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Asteroid Deflection and Exploitation: Possible Synergies

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The asteroid and cometary impact hazard has long been recognised as an important issue requiring risk assessment and contingency planning. At the same time asteroids have also been acknowledged as possible sources of raw materials for future large-scale space engineering ventures. This paper explores possible synergies between these two apparently opposed views; planetary protection and space resource exploitation. In particular, the paper assumes a 5 tonne low-thrust spacecraft as a baseline spacecraft for asteroid deflection and capture (or resource transport) missions. The system is assumed to land on the asteroid and provide a continuous thrust able to modify the orbit of the asteroid according to the mission objective. The paper analyses the capability of such a near-term system to provide both planetary protection and asteroid resources to Earth. Results show that a 5 tonne spacecraft could provide a high level of protection for modest impact hazards: airburst and local damage events (caused by 15 to 170 meters diameter objects). At the same time, the same spacecraft could also be used to transport to bound Earth orbits significant quantities of material through judicious use of orbital dynamics and passively safe aero-capture manoeuvres or low energy ballistic capture. As will be shown, a 5 tonne low-thrust spacecraft could potentially transport between 12 and 335 times its own mass of asteroid resources by means of ballistic capture or aero-capture trajectories that pose very low dynamical pressures on the object.

INTRODUCTION

The threat that asteroids pose to life on Earth has long been acknowledged. Initial concerns focused on the potential threat from mass extinction events, similar to that of the cretaceous-tertiary period. These events, albeit having an almost vanishingly low probability of occurrence, could potentially have catastrophic consequences. First surveying efforts therefore focused on discovering all objects larger than 1km diameter [1], thus those with potential to cause global damage. After almost 20 years of asteroid surveys, the census of asteroids larger than 1km diameter is almost complete, and thus the remaining impact risk has gradually switched towards smaller objects.

A detailed analysis on impact hazard, carried out by Stokes et al. [2] in 2003, showed an important residual risk for objects smaller than 1 km diameter, with a maxima at objects of order 300 meters diameter. The latest analysis on impact risk [3], though, seem to refute Stokes et al. [2], drawing two clear risk bands: a residual global threat posed by plausible large undiscovered objects and a local threat posed by the undiscovered population of numerous small objects ranging from 10 meters to 100 meters diameter (see figure 2.7 in 2010 impact hazard report from the National Academies Press [3]). The reason for this recent change is two-fold: firstly, the latest estimates on the population of Near-Earth Objects (NEOs) show a drop on the expected number of objects between 10 to 500 meters diameter [4], with a maximum difference of a factor of 2 to 3 on the total accumulative number of asteroids of order 100 meters diameter; secondly, the capability to yield ground damage of Tunguska type of events seem to have been underestimated [3].

Work on asteroid deflection systems, for planetary protection purposes, has generally focused either on investigating the feasibility of new exotic methods (e.g., [5] and [6]) or on comparing different methods in terms of efficiency (e.g., [7] and [8]). This paper, on the other hand, will focus on the possible synergy between space systems capable of deflecting realistic current impact threats and, at the same time, capturing small asteroids for later resource exploitation in the Earth's neighbourhood. The concept of capturing near Earth asteroids may prime future large-scale space engineering ventures such as space solar power, space tourism, human space exploration, etc. Importantly, as will be shown, these

potentially capturable targets are sufficiently small that they pose no direct impact hazard to the Earth during the capture manoeuvres.

In particular, this work analyses a low-thrust *tugboat* as a system capable of both asteroid deflection and capture. The tugboat concept assumes a low-thrust propulsion spacecraft attaching itself to the surface of the asteroid and providing a continuous thrust. On the deflection scenario, the purpose of the thrust is clearly to move the asteroid away from a potential collision trajectory with Earth. The paper then first presents an assessment on the capability of such a system to deflect realistic impact threats.

