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Physical properties of Near-Earth Objects that inform mitigation

P. Michel *

Lagrange Laboratory, University of Nice-Sophia Antipolis, CNRS, Côte d'Azur Observatory, B.P. 4229, 06304 Nice Cedex 4, France

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ABSTRACT

Various methods have been proposed to avoid the collision of a Near-Earth Object (NEO) with the Earth. Each of these methods relies on a mitigation concept (deflection or fragmentation), an energy source (e.g. kinetic, gravitational, solar, thermal, etc.) and a mode of approach (e.g. remote station and interaction). The efficiency of each method depends on the physical properties of the considered NEO that influence the way the body will respond to the considered energy source. While the knowledge of properties such as the mass, spin rate and obliquity as well as the shape is generally required for all mitigation methods, there are other properties that are important to know for some methods and that have no great influence for other ones. This paper summarizes the current knowledge of main physical properties of NEOs and their importance for the most usual mitigation strategies that have been proposed, i.e. the kinetic impactor, the gravity tractor, strategies based on anchoring or depositing material on the surface, and strategies aimed at modifying the thermal properties of the NEO in order to either modify or cancel the Yarkovsky effect, or cause surface vaporization.

1. Introduction

Various methods have been proposed to prevent the collision of a Near-Earth Object (NEO) with the Earth, but none have actually been tested yet. Therefore, we are still not sure of our ability to employ a given method to achieve the desired effect. The aim of this paper is not to discuss the technological difficulties associated with different methods, or to discuss which is the most appropriate choice for a given case. Here, I rather discuss the physical properties of NEOs that need to be known to make sure that a given method has enough information for its design. Indeed, the efficiency of each method depends on physical properties of the considered NEO that are not necessarily known a priori and the precise influence of those properties is not necessarily well understood. Therefore, a good knowledge of the physical properties of NEOs and on their response to various kinds of stresses that correspond to those imposed by different mitigation methods is required to design an efficient mitigation tool. In this paper, our current knowledge of the main properties of NEOs is briefly discussed, and then the properties that must be known for different kinds of mitigation methods are indicated; I will show as an example how different surface properties can qualitatively influence the momentum transfer efficiency of a kinetic impactor, based on preliminary numerical simulations of a projectile impacting a 1-km diameter target.

2. Physical properties of NEOs

In this section, the main properties of the NEO population estimated from ground/space-based observations and numerical modeling are summarized. Note that this is not a complete review on the current knowledge but

* Tel.: +33 4 92 00 30 55; fax: +33 4 92 00 30 58.
E-mail address: michelp@oca.eu

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just a summary of the most important properties. Also, spectral observations are not presented here, as there is no great influence of spectral properties on the design of the considered mitigation concepts.

2.1. Size distribution of NEOs

The sizes of NEOs that can pose a threat range from a few tens of kilometers for the largest ones down to the minimum size of a body that can survive Earth's atmosphere entry, which depends on the body's physical properties. The number of NEOs decreases with increasing size, as exposed below, and as a consequence, the impact frequency of smaller bodies is greater than that of larger NEOs (see Fig. 1).

A model of the debiased orbital and absolute magnitude distribution of NEOs has been developed in the last decade [1]. From this model, the total NEO population is estimated to contain about 1200 objects with absolute magnitude $H<18$ and semi-major axis $a<7.4$ AU. It is usually assumed that an object with $H=18$ has a diameter of 1 km, although the exact relation depends on the albedo of the object. The cumulative number of NEOs grows as $10^{(0.35\ \pm 0.02)H}$ in the range $13<H<22$, implying $29{,}400 \pm 3600$ NEOs with $H<22$ (see [1]). Assuming that the albedo distribution is not dependent on H, this magnitude distribution implies a power law cumulative size distribution $N(>D) \propto D^q$ with exponent $q=-1.75 \pm 0.1$. This distribution is in perfect agreement with that obtained by [2], who directly debiased the magnitude distribution observed by the NEAT survey, and slightly shallower than that obtained using the LINEAR database [3]. The model of NEO population [1] will still need to be improved, as there seems to be an observed excess of high inclination NEOs compared with the model predictions.

