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Acta Astronautica 59 (2006) 77–83

ACTA ASTRONAUTICA

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A captured asteroid : Our David’s stone for shielding earth and providing the cheapest extraterrestrial material

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Abstract

The issue of protecting the Earth against an asteroid impact is very popular and many concepts have been proposed to fulfil this objective. In this paper, we develop the idea of capturing a small size asteroid from an orbit close to Earth’s in terms of energy and placing it into a loose Earth-bound orbit in order to use it as a shield by engineering its collision with any incoming, threatening body prior to its impact with the Earth.

The operations for turning the captured asteroid into an efficient shield appear to be quicker, easier, cheaper and safer than an mission aimed at landing on an incoming impact-bound asteroid either for altering its trajectory or attempting to destroy it. The aim is an asteroid typically 20–40 m in diameter, too small to cause damage on Earth if an improper management leads to its crash, but big enough to destroy and deviate any incoming body if a collision is engineered with it preferably at more than one million km from Earth. Such a collision could be implemented within a 8 month time frame.

Such an asteroid would also be a source of material such as liquid oxygen for exploratory missions. We show that the production of this material is much more efficient from an asteroid’s surface than from the Moon’s. As the celestial surface most accessible from Earth, a captured asteroid is also easier to engineer. Several thousands of tons of oxygen might become available sitting on the outer rim of Earth’s gravity field.

We examine the advantages and drawbacks of this concept and we propose a stepped approach for making it a reality within a foreseeable future. Key factors are first the detection of a candidate, whose small size make it difficult to spot, among a population of asteroids easy to reach from the Earth. We have identified such a potential candidate in 2000SG344 and describe the parameters of its capture. The second key point is how to deviate the candidate into an loose Earth bound orbit. Our preferred concept is to deposit a small robotic instrument aimed at throwing up matter gathered on the surface of the body with typical velocities of tens of meters per second. The robot would require a year and a few hundreds of watts continuously to alter the velocity of the asteroid in such a way as to inject it through an Earth–Sun Lagrange point, and then to control a Lagrangian quasi-periodic orbit with a typical 6-month period. We conclude that such an enterprise is far from being unfeasible and that it can probably be conducted using today’s systems and exploratory tools in a few years time frame.

Many references address the threat posed by asteroids [1–3]. Although certain in the long term, such impacts are highly random in any given time frame. While celestial bodies capable of erasing almost all life forms on Earth are very rare, with a recurrence of typically 100 million years, smaller bodies capable of devastating a large city are much more likely to hit our planet within our lifetime. The radius of the asteroids we are likely to protect our planet from ranges from 30 to 100 m with probabilities of impact ranging from one every 50 years

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0094-5765/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2006.02.030

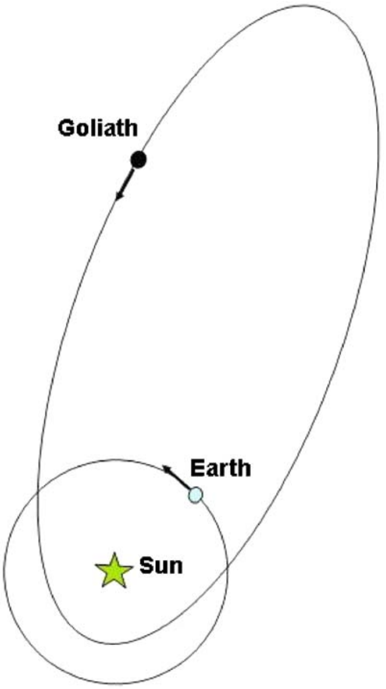

Fig. 1. Artist's impression of the relative positions of the Sun, the Earth and Goliath. The semi-major axis we imagined for Goliath is three times that of Earth, with an eccentricity of 0.8 which allows Goliath to cross Earth's orbit. The period of Goliath is 5.2 years and the modulus of the collision velocity with the Earth would be 23 km/s. It would reach 65 km/s if Goliath'orbit were retrograd.

to one every 1000 years. The associated masses range from 30 000 ton to one million tons, assuming an average density of 2000 $\mathrm{kg/m^3}$. In order to avoid falling into multiple case studies in this paper we fix the worst case parameters of the incoming body we would like to target: our threatening asteroid, called Goliath for convenience, has a diameter of 300 m and a mass of 15 million tons. Its semi major axis is three times that of the Earth, making its period in excess of five years. An eccentricity of 0.8 allows Goliath to cross Earth's orbit (Fig. 1). We assume that the threat is discovered typically 10 years before the potential impact, a performance which may not yet lie within our observational capabilities [4]. Another point of interest is the gravitational energy of Goliath, expressed as $E = 3\,GM^2/5R$ (respectively gravitational constant G, mass M and radius R), totalling only 60 MJ, representing less than 10 kg of chemical explosives.