The assessment assumes a 5 tonne payload launched to Earth escape with a rendezvous trajectory towards a virtual threatening asteroid and attempting to deflect it from its collision trajectory. This deflection process is then repeated over a set of more than 17 thousand virtual threatening asteroids, which have been carefully chosen to provide a comprehensive overview of all possible asteroid impact scenarios. The results from the set of deflection attempts provide a good estimate of the level of planetary protection that such a system could be capable of.

Secondly, the paper focuses on estimating the statistical population of small asteroids (i.e., diameters on the order of meters to tens of meters) that could potentially be manoeuvred and captured into a bound Earth orbit using the same tugboat system. This statistical population of capturable asteroids can be estimated by comparing the regions of accessible Keplerian orbital element space with an NEO model able to predict the statistical probability of the existence of an asteroid with a given set of both orbital elements and diameters. For the latter purpose the theoretical NEO model published by Bottke et al. [9] will be used to estimate the orbital element distribution, whereas the size population estimates will consider Harris [4].

Since the only propulsion system used is low thrust, the asteroid orbital insertion at Earth must be provided either ballistically (i.e., a natural low energy gravitational capture into an Earth bound orbit) or by means of aero-assisted trajectories. The paper will show that by using very small aerobraking manoeuvres, posing dynamical pressures much smaller than those for which the object would be expected to fragment, a non-negligible statistical population of asteroids can be captured within the Earth's gravity well. The low-thrust tugboat is here assumed to be used only to trim the orbital phasing of the object so that it meets the Earth at the orbital intersection, hence only objects with very well defined orbital geometries can be suitable targets for capture.

TUGBOAT SYSTEM

The baseline design of the tugboat system is fixed throughout the paper. The reason for this is that the purpose of the paper is to investigate the capability of a plausible deflection system, and then compare it with its capability to transport material to Earth's neighbourhood for capture. By plausible we mean a mission of a similar size to current asteroid missions, for example NASA's Dawn mission [10] with a wet mass at launch of 1,250 kg or ESA's Rosetta mission[1] with a wet mass of 3,000 kg. It is envisaged then that a wet mass of 5,000 kg with an Earthescape velocity v_∞ of 2.5 km/s is a plausible mission, requiring levels of investment comparable to medium-to-large current science exploration missions. Thus, such a mission would still require a dedicated launch with a heavy lift launch vehicle, but the wet mass and excess velocity is within the current launch capabilities of Ariane V and Delta IV-H [8]. Note that this is a relatively small mission if compared with both ambitious solar system exploration concepts (>10,000 kg wet mass [11]) or with proposed deflection missions (>100,000 kg in some cases [12]).

The Spacecraft and Transfer
Together with the concept of kinetic impactor (i.e., involving changing the asteroid's linear momentum by impacting a spacecraft onto it), the low thrust tugboat system is one of the simplest deflection concepts proposed for the purpose of impact hazard mitigation. The concept consists of a spacecraft landing on the asteroid and using its propulsion system to push the asteroid away from the impact trajectory. The preferred choice for the propulsion system is to use low thrust, since these provide specific impulses 10 times higher than chemical propulsion and therefore require significantly less reaction mass to impart the same change in momentum.

The drawback of the higher specific impulse is that its lower level of thrust requires a long duration to provide a useful change to the asteroid's trajectory. Due to this, the rotation of the asteroid becomes an issue, since on a rotating asteroid the thrust vector of the system will not maintain a constant pointing direction. The propulsion system will therefore have to be switched on and off when the correct thrusting direction occurs or, alternatively, the asteroid rotation will have to be modified so that the propulsion system can be continuously active. The first option, switching the propulsion system on and off when the pointing is within tolerable misalignments, is deemed to be much simpler to implement, since, for example, the asteroid-to-spacecraft attachment will not require a gimbaling system , while still providing adequate efficiency [7].