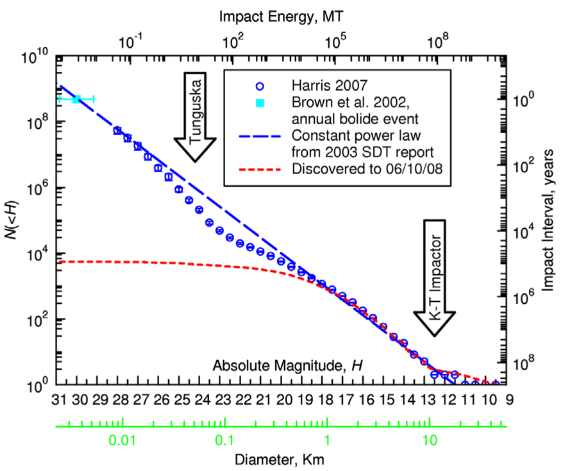

Fig. 1. Open blue circles represent the cumulative number of NEOs brighter than a given absolute magnitude H, defined as the visual magnitude V that an asteroid would have in the sky if observed at 1 AU distance from both the Earth and the Sun, at zero phase angle. A power-law function (dashed blue line) is shown for comparison. Ancillary scales give impact interval (right), impact energy in megatons TNT for the mean impact velocity of ~20 km/s (top), and the estimated diameter corresponding to the absolute magnitude H (second scale at bottom). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Courtesy of A.W. Harris

The comparison between the debiased orbital-magnitude distribution of NEOs with $H<18$ [1] and the observed distributions of discovered objects suggests that most of the undiscovered NEOs have H larger than 16 (<2 km in size), and semi-major axis in the range 1.5–2.5 AU. More recently, three overlapping methods were used to estimate the population of NEOs (disregarding long period comets) [4]. In the largest size range, to about $H=16$, current surveys are essentially complete, so the number of objects discovered up to this magnitude anchors the H-distribution of the NEO population at the bright end. In the intermediate range, up to about $H=20$, the fraction of completeness was estimated from the ratio of re-detections of already known NEOs to the total number of detections for known and new objects in the interval 2005–2006. The re-detection ratio had been bias-corrected using a survey simulation model to allow for the fact that NEOs are not equally easy to observe. The resulting size–frequency distribution, represented by cyan circles in Fig. 1, deviates substantially from a power law with fixed exponent in the size range from 1 km down to 10 m. Consequently the number of NEOs of about 100 m in diameter is almost an order of magnitude smaller than that predicted by extrapolation of a power law. The size of 100 m is of the order of the estimated size of transition from “rubble pile” (gravitational aggregates) to “monolithic” bodies, and the “dip” of the NEO distribution may be related to this transition in physical strength.

2.2. Spin rate distribution of NEOs

The spins of approximately 1500 asteroids are shown plotted versus the asteroid diameters in Fig. 2 (taken from [5]). The majority of the data shown are from the asteroid compilation of Harris and Pravec (A. Harris, private communication). In addition, in just the last few years the small, fast-spinning near-Earth bodies on the left were discovered. For completeness, about 20 large trans-neptunian objects are also included in the plot.

The spin database indicates that asteroid spin periods can cover a wide range of values, from several days to less than a minute. One can see very distinct structures in the data related to the strength properties of the object. The broad horizontal line is the spin limit for bodies having zero cohesive or tensile strength. The period of about 2.1 h was identified as the maximum spin a body can sustain without spinning off material from the longest axis [6]. More refined analyses have been performed [7,8], showing that a more typical spin limit before major shear failure is 2.6 h. Until a few years ago, all known spins of asteroids with a size greater than a couple of km were, to within error bars, below these limits: this observation led to the erroneous conclusion that all those bodies have a rubble-pile structure. An analysis of those spins using a comprehensive strength model approach was then done [9]. The results show that the larger bodies have their spin limits constrained by their self-gravity, independently of their cohesive strength. Therefore, the so-called spin barrier is not evidence that all those bodies must be rubble pile; they can be, but not simply based on this observation. For