Among the concepts proposed to avoid an impact are: landing on the incoming asteroid several years in advance of collision in order to alter its trajectory in a timely fashion or landing on the asteroid, possibly within shorter notice, and destroying it by a thermonuclear blast. Then a correct coupling of the explosive force requires it to take place underground. Another more elaborate concept is to engineer wandering asteroids in the asteroid belt in order to being able to alter their course and send them colliding with an Earth-threatening body. All these solutions demand a landing on bodies which are "far" from the Earth in terms of energy. In particular, reaching such orbits is likely to require efficient electric propulsion on a level such that space nuclear energy is the most practical technology. This situation in turn may shape the solution for altering the trajectory: in the B612 foundation [5], an efficient, nuclear-based, electric propulsion is used to reach the proper orbit and then is readily available to push the asteroid out of Earth's path. In contrast, the concept we propose involves capturing an asteroid we select on the sole criterion of being easy to access from the Earth. Because of its limited size, our asteroid is not Earth-threatening. Its trajectory does not need to intercept Earth's path. The project can be based on existing launchers and technologies.

1. The concept

Our concept is first to detect an easy-to-access asteroid, sufficiently light for us to alter its trajectory in three phases: first to capture it into an Earth-bound orbit, second to monitor and correct this orbit as a parking place, third to leave this orbit for a trajectory impacting Goliath. For a source of extraterrestrial material such as oxygen, only the first step is required. If it appears that adequate small size asteroids are currently transitioning between Earth–Sun Lagrange points, the first step may be omitted. The capture may also be regarded as a "life insurance" and be undertaken without any actual threat in order to cut considerably our time of reaction should a threat materialize quickly. As we have done for Goliath and for the sake of simplicity, we will name our small asteroid David's stone, or even more simply David. We then have a detection challenge: we seek an asteroid small enough to be manoeuvred "easily"—i.e. within a 10-year time frame and with a typical ΔV which we set at 50 m/s—while large enough to ensure the destruction or the deviation of Goliath. David must be energetically close to the Earth, which means that its initial semi major axis is close to one astronomical unit and its eccentricity as well as its inclination are small. David may be too small to be easily detected by optical means, in addition of being often in the angular vicinity of the Sun. The best way to detect efficiently such an asteroid might be by radar survey. We know the asteroid must cruise not too far from Earth, at least at some period of time. We also know that its velocity relative-to-Earth is not large, which can be specified as a Doppler offset. Despite the difficulty of detecting it, the asteroid belongs to a large population estimated to one hundred million in the inner solar system, raising hopes that many adequate bodies exist. In addition, the scenario is more acceptable politically if it cannot threaten the Earth by itself. For the sake of simplicity we fix David's main features as we have done for Goliath: It is 40 m in diameter with a mass of 40 000 ton. Following what is believed of most of the asteroids, David is a relatively loose aggregate of pebbles and has no other cohesion than the one brought by its very weak own gravitational pull. Therefore, its period of rotation cannot be less than 2 h or it would disintegrate, a condition obeyed by all asteroids, and expressed by $\Omega^2 R < GM/R^2$ (Ω being the angular velocity in Rd/s). Assuming ρ is the density of the asteroid, this equation is actually independent of R and gives: $\Omega^2 < 4\pi G\rho/3$ which corresponds to a rotation period of 2 h when $\rho = 2700\,\mathrm{kg/m^3}$. We can then assume that the peripheral velocity of David is at most less than 1 m per minute with two consequences: first in the process of altering David's course, we cannot give it more than 1 m per minute of peripheral velocity, less it disintegrates. Second, the order of magnitude of this velocity is such that we can easily change the rotation vector of David within this limit, or, in particular, stop its rotation completely if required. Of course David is neither necessarily spherical in shape, nor is Goliath. Finally, if David is to remain as a single piece, it must not come to within the Roche limit of the Earth, where the differential pull of the Earth on each side of the asteroid exceeds its own gravitational pull. The condition is expressed by: $2RGM_\mathrm{E}/D^3 < GM/R^2$ where M_E is the mass of the Earth (6×10^{24} kg) and D its distance to David. Again we can eliminate R in the expression, obtaining: $D^3 > 3M_\mathrm{E}/2\pi\rho$ The Roche limit is then about 12 000 km for likely values of ρ. We should avoid bringing David closer to Earth than the Roche limit even if the asteroid would "condense" again as it gets farther from the Earth. This is especially true if we are to continue applying slight trajectory corrections when David is at its closest point of approach in order to make the final adjustments for its collision with Goliath. We will see, however, that the Lagrangian quasi-periodic orbits followed by David in the vicinity of Earth never bring it that close to Earth.