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[1] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=13

The tugboat deflection system modelled in this paper assumes two equal spacecraft, each requiring half of the 5,000 kg launch mass, landing on opposite sides of the asteroid and thrusting through the centre-of-mass of the object. By properly scheduling the periods when the thrusters are switched on and off, we can obtain a quasi-constant thrust and a limited scattering factor. The scattering factor takes into account the misalignment from the optimal thrust direction, and by multiplying it by the thrust results in the effective force applied in the optimal thrusting direction. As shown in Sanchez et al. [7], no matter the shape and obliquity of the asteroid's equator, it is always possible to achieve at least 25% of thrust efficiency, and mean efficiencies of 30%, without changing the rotational state of the asteroid.

The mass of the system at arrival at the asteroid m_i includes the propellant mass for the deflection manoeuvre and the dry mass m_d of the spacecraft. The dry mass m_d defines the size of the power system m_{power}, which is assumed here to be 50% of the dry mass of the spacecraft (this includes common payload mass fractions into the power subsystem [13]). The thrust T of the system can then be estimated using the following linear relationship:

$$T = m_{power} \frac{\xi}{\tau} \tag{1}$$

where the specific thrust ξ is set equal to 34 mN/kW, which represents an average value for the most common ion thrusters [13], and the mass-to-power ratio τ is set to 25 kg/kW [13]. Note that T is the total thrust of the system and that each half-spacecraft landing on opposite sides of the asteroid will have a thrust $T/2$. The proportion of the mass at arrival m_i which is dry mass m_d or propellant for thrusting also requires to be optimised to achieve maximum deflection. This proportion is defined by the length of the thrusting operation and is not necessarily the same as the time left to impact, since shorter push manoeuvres allow the transfer of higher levels of impulse to the asteroid earlier, which then enhances the deflection achieved by the passive drift of the asteroid with the Earth. Further details on the system can be found in [7, 12].

In order to compute the mass at arrival m_i, the cost of the rendezvous trajectory with the asteroid needs to be estimated. The propulsion system used is a low-thrust system, and therefore, the trajectory should ideally be computed using a low-thrust optimisation technique such as, for example, optimal control theory. Unfortunately, the work presented here required the optimisation of the trajectory to over 17 thousand asteroids, and therefore, a full low thrust optimisation would have taken an unfeasibly long computational time. Thus, trajectories have been computed by optimising the minimum Δv Lambert-arc connecting the asteroid and Earth's orbits and applying a 2.1 factor to the optimised Δv in order to account for gravity losses [14]. At the arrival of the tugboat at the asteroid then, the mass of the system needs then to be reduced according the $2.1 \times \Delta v$ cost necessary for rendezvous with the specific asteroid. The mass at arrival m_i can be computed by means of Tsiolkovsky's rocket equation and assuming a I_{sp} of 3000 seconds, as a mean specific impulse of common ion thrusters [13].

We refer here to a *lead time* as the time spanned from the moment at which the tugboat system is deployed and ready at the asteroid until the collision time. Within the available lead time, a push maneuvre will be optimised for each asteroid in order to achieve a maximum deflection distance. As noted earlier and as shown in previous work [7], the tugboat system requires long duration push manoeuvres, i.e., several years, in order to achieve acceptable deflection distances. The lead time then is a crucial parameter of the deflection scenario. Five representative lead times have been chosen for analysis; 1, 2.5, 5, 10 and 20 years.

DEFLECTION SCENARIO

As noted previously, over 17 thousand virtual impactors were created in order to provide a comprehensive overview of asteroid impact scenarios. This section provides a brief description of how the set of impactors was built, but a more comprehensive description can also be found at [15]. The levels of planetary protection expected to be achieved by a tugboat system as described in the previous section are presented at the end of this section.
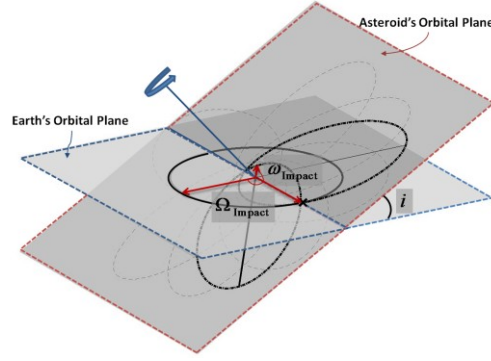
Fig. 1. Orbital geometry of possible impactors for a given semi-major axis *a*, eccentricity *e* and inclination *i*.