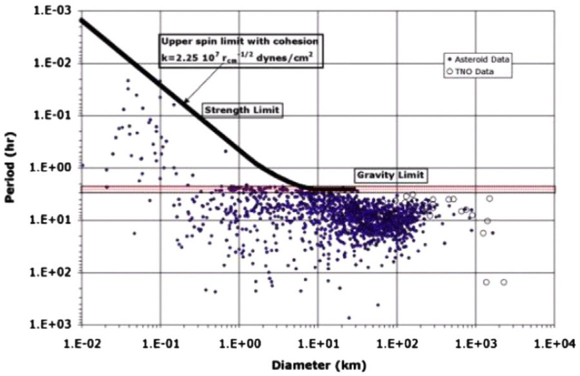

Fig. 2. Spin limits and data for small Solar System bodies. The dark sloped line assumes a size-dependent strength; it joins the horizontal red band for materials without cohesion. On the left, the spin limit is determined by the cohesive/tensile strength of the bodies and defines a strength regime. The horizontal asymptote on the right characterizes a gravity regime where tensile/cohesive strength is of no consequence. Those gravity regime values actually depend on shape and friction angle of the material composing those bodies, so average values have been assumed. The data in the upper left triangular region are for the fast spinning NEOs. The triangular points for the large diameter bodies on the right are trans-neptunian objects (from [5,9]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bodies less than about 10 km in diameter, the strength is sufficient to allow them to spin faster than what pure gravitational binding would allow. This is the case of the so-called fast rotators. Fig. 2 shows lines corresponding to the strength limit of bodies that is believed to decrease with size, because of the increasingly larger cracks and faults with increasing body size. The curve for the size-variable strength with $k=2.25\times10^7/r^{0.5}$ dyn/cm^2 (where r is the object's radius in cm) gives a very good upper envelope for the current data over the entire range of asteroid sizes (there is actually a theoretical reason to expect the strength to decrease with the body size to the -0.5 power), although that strength relation implies a laboratory-sized (cm-sized) strength about one order of magnitude less than expected. Actually, the analytical estimates suggest that even small amounts of strength or cohesion in a rubble pile can render rapidly spinning small bodies stable against disruption. Therefore, while the spin barrier at large sizes does not necessarily imply that all large bodies are rubble piles, even if they may well be, the fast spin rates of smaller bodies do not necessarily imply either that smaller bodies are fully monolithic.

The spin database will certainly increase in the future, so this picture and the strength estimates may change. Finding bodies of any given size spinning substantially faster than those found to date would imply a shift of the strength curve toward the top of the plot, indicating some stronger bodies. Then, groupings into different taxonomic types might give a more detailed picture of variations in strength between the bodies to replace the simple density dependence used here. For mitigation purpose, this would obviously be important information. But for now, the important information provided by the spin database is that the actual spin rate of the next potential threatening body is an important parameter, especially because according to the database, it can be very high for very small bodies that are the most frequent Earth impactors. For all the classical mitigation concepts, dealing with a very fast spinning body would be a big issue and this needs to be known in advance.

2.3. Thermal properties of NEOs

Measurements of the thermal flux density of a NEO at a single wavelength give an estimate of the dimensions of the object. Such an estimate has lower uncertainty than a similar measurement of the reflected sunlight in the visible spectral region. If the two measurements can be combined, both the effective diameter and the geometric albedo can be derived, which are crucial information for the impact risk assessment. In addition, thermal measurements at two or more wavelengths, plus the visual region flux density, give information on the thermal properties that are useful in evaluating the magnitude of the Yarkovsky effect and consequently in determining more accurately the orbital evolution of a NEO and its probability of impact with the Earth. Observations of NEOs have been performed in the thermal infrared that suggest that kilometer- and sub-kilometer-size objects generally have insulating dust layers that are less extensive than on larger asteroids, but sufficient to cause a significant anisotropy to the emitted thermal radiation. In effect, the distribution of the so-called beaming parameter, η, which acts as a proxy of both surface roughness and thermal inertia (a measure of resistance of the surface to changes in temperature), suggests that most NEOs have lower thermal inertias than that of the bare rock, but greater than that of the lunar regolith, indicating the presence of an insulating layer of granular material on their surface [10]. Moreover, there seems to be a trend, maybe related to the gravitational environment, as observational data suggest that smaller objects (with lower gravity) may have a thinner regolith layer consisting of coarse grains, while larger objects may have a thicker regolith layer consisting of fine grains. This is also important information for mitigation concepts, in particular for those aiming at performing an impact or attaching a device to the surface. However, the detailed properties of this regolith layer is not known by such kinds of observations, and only in-situ space missions can tell us what it actually consists of, as indicated in the next section.