2. Altering the trajectory of the selected asteroid in order to capture it

Several options are available to create the few tens of meters per second we allocate for long term change of the trajectory. For convenience we fix this ΔV budget to 50 m/s. Conventional propulsion leads to unrealistic masses to be brought from the Earth: using a typical solid propellant with about 3000 m/s ejection velocity, the propellant mass should be almost 700 ton, not counting the rocket case. Furthermore, even a gentle conventional rocket propulsion is likely to break apart the asteroid. Advanced propulsion such as plasma thrusters requires much less propellant mass, but a sophisticated and possibly heavy system for power generation. With an exhaust velocity V of 50 km/s, the propellant mass is still 40 ton (one-thousands of the asteroid mass), which is more feasible. However, to implement the ΔV within a year demands a continuous power supply of at least 150 kW as indicated by the following: the rate F of fuel of 1.2 g/s (40 ton in a year) must be given the velocity V with the power $P = FV^2/2$ assuming no losses. Such a power would probably have to be produced by a nuclear reactor, raising the technology challenges and the mass budget of the solution.

We favour a completely different approach. The thrust is the product of the mass ejected per second by the velocity given to this mass. Keeping this product constant, a large mass with a low ejection velocity is as efficient as a low mass with a large ejection velocity, but the former is much less demanding in energy. Assuming a small robotic catapult (Fig. 2) can collect samples from the surface of the asteroid and simply throw them into space, we might economically alter the course of the asteroid. More precisely if we set the ejection velocity of the catapult to 50 m/s (or 180 km/h or 112 mph), the "propellant" is the material of the asteroid itself. The relationship well known to rocket designers applies: $V = V_\mathrm{E} \ln(M/M_0)$ where V is the final velocity, V_E is the ejection velocity, M is the initial mass (propellant, dry mass and payload) and M_0 the remaining dry mass and payload. If, in our case, $V = V_\mathrm{E}$ then $M = 2.7183\, M_0$. The coefficient $e = 2.7183$ is such that $\ln(e) = 1$.

As a result we would throw almost two-third of the mass of the asteroid into space in the process of giving a ΔV of 50 m/s to the residual asteroid! The ejected mass amounts to 25 000 ton and the remaining mass amounts to 15 000 ton. Nevertheless, if we assume a constant power rate during a year, we come up with a reasonable requirement of 1000 W. At this stage we make several observations: first, a constant power rate implies a non-constant acceleration as the same power

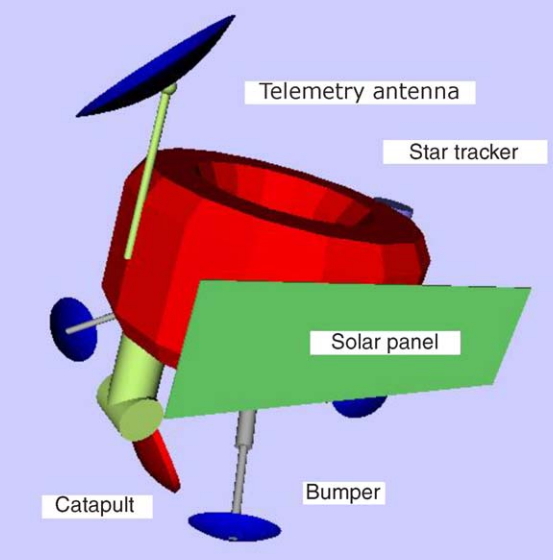

Fig. 2. Artist's impression of the robotic catapult that could be used to alter the trajectory of the asteroid it sits on. In this very preliminary sketch, the device hops on the asteroid, gathering a shovel of material while it bumps into the asteroid, then catapulting the material away and propelling itself back to the asteroid to which it transmits its impetus. A solar panel is adequate to feed the device in energy.