In order to build the set of impactors, the {*a,e,i*}-domain was first divided into a three-dimensional grid homogeneously distributed within a semi-major axis *a* from 0.05 to 7.35 AU with a step-size of 0.1 AU, eccentricity *e* from 0.025 to 0.975 with a step-size of 0.05 and inclination *i* from 0 to 87.5 deg with a step-size of 5 deg. Only 8,759 locations in this grid correspond to orbits with a perihelion smaller and aphelion larger than 1 AU, and these correspond to a 17,518 virtual impactors, since each location in the grid has two possible arguments of periapsis ω that allow an intersection with a 1 AU circular orbit (i.e., assumed Earth orbit), as seen in Fig. 1. Thus, each virtual impactor from the set is defined by the six Keplerian elements leading to an impact at a specified epoch. The impact velocity v_{impact} of the asteroid with the Earth is as a consequence also defined by the Keplerian elements of the impactor. Since impact energy is the result of:

$$E_{impact} = \frac{1}{2} M_{Ast} v_{impact}^2 \tag{2}$$

where M_{Ast} is the mass of the asteroid, the objective is then to compute the mass of the largest object that the tugboat system could deflect from each one of the impacting orbits. This figure will allows us to assess the level of planetary protection that this system would be able to offer.

The set of 17,518 impactors is not yet a good overview of realistic impact scenarios, since the set has been created by homogenously distributing a grid through the entire domain of impact geometries. The realistic statistical population of impactors must be the result of a complex relation between populations of near Earth asteroids (NEA) and the different impact geometries. Therefore, each virtual impactor on our set can be weighted by a normalised impact frequency, which takes into account the frequency of occurrence of each virtual impact on the set. This relative impact frequency of each impactor needs to be assessed by means of two multiplying factors; first, the NEA orbital distribution that defines the actual asteroid probability density, and second, the collision probability that an impactor with a given set of {*a,e,i*} has. **Fig. 2** shows the complete set of impactors as dots in the {*a,e,i*}. Each dot in the figure has been sized and colored according to its relative impact frequency.
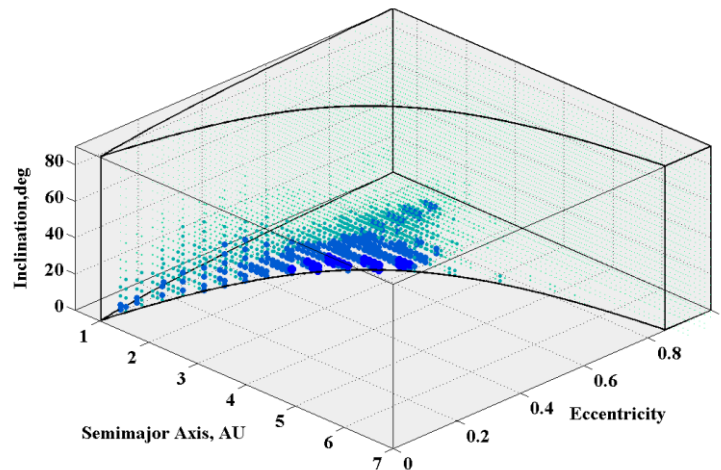

Fig. 2. Set of virtual impactors plotted as dots of size and colour as a function of the relative frequency that should be expected for each impactor. Five different dot-types have been used in this figure to represent average relative impact probabilities as follow: ● <p>=1%, • <p>=0.2%, · <p>=0.05%, · <p>= 0.01% and · <p><0.005%.