2.4. Surface properties of NEOs

Not much is known regarding the detailed surface properties of NEOs. Indeed, ground-based observations allow us to get an estimate of the only global surface roughness. If those observations indicate that all observed NEOs, including the very small ones, are not perfectly bare rocks, but rather covered with some sort of regolith, no information can be obtained regarding the precise properties of this regolith, such as the size distribution of the grains that compose it, its depth, its angle of friction, its porosity, etc. Such information can only be obtained by in-situ investigation or sample return space missions. So far, only two space missions have been devoted to the investigation of a NEO, namely the NEAR-Shoemaker mission (NASA) that visited the 17 km-size NEO Eros for one year in 2000–2001, and the Hayabusa mission (JAXA) that visited the 320-meter size NEO Itokawa for 3 months and successfully brought a sample back to Earth. While both asteroids belong to the same S taxonomic class, images obtained by those missions showed two drastically different surfaces (Fig. 3). Eros′s surface is composed of a layer of regolith whose depth is estimated to be from 10 to 100 m, and composed of very fine dust. On the other hand, Itokawa's surface contains both smooth and very rough areas, and is covered by a layer of regolith whose average depth is estimated to be of the order of a few tens of centimeters. This regolith layer is essentially composed of unconsolidated gravels, which are typically piled on each other without being buried by fines [11]. The finest observed particles are centimeter-sized pebbles, whose concentrations are found on smooth terrains. More powdery materials believed to be created through impact processes might have been electrostatically levitated and removed by solar radiation pressure, and/or had much higher ejection velocity after impacts to restrict their reaccumulations and/or have been segregated into the interior.

However, given the size/mass difference between the two objects, the gravity conditions are also extremely different. This may explain their different geological properties despite their similar spectral type. Actually, if gravity is the discriminator, then Itokawa is expected to be as different from Eros, geologically, as Eros is from the Moon [12].

Note that so far, we do not have such level of details for the surface of any dark-type asteroids (such as C, D), that are believed to be the most primitive ones, and that dominate the population of asteroids (most of them reside in the outer main asteroid belt). A space mission devoted to a primitive NEO is therefore urgent and three sample return space missions to a primitive NEOs are under study or selected in the three main space agencies. The mission OSIRIS-Rex has been selected in the program New Frontiers of NASA in spring 2011 and will be launched in 2016. It will visit the B-type NEO (101955) 1999RQ36 in 2020 and return a sample to Earth in 2023. Note that 1999RQ36 has a non-zero impact probability with the Earth before 2200 [13], and it will therefore be very interesting to determine its properties in great detail, thanks to this mission, as it belongs to a spectral class for which we have no information so far from any space mission. The mission Hayabusa 2 is now a project in phase B at JAXA. Its target is the C-type NEO (162173) 1999JU3. The launch is planned in 2014 for a visit of the asteroid in 2018 and a sample returned to Earth in 2020. Finally, the mission MarcoPolo-R has been selected by the European Space Agency for the assessment study phase of Medium Class missions of the program Cosmic Vision 2 in 2011. The next selection phase will take place in 2013. The baseline target is the primitive binary asteroid (175706) 1996FG3 and the launch would be planned for 2022. Note that 15% of the population of NEOs are binary systems.

In conclusion, asteroid surfaces are very diverse, and each rendezvous with an asteroid has required great revisions of our geological understanding in areas of, e.g., granular mechanics, landslides, earthquakes, faulting, and impact cratering. It is obvious that future missions devoted to these small bodies will provide a great science return, and it is also very likely that some of our assumptions will have to be reconsidered.

2.5. *Internal properties of NEOs*

The only knowledge regarding the internal structure of NEOs comes from the bulk densities measured by spacecrafts, either during fly-bys or during rendezvous missions. The spacecraft perturbation due to the asteroid's gravity allows a determination of the asteroid's mass and the volume is estimated through a model of the asteroid's shape. Mass and volume allow the derivation of the bulk density whose error bars are usually dominated by the errors made on the volume estimate. These measurements indicate that dark-type bodies have a density that is lower than bright type ones. For instance, the NEAR-

