of the manoeuvre would be of about 1 round every 100 minutes.

After the deployment phase is completed a change in strategy is needed in order to push the asteroid spin rate to a higher level where the stress loads induced in the asteroid interior exceeds the breaking stress of most terrestrial rocks.
Ideally, one could think about increasing the spin rate of the tethered masses indefinitely until the counter-rotating asteroids reaches a desired spin rate. Unfortunately, as it is shown by Lorenzini [7], 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. In order 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 manoeuvre is equivalent to 'desaturating' a reaction wheel and does not affect the ability to continue to exert a torque on the asteroid.

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

$$F = \frac{2\eta P_{th}}{I_{sp} g} \tag{14}$$

Where I_{sp} is the specific impulse, P_{th} is the available power, g is the see-level gravitational acceleration and η is the overall electrical thruster efficiency. Considering off-the-shelf Hall-effect thrusters [15] a thrust of 0.512N can be achieved with 1900s of specific impulse and 8 kW of power.

The increase in asteroid angular rate is simply:

$$\Delta\omega = \frac{2FR_{\max} t}{I_a} \tag{15}$$

And the overall propellant mass spent by the thruster pair:

$$m_p = 2\frac{F}{I_{sp} g} t \tag{16}$$

Finally the corresponding increase in kinetic energy of the asteroid is simply given by:

$$\Delta E_{spinup} = \frac{1}{2}\frac{\left(2FR_{\max} t\right)^2}{I_a} \tag{17}$$

The results from Eq. (4) and Eq.s (14-16) are plotted in Fig. 3 for a range of asteroid diameters modelled as homogenous spheres with bulk density of 2.0 g/cm^3. Also Asteroids up to 200 m diameter can be spun up to rotation periods of less than a minute and with a rotation rate that increases exponentially for decreasing diameter. At this level most terrestrial rocks would necessary break in smaller fragments and it is likely that asteroids will follow the same process.
It is interesting to evaluate the overall energy content that can be transferred to a given asteroid with available fuel resources can be extremely high. For example for the limit case of a 200m asteroid that can be strong enough to reach a spin period of 1 minute the corresponding increase in internal energy would be of the order of 10 megatons, corresponding to more than 600 Hiroshima bombs. This enormous amount of energy would be more than 1000 times the energy needed to shatter the asteroid in fragments less than 10 m in size with a buried nuclear charge.
Note also that given the exponential relation between achievable spin rates and asteroid diameter it would actually be relatively cheap to set up a mission to quickly fragment a relatively ‘small’ asteroid (<100 m in diameter) and test the proposed concept with considerable scientific return.

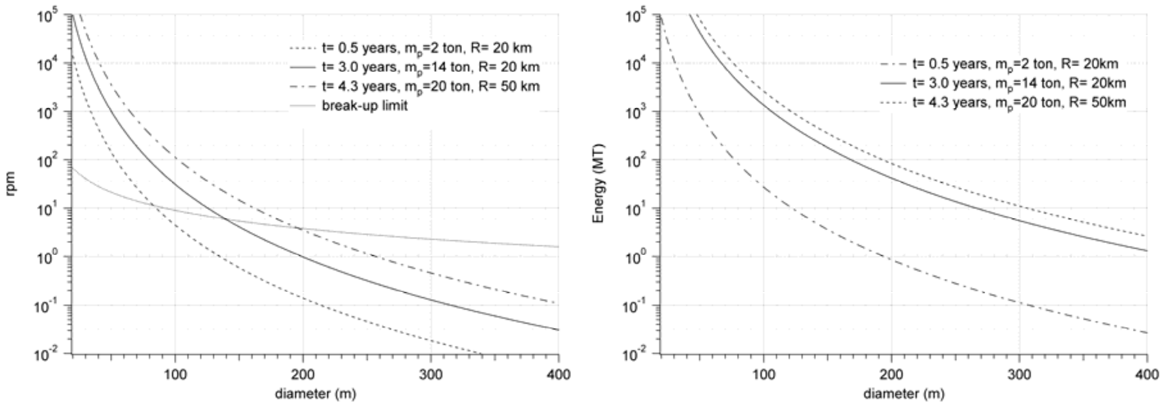

Fig.3 Achievable asteroid spin rate and kinetic energy at mission end. Each end spacecraft is equipped with an ion propulsion thruster with 10 kW of power, 0.5N of thrust and 1900s of specific impulse.

SUMMARY

The work demonstrates, for the first time, the possibility of spinning up a celestial body with artificial means beyond the limit at which fracturing and fragmentation begins. The proposed solution exploits a very simple, yet powerful 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 in the worse case scenario the necessary spin-up manoeuvre can be carried out for a 200 m asteroid with a centrifuge of 100 km and employing 20 tons of propellant in less than 5 years. Of course these data can change widely depending on the chosen propulsion system and power availability. 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. A future scientific mission aimed at breaking a 50 m asteroid could be accomplished with a 10km tether and little more than 1 ton of fuel in 4 months time. The innovative concept could open up new technological capabilities in the three main areas of asteroid threat mitigation, asteroid science and resources utilisation.

Further analysis should be concentrated into modelling the outcome of the centrifugal fragmentation processes of solid bodies with different material and structural properties. Considerable theoretical and experimental work has already been carried out for collision-induced and tidal fragmentation processes, and could be extended to the centrifugal case. Also a more refined model for the asteroid including elasticity should be investigated as deformation could have a non-negligible effect on the spin-up and fragmentation dynamics.
Finally a detailed analysis will be needed to assess the system dynamical behaviour in off-nominal conditions as for example after an instantaneous change of inertial properties of the asteroid as a result of partial fragmentation.

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