Expected planetary protection.

The level of planetary protection that the tugboat is capable of providing can now be estimated. Firstly, the largest asteroid size that the tugboat is able to deflect from each of the 17,518 orbits impacting the Earth requires to be computed. The deflection can be computed as a function of the asteroid mass, and thus, a root finding procedure can find the exact asteroid mass that allows a minimum safe deflection distance. The deflection distance is defined as:

$$d_{\oplus} = r_{\oplus}\sqrt{1 + \frac{2\mu_{\oplus}}{r_{\oplus} \cdot v_{\infty}^{2}}} \; , \tag{3}$$

where v_{∞} is the excess velocity of the impactor, $r_{\oplus}$ refers to the radius and $\mu_{\oplus}$ to the gravitational parameters of the Earth, which defines the threshold between a collision and a close encounter.

The tugboat achieved deflection distance for each simulation is computed here by using the proximal motion equations expressed as a function of the variation of the orbital elements. The variation of the orbital elements is computed by numerically integrating Gauss's planetary equations over the interval on which the tugboat is performing the deflection manoeuvre. A complete description of the deflection models can be found at [7].

Table 1. Impact hazard categories

Type of Event	Approximate range of Impact Energies (MT)	Approximate Range Size of Impactor
Airburst	1 to 10 MT	15 to 75 m
Local Scale	10 to 100 MT	30 to 170 m
Regional Scale	100 to 1,000 MT	70 to 360 m
Continental Scale	1,000 MT to 20,000 MT	150 m to 1 km
Global	20,000 MT to 10,000,000 MT	400 m to 8 km
Mass Extinction	Above 10,000,000 MT	>3.5 km

Following approximately the definitions proposed in [3], we have divided the impact hazard into the six categories defined by their range of impact energy, as described in Table 1. Assuming spherical asteroids with average density (2600 g/m^3 [16]), an approximate size range can also be estimated by considering the extreme variations of the impact velocity of the set of impactors considered in this paper. Fig. 3 shows the maximum energy deflected as a function of $\{a,e,i\}$ for the particular deflection scenario with 20 year of lead time.
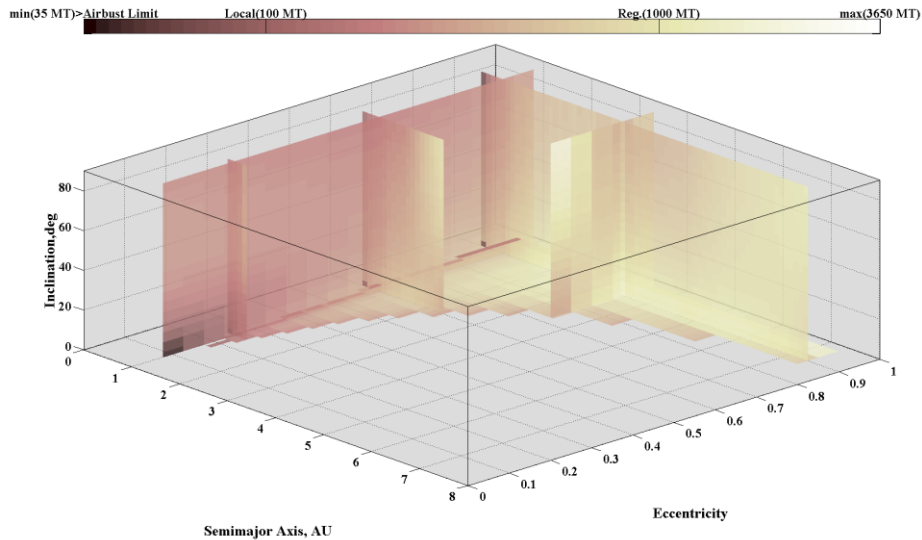

Fig. 3. Deflected energy with 20 year lead time.