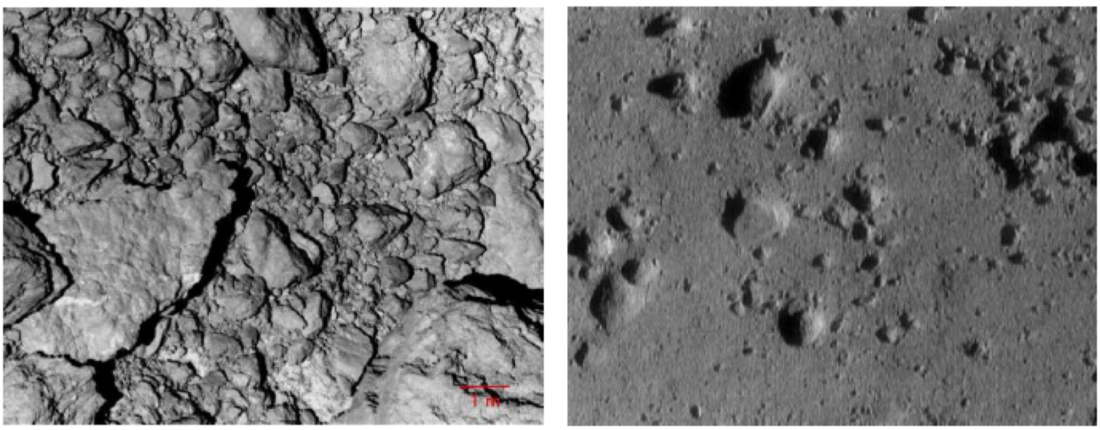

Fig. 3. Nature of the regolith at the surface of airless bodies. Close-up images of the very rough surface of the 320-m size Itokawa (left) taken by Hayabusa (the scale is indicated on the image), and of the surface of the 17-km size Eros (right) taken by the NEAR Shoemaker from a range of 250 m (the image is 12 m across). Note that despite their drastically different regolith properties, Itokawa and Eros belong to the same taxonomic type (S). Images from JAXA and NASA.

Shoemaker space probe flew by the dark C-type asteroid Mathilde in 1997 and the bulk density of the asteroid was estimated to be about 1.3 g/cm^3 [14]. On the other hand, the bulk density measured by the same space probe of the bright S-type asteroid Eros is about 2.67 g/cm^3 [15], that of the S-type asteroid Itokawa measured by the Hayabusa space probe is about 1.9 g/cm^3 [16] and that of the 28 km-size asteroid Ida (also an S-type) measured by the Galileo space probe on its way to Jupiter is about 2.6 g/cm^3 [17].

The amount of porosity has been inferred through the comparison of the bulk density of the asteroids with that of their meteorite analogues [18]. Despite the small number statistics, from this comparison, it is found that asteroid internal structures must contain in general some degree of porosity. However, dark-type asteroids seem to contain a higher degree of porosity ($>40\%$) than bright-type ones. However, the nature of this porosity is entirely unclear. The scale of porosity must be defined in comparison with the other relevant dimensions. Microscopic porosity can be defined as a type of porosity characterized by pores sufficiently small that their distribution can be assumed to be uniform and isotropic over the relevant scales of the asteroid. In this case, the sizes of the pores are typically smaller than the thickness of the shock front resulting from an impact. A rock such as pumice contains such kind of porosity. Macroscopic porosity, on the other hand, is characterized by pores whose sizes are such that the medium can no longer be assumed to have homogeneous and isotropic characteristics over the scales of the object. It corresponds to large voids in an otherwise non-porous rock. While macroporosity may explain the difference in density between S-type asteroids and their meteorite analogues (ordinary chondrites), some fraction of microporosity may still be needed in addition to explain the lower bulk density of C-type asteroids.

However, we do not have any direct evidence of the kind of porosity that resides inside an asteroid, even the ones for which the density was estimated. For instance, is Mathilde microporous, in the manner of the cometary dust balls [19], and as recently proposed to explain Mathilde's giant craters [20]? In effect, a body containing microporosity may be crushable: cratering on a microporous asteroid might be an event involving compaction rather than ejection because a part of the kinetic energy is dissipated by compaction of the micropores, which leads to less ejected mass and lower speeds of the ejected material (see e.g. [21]). Then despite its possible microporosity, is Mathilde cohesive, as one might expect for microscale grain structure? Or does Mathilde, and the other primitive asteroids with comparable densities (as determined by analyses of their satellite orbits [22]), possess huge voids as one would expect from collisional disruption and reaccumulation of major fragments [23,24]? And at which asteroid sizes can we expect that asteroids are generally monolithic (even with microporosity) rather than gravitational aggregates?