will be more efficient on a lighter asteroid at the end of the process. Second, this is without considering losses but these are expected to be small because converting electricity to mechanical energy can be quite efficient. Third, since the asteroid in close to Earth in terms of orbital parameters, solar arrays are a proven, reliable way of producing energy at the requested level with a typical exposed surface of a few square meters.

The main design challenge for the robotic catapult is to stay on the asteroid despite the low gravity while throwing material in the right direction. In addition the rotation of the asteroid constantly changes the orientation of the catapult, which must remain illuminated by the sun as much as possible. Without detail, the solution could consist in a hoping device which would gather dirt when it impacts the asteroid, possibly with a slight rebound. Then throwing the dirt in the right direction would give the catapult an impetus toward the asteroid which would be transferred to it by the next contact. In doing this the catapult could hop in order to compensate for the very slow rotation of the asteroid while taking care of maintaining the average torque delivered to the asteroid close to zero. The displacement of the catapult would also allow it to change the places where it collects ground material. The catapult could feature a stellar sensor to maintain attitude and any kind of radio transmitter that would allow an accurate determination of velocities and positions from the Earth, possibly by very large base interferometer (VLBI). It is expected that after several months of operation the centre of gravity, the mass and the inertia of the asteroid would be monitored very precisely as they continuously change. The thrust delivery is unusually accurate because if the system is capable of delivering at most 1 m/s in a week, it amounts to only about 6 mm/s/h. If we assume a rate of about 800 g/s (or 25 000 ton a year) and a launch every 3 s, the 6 mm/s will probably be obtained by more than 1000 launches. So even if the impetus delivered by an individual launch is known only within 10%, an unlikely uncertainty, the result over an hour would be known within 0.3% (i.e. to within $20\,\mu/\mathrm{s}$). The individual velocity change delivered by a single launch would not exceed $8\,\mu/\mathrm{s}$ even when the asteroid is the lightest (15 000 ton).

Given the features of Goliath, it will collide with the 1000-fold lighter David at 23 km/s, generating 4×10^{15} J (the destructive power of 40 Hiroshima bombs). The resulting pull applied to Goliath will be on the order of 25 m/s, hardly enough to make it miss the Earth unless the collision takes place at least 10 days before impact, more than 20 million km away. However, a perfect distribution of this energy, delivered at the core of Goliath and much larger than its gravitational stability, corresponds to a random, quadratic velocity of Goliath's debris of more than 700 m/s. Therefore, 90% of the debris would miss the Earth as soon as the collision takes place at least 500 000 km away from the Earth (more than the distance of the Moon). The remaining 10% or less would be stopped by the atmosphere if they do not exceed a few meters in diameter. It is unlikely that this event would increase the population of space debris since all the pieces have velocities in excess of Earth's liberation velocity, and can only hit or run. Actually our asteroid's energy could break up much larger bodies and, for instance, matches the gravitational energy of a comet nucleus approaching at 20 km/s (5 km radius, density of $1000\,\mathrm{kg/m^3}$).

A simple way to enhance the destructive power of David would be to deposit a thermonuclear device on it, located at the predicted point of impact of Goliath. If triggered a split second before collision, the bomb will detonate exactly between the masses of David and Goliath, ensuring a very efficient coupling without the complexity of burying the bomb typical of most "nuclear" scenarios. In our example, a 10 Mton device would multiply by 25 the energy delivered and by 5 the mean quadratic velocity of the debris.