Finally, Table 2 summarises the results for all the lead times by showing the total level of protection offered by the tugboat system. The level of protection is calculated by summing up the relative impact frequency of each virtual impactor that can be deflected up to a given level of energy. Thus, for example, for a 20 year lead time, as shown in Fig. 3, the airburst protection offered by the tugboat is computed by summing the normalised relative impact probability of all the objects in the region with deflected energy above 10 MT. Since the minimum amount of energy deflected by the tugboat with 20 years of lead time is 35 MT, then the tugboat is offering a 100% protection against airburst events at this lead time.

Table 2: Protection levels

TYPE OF EVENT	LEAD TIME				
	1 year	2.5 years	5 Years	10 Years	20 years
Airburst	**51%**	**93%**	**99%**	**100%**	**100%**
Local Damage	**0.01%**	**1.6%**	**18%**	**78%**	**98%**
Regional Damage	**0%**	**0%**	**0%**	**0%**	**6%**
Continental Damage	**0%**	**0%**	**0%**	**0%**	**0%**
Global Damage	**0%**	**0%**	**0%**	**0%**	**0%**

As the table shows, the tugboat system analysed here should be capable of protecting Earth against all airburst events if 10 years or more of lead time are available. Even with less available lead time the levels of protection at this energy level are in fact very high. Also, Local Damage events can be reasonably well protected with this deflection system if deployed on the threatening object 10 years or more before the impact. Unfortunately, the tugboat would not be able to provide sensible planetary protection against any of the three largest types of events. Yet these results demonstrate the capability of a relatively small tugboat system to completely protect the Earth against any impact threats from the first impact-risk band (as discussed in the Introduction or seen at the figure 2.7 on [3]).

CAPTURE SCENARIO

Having shown that a small-to-medium tugboat mission has a good capability to provide planetary protection, we can now discuss the possibility of using the same tugboat system for a completely different mission: pushing a small object in order to facilitate its capture in the Earth's neighbourhood. Any envisioned future for space exploration involves both a growth in large space structures and a human presence (e.g., space solar power, space tourism or more visionary human space settlements). This, of course, implies a large mass of material in-use in Earth orbit, for both structural mass and life support for human presence in space. The traditional approach to deliver such material into Earth orbit has always been limited by the Earth's gravity well. This is, arguably, not the most effective means of delivery, since unprocessed material resources requiring less energy for transportation are in abundance in space [17]. This paper now focuses on the possibility of pushing small near Earth asteroids and inserting them onto Earth bound trajectories for capture and utilisation, or indeed for in-situ science exploration of a small, complete NEA returned to Earth orbit. The interesting question that arises is then how much material could a 5,000 kg low thrust spacecraft transport back to Earth. The analysis will provide an estimate of the leveraging which can be achieved with such a system.

Ballistic and Aero-assisted Capture

The most restrictive constraint set by the tugboat, as described here, is its limited thrust. If the level of thrust, and thus acceleration of the asteroid was not a constraint, we could envisage a system able to transfer to a suitable target asteroid and provide first the small push required to provide a precise phasing with the Earth so that the two objects meet at their orbital intersection point. A secondary maneuver during encounter would then place the asteroid into a bound Earth orbit. Unfortunately, the tugboat requires a long duration to provide a useful change in the velocity of the asteroid, thus allowing very limited manoeuvrability of the asteroid during Earth fly-by. This limitation entails then that the tugboat would only be able to provide small orbital element changes requiring relatively long push manoeuvres and, as a consequence, the final Earth orbit insertion needs to be ballistic, or at least largely unaided by the propulsion system.