These last questions do not have any clear answer yet, and only space missions aiming at probing the internal structure of an asteroid (for instance by using radar tomography techniques, and/or by performing a seismic experiment) can provide some answer. As we will see in the following, such knowledge is crucial for mitigation methods aimed at disrupting a small body. The specific impact energy leading to a given degree of disruption depends on the asteroid's mass. The knowledge of the structure and porosity properties in the area of the impact (surface and subsurface) is also fundamental for the design of a kinetic impactor and its momentum transfer efficiency.

3. Mitigation methods and influence of target's physical properties.

Various methods have been proposed on paper to protect the Earth against a threatening object. However, none have been tested yet, and we have so far no direct evidence that any of them would reach its objective. Apart from the technological complexities associated to each method (that will not be discussed in this paper), the efficiency of each of them depends on some physical properties of the object. Table 1 indicates which main physical properties must be known for each considered method. As can be seen, some properties must be known for all of them: the mass, the shape and the rotational properties. Those three properties are actually the only ones that are fundamentally needed for the design of a gravity tractor. Indeed, the definition of the tractor's mass depends on the mass of the asteroid. As the attraction depends on mass and distance, according to Newton's law, for a fixed tractor's mass, one can play with the distance to the asteroid to make sure the attraction is the

Table 1
Main physical properties of a NEO that need to be known for the most usual mitigation concepts, namely the gravity tractor, the kinetic impactor (for deflection), methods relying on the attachment of a device (e.g. a solar sail) and/or on anchorage, methods aimed at playing with the thermal properties of the object (e.g. for altering the Yarkovsky effect or for vaporizing a surface portion), and methods aimed at fully disrupting the NEO into small pieces.

	Gravity tractor	Kinetic impactor (for deflection)	Surface attachment	Thermal effects	Complete disruption device
Mass	X	X	X	X	X
Shape	X	X	X	X	X
Spin properties	X	X	X	X	X
(Sub)Surface properties		X	X	X	X
Thermal properties				X	
Internal structure					X

required one. However, the shape and rotational properties of the object limit the distance at which the tractor can approach to avoid the risk of a collision. For all the other methods, the knowledge of additional physical properties is needed. For instance, for a kinetic impactor, the surface and subsurface mechanical properties must be known, as they dictate the efficiency of momentum transfer (see further). Thermal surface properties are also important for mitigation strategies relying on vaporization of the surface that depends on the heat capacity, and for those related to the Yarkovsky effect. For the mitigation strategies aimed at disrupting and not only deflecting the small body, the internal properties (and not only subsurface and surface ones) must be known, and a good understanding of how the internal properties influence the outcome of a disruption is also required. Indeed, it has been shown (see e.g. [24,25]), that the degree of disruption and the outcome properties (in terms of fragment sizes and ejection velocities) highly depend on the internal structure of the target, but we are still far from fully understanding, in a quantitative way, what this dependence means. I do not mention here the case of binary asteroids, although they represent 15% of the NEO population, and several studies of some of the mentioned concepts are made specifically for these systems.

Knowing which physical properties must be known for a given mitigation concept, as indicated in Table 1, dedicated studies must be done to understand how these physical properties quantitatively influence the target's response to the considered mitigation concept. This is obviously a complex task that requires the development of numerical models, experiments and possibly space mission demonstrations. In the following, the example of a kinetic impactor is considered, and preliminary impact simulations are presented showing the sensitivity of the momentum transfer efficiency on the target's material properties in the area of the impact point. Note that, as already stated, the knowledge of the entire internal structure is not required, as long as the impact is just aimed at making a crater whose volume is small compared to the full volume of the asteroid, i.e. the shock wave resulting from the impact will not go through the entire body.

Preliminary simulations of momentum transfer from a small impactor impacting a 1 km-diameter target have recently been performed [26]. Some of the results indicated in the mentioned paper are presented below. They should not be considered as accurate quantitative estimates, as further work is needed to improve the reliability of those simulations (see [26] for details on the limitations of these simulations); however they show at least qualitatively that the outcome depends much on the properties of the target, which are here limited to the presence or absence of microporosity, in the region of the impact.