As seen in Ref [18], ballistic Earth escape or capture trajectories with relative velocities, v_∞, bellow 1 km/s are possible. Hence, all objects with orbits that approach the Earth with such a low relative velocity are realistic targets for a completely ballistic capture. However, for objects that approach the Earth at higher relative velocities a possible alternative could be the use of grazing aero-assisted trajectories to eliminate the excess energy. The Δv change provided by an aero-assisted manoeuvre can be estimated by approximating the object's trajectory to a Keplerian orbit. This is well satisfied for any high eccentricity or hyperbolic orbits whose periapsis grazes the Earth's atmosphere for only a short arc of true anomaly. These assumptions allow approximating the Δv change of an aero-assisted trajectory, as [19]:

$$\Delta v = \left(1 - e^{\mathrm{B}\rho\sqrt{2\pi r_p H(e+1)/e}}\right) \cdot v_p \tag{4}$$

where B is the asteroid ballistic coefficient computed as $B = C_D \cdot A / 2M$, where the drag coefficient C_D of a sphere (e.g. 0.47) and the area-to-mass ratio A/M can be also computed assuming an sphere with an average density equal to 2600 g/m³ [16], r_p is the periapsis distance and e is the orbit eccentricity. The atmospheric density ρ can be computed using an exponential model such as $\rho = \rho_0 e^{-h/H}$, where H is the scale height, ρ_0 is the sea level atmospheric pressure and h is altitude from sea level. It can be also assumed, as in Hills and Goda [20], that the fragmentation of the asteroid would occur when the dynamical pressure P_{ram} during aero-assisted passage reaches the material strength S of the asteroid. The dynamical pressure P_{ram} then sets a maximum limit to the Δv change that can be tolerated by an asteroid without risking fragmentation. P_{ram} can be computed as:

$$P_{ram} = \rho \cdot v^2, \tag{5}$$

where ρ is the local atmospheric pressure. An upper bound on the maximum ram pressure can be computed by assuming the velocity at periapsis is the maximum velocity of the asteroid during its grazing atmospheric passage. Fig. 4 shows the expected material available with orbits that could potentially be either ballistically captured or aero-captured. The maximum ram pressure has been set to the same value or lower fractions of common material strengths as in reference [20], where dustball (e.g., cometary body or rubble pile asteroid) is assumed to have a strength of order 10^6 N/m^2, stony (chondritic) asteroids of order 10^7 N/m^2 and nickel-iron asteroids of order 10^8 N/m^2. The catalogue of capturable objects, as shown in Fig. 4, are objects that have orbits such that their minimum orbital distance is smaller than $d_\oplus$.

This requirement is due to the fact that the tugboat would be able to effectively change only the phasing of the orbit, but not the geometry of the Earth encounter itself, due to the tugboat's low thrust. This distance then ensures that, provided the correct phasing, the Earth and the asteroid will meet with any required periapsis distance.

Object Phasing maneuvre

The five thickest lines in Fig. 4 represent the total amount of material available. This material has been computed by integrating the NEA population density over the volume of Keplerian element space that allows the object to satisfy the required fly-by conditions at the Earth. Thus the estimations are the statistical amount of material expected to be found. It is now required to determine the material that could actually be forced by the tugboat to meet the Earth at the encounter point, and thus proceed with the capture maneuvre. The paper has used a low thrust model that provides an estimation of the phasing capability of the tugboat at each encounter opportunity for an asteroid with a given $\{a,e,i\}$ set of Keplerian elements. A complete description of the model is given in reference [21]. Since the mean anomaly of asteroids can be well modelled as a uniformly distributed random variable, the low thrust model can provide the percentage of material from each $\{a,e,i\}$ initial orbit that can be phased with the Earth given a lead time and an asteroid size. Fig. 4 shows then also the results of the material that could be phased by the tugboat in order to provide either an aero-assisted capture or a purely ballistic capture in 5 or 20 years of lead time.
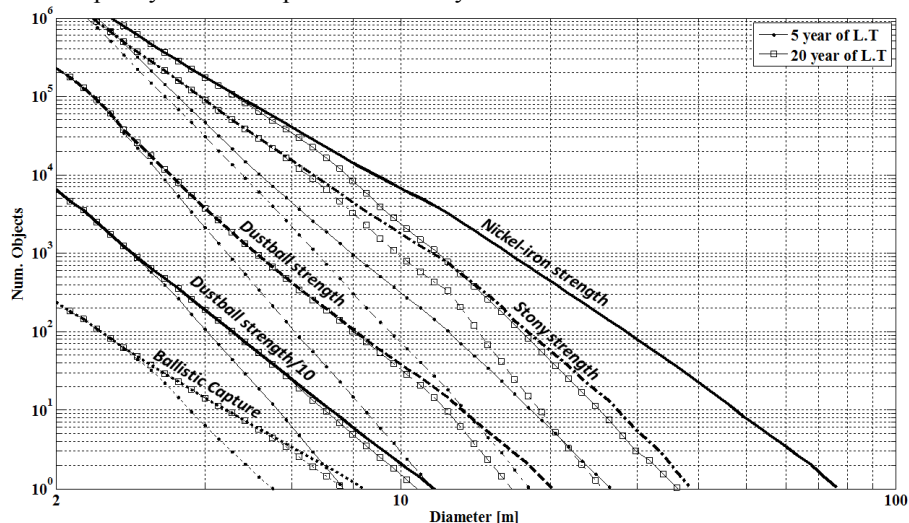

Fig. 4. Total number of available objects (i.e., statistical expectation) and capturable objects assuming a 5 and 20 years lead time for the tugboat to schedule a phasing manoeuvre.

CONCLUSIONS

This paper has demonstrated the capability of a 5-tonne low thrust tugboat system to deflect potential impact threats, but also to transport useful quantities of asteroid material to a bound Earth orbit. Such a system would require levels of investment comparable to medium-to-large current science exploration missions. It would offer complete protection against impact threats with energies lower than 10 MT, if the tugboat could be deployed at the threatening object 10 years or more before the impact (i.e., lead time longer than 10 years). With the same early deployment, the system would also offer very reasonable levels of protection against 100 MT impacts. In addition, high levels of protection are provided for 10 MT events (i.e., Airburst type like Tunguska) with shorter deployment times. The levels of protection shown, of course, assumes that the threatening objects are discovered in advance, allowing the tugboat to be launched and deployed within the required lead time.

The same tugboat system could also be used to transport small asteroids for later utilisation in Earth orbit. As shown, if the tugboat is deployed with 5 years of lead time at the target object, the largest object that can be transported back to Earth has an average diameter of 5.5 meters if a ballistic capture is intended or from 7.5 to 26 meters if aero-assisted trajectories are used instead. If the latter type of capture is intended the diameter of the largest size object depends on the level of dynamical pressure that is allowed on the object during aero-capture. In the case that the target object is known to be an M-class asteroid, large objects up to 26 meters could be captured using aero-capture trajectories that

should not fragment the asteroid. If the target asteroid is known to be a rubble-pile, diameters up to 11 meters could be captured. Lastly, objects of 7.5 meters could be captured by means of aero-capture trajectories posing dynamical pressures one order of magnitude smaller than the weakest material strength, allowing sufficient margin to avoid fragmentation. Even if these objects are relatively small, capturing an object of 5.5 meters implies a mass return between 15 and 100 times the 5 tonne tugboat mass launched to Earth escape, depending on the shape and density of the object, while a 26 meter M-class object could imply a 10,000 times mass return. This represents a very significant leverage in mass delivered to Earth escape. Importantly, such small objects would not pose any impact hazard to Earth, in case of a failed aero-capture manoeuvre. The results shown here, of course, are only statistical averages. Thus, even if no objects are known with orbits such that could they be easily captured, the analysis presented here shows that they statistically should exist and provides an order of magnitude estimate of their size.

ACKNOWLEDGEMENTS

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