The momentum transferred during a collision, which will result in a change of the orbit, is largely determined by the amount of material ejected from the crater produced by the impact. Thus, the material characteristics of the target in the region of the impact obviously play an important role. The momentum transferred to the target P_{target} is given by the momentum of the projectile $P_{projectile}$ plus the momentum carried away by the ejecta P_{ejecta}. This can be expressed by

$$P_{\rm target} = \beta P_{projectile} = P_{projectile} + P_{ejecta},$$

where we consider the component of the momentum only in the impact direction and β is a parameter which is often called the *momentum multiplication factor*. In general, we have $\beta > 1$ (unless ejecta are released in the forward direction), and in the limiting case of an impact without ejecta we have $\beta = 1$. The actual value of β not only depends on the target characteristics but also on the impact speed. One of the main goals of studies of the kinetic impactor method is to determine β for objects of given sizes for different impact speeds assuming different kinds of surface/subsurface properties and morphologies (e.g., boulders and craters).

Preliminary simulations have been performed using a smoothed particle hydrodynamics (SPH) code that includes a model of brittle failure of non-porous material [27], developed in the mid-1990s [28]. This hydrocode was then extended to include a model of fragmentation of microporous materials [21] that was validated by comparison with impact experiments on pumice material [29]. For these preliminary simulations, a 400 kg aluminum sphere was used as a projectile and a target diameter of $D = 270$ m was considered, which corresponds to the size of the asteroid Apophis. However, as a simulation domain, only a small part (half-sphere) of the actual asteroid was simulated, which must be at least larger than the size of the region that gets damaged by the impact. In order to have a reasonably high resolution, the simulations were limited to rather small impact speeds. Therefore, only impact speeds of 1.33, 2.0 and 3.0 km/s were considered, while higher velocities (of the order of 10 km/s) may be used in a real case. Indeed, for higher velocities, as the damaged zone increases, the minimal size of the computational domain becomes too large and therefore, the resolution that could be reached using reasonable computational time was too small at the time these simulations were performed. In each case, two different kinds of internal structures were considered: (a) a non-porous (basalt) target (bulk density $\rho_0 = 2.7$ g/cm^3), and (b) a porous (bulk density $\rho_0 = 1.3$ g/cm^3) target with material parameters corresponding to pumice. For each impact speed considered, the projectile mass and impact angle (head-on impact) were fixed. Fig. 4 shows a vertical cut through the 3D target (half-sphere) at a time corresponding to 20 ms after the impact of the projectile at 2 km/s. There is a clear difference between the impact response of the non-porous (left) and porous (right) materials. In particular, in the porous case there is much more compaction (resulting in a deeper crater) and less ejection than in the non-porous case. This can also be seen looking at the momentum transferred by each particle (indicated by the colors in Fig. 4). The amount of momentum transferred by ejecta with velocities higher than a certain velocity is shown in Fig. 5 (again for the 2 km/s impact). These two figures indicate that the amount of transferred momentum from a porous body is significantly smaller than that from a non-porous body. This is a

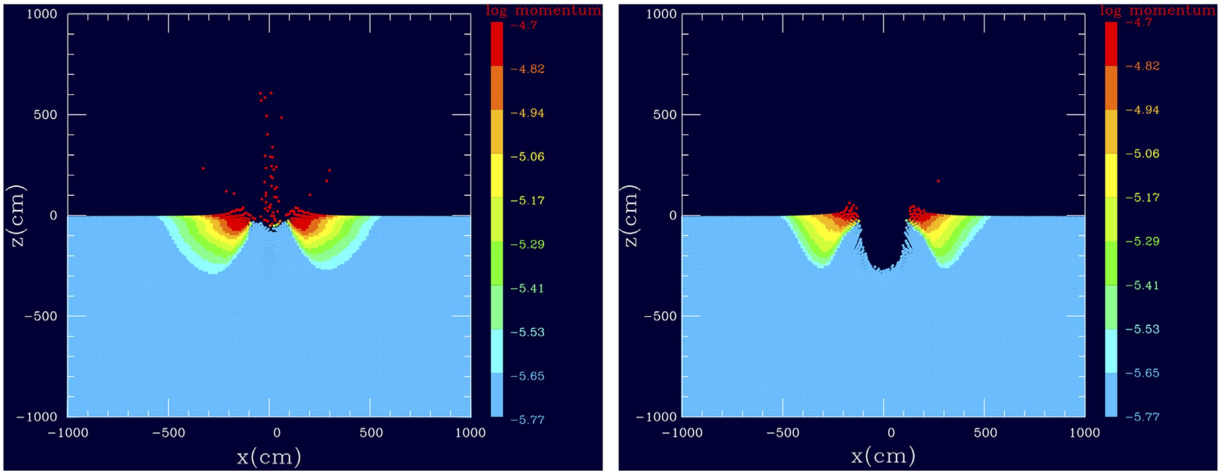

Fig. 4. Vertical 2D slice through the target (top: non-porous, bottom porous). The colors indicate the amount of momentum transferred (log scale); from [25]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

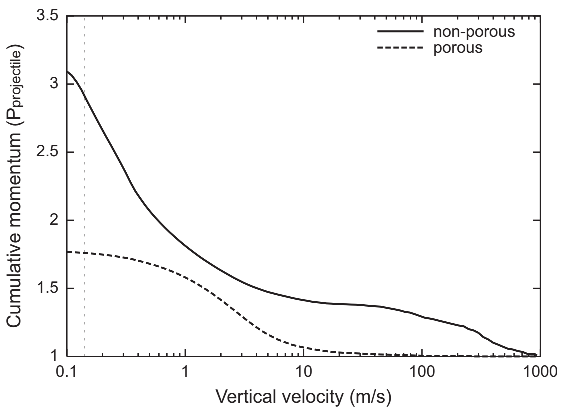

Fig. 5. Cumulative momentum for both the non-porous and porous targets. The total amount of transferred momentum (β) is given at the escape velocity $v_{esc}=14$ cm/s indicated by the vertical line. From [25].

consequence of the lower velocities of the ejecta and the fact that there is less material ejected from the porous targets. Note that the total amount of transferred momentum (in units of the projectile momentum) corresponds to the β factor. In these preliminary simulations, we also found that for both kinds of targets, the amount of transferred momentum increases with increasing speed (note that this is not obvious a priori since we consider here the amount of transferred momentum normalized by the momentum of the projectile). However, the increase of transferred momentum with increasing impact speed is stronger in the non-porous case than in the porous case.

Obviously, these estimates must be refined in future works and cannot be considered appropriate for a kinetic impactor aimed at impacting at much higher speed. The momentum transfer efficiency depends greatly on the impact speed, and among future works, one will be able to provide a quantitative estimate of this dependency.

4. Conclusion

The population of NEOs is composed of small bodies whose physical properties start being on average well established, in particular regarding their size, spin rate, spectral type distributions and to some extent, thermal properties. However, the actual physical properties of a specific body cannot be assumed from this statistical knowledge, as images of space missions (e.g. NEAR, Hayabusa) showed that even two asteroids belonging to the same spectral type can have very different structural properties. Moreover, the various mitigation concepts are so sensitive to some of these properties, that these properties must be well established in advance for the considered target in order to optimize the mission design and make sure that the chosen concept is adapted. For instance, knowing that a body smaller than a few hundreds of meters can rotate with a rotation period as long as a few tens of hours, but also as short as a few minutes or less, one must make sure that the actual target of a mitigation mission in this size range has a rotation period well known in advance given the wide range of possible values. Also, there is no way to obtain the required accurate knowledge about the surface, subsurface and interior properties of a small body from ground-based observations, and yet this knowledge is required to determine with good confidence the efficiency of deflection concepts using a kinetic impactor or disruptive ones. Therefore, precursor missions to potential targets should be planned to perform the necessary in-situ investigations so that sufficient knowledge is obtained to assess the efficiency of mitigation concepts that may be used for those targets. Also, mitigation precursors (tests), such as the Don Quijotte deflection mission that was studied in phase A at ESA in 2007, should also be planned to check our ability to achieve the expected goal, as written on paper, and to calibrate on a real case the numerical models aimed at predicting the expected effect. Unless we make such checks, we will never know whether what we believe feasible on paper is achieved in practice and we probably do not want to wait the next actual Earth collider to check this.

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