3. Available options for trajectories

Three options of Earth bounded orbits have been considered for David orbital scenario: high Earth orbits, quasi-periodic orbits around the Earth–Moon Lagrangian points and quasi-periodic orbits around the Sun–Earth collinear points L1 and L2. The L1, L2 Sun–Earth lagrangian points scenario appear to be the best option to park David. Their high distance from Earth (1.5 million kilometres) eliminates hazards of collision with the Earth in case of a management failure. they are also the easiest accessible location for near Earth objects (NEO) that could be captured. In the same time, a David asteroid parked at L1 or L2 Sun–Earth Lagrangian point offers a large coverage of the potential impacting zone and thus constitutes an efficient shield against any asteroid threat as we will see. In this option David orbital scenario would be divided into three parts:

3.1. The capture phase

The capture phase is certainly the most spectacular and probably the most challenging. The aim of this phase is to perform the transfer of a NEO from its heliocentric orbit to the stable manifold of a periodic orbit around L1 or L2 [6,7] and then let it derive to a targeted Lissajous or Halo orbit. But to compute the stable manifolds of periodic orbits as far as several tenths of AU is a very challenging task and to compare the result to NEO trajectories databases is a huge work.

Table 1
Keplerian elements of asteroid 2000SG344 at epoch 53 600 of 2000SG344

	Element value	$1-\sigma$ variation
a (AU)	0.977369	7.435e − 07
Eccentricity	0.066934	3.956e − 06
Inclination (deg)	0.11	8.667e − 06
Asc. node (deg)	192.335	0.001636
Arg. perih. (deg)	274.895	0.001726
M (deg)	288.376	0.002134

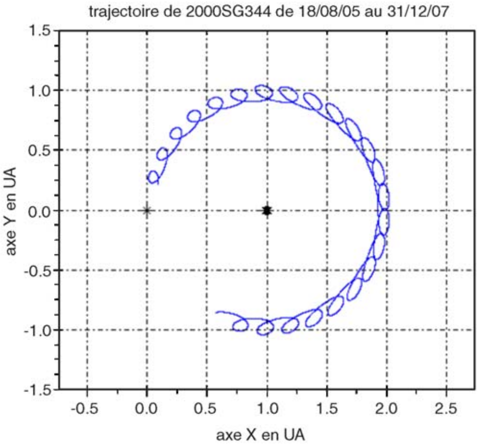

Fig. 3. Trajectory of asteroid from 2005 to 2027, until the manoeuvre of its insertion and escape from L2 in synodic reference frame (Sun and Earth sit motionless while the relative trajectory of 2000SG344 is shown, scales are in astronomical units).

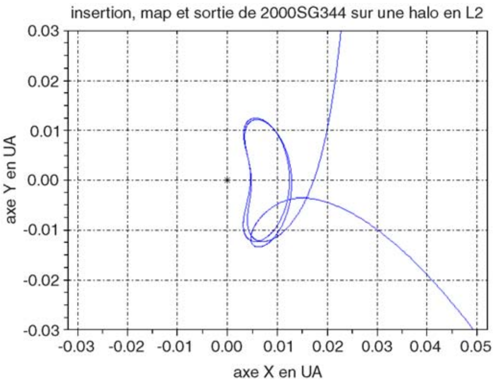

Fig. 4. Zoom of L2 region showing the capture and escape sequence in the vicinity of the Earth. Scales are in astronomical units.

Fortunately, one of the biggest question mark in our study—namely the existence of adequate NEO—has been lifted after we identified a good candidate for David, labelled 2000SG344 [8], that we have managed to capture around L2 on a high time range simulation. 2000SG344 has two very helpful features for its capture: first its orbital energy is very close to orbital energies of quasi-periodic orbits around L1 and L2 and second its orbit inclination is very low which make easier and cheaper the injection on the stable manifold of L1 or L2. Table 1 show its osculating keplerian elements. The capture of 2000SG344 (shown on Fig. 3) is consequently relatively easy to perform when it cruises very close to the Earth around 2029. In the case shown on Fig. 3, the first point is an extrapolated position of 2000SG344 at the 31st of December 2027. It has been computed with an analytical theory, in a perturbed environment with the nine planets of the solar system and without any manoeuvres. On the year 2028, a global ΔV of 54.8 m/s enable the injection of 2000SG344 in the Lagrangian corridor of the Earth. In the corridor the asteroid never get closer to the Earth than 102 800 km, meanwhile, it goes in the very close vicinity of L2 (less than 75 000 km). In the vicinity of L2, at less than 200 000 km (Fig. 4), the trajectory presents two positions where the unstable eigenvector of 2000SG344 motion could be nulled with a ΔV lower than 0.8 m/s. These two points are two options (nominal and backup) for starting the station keeping phase by a low cost insertion on a Lissajous orbit around L2. Regarding the resulting small ΔV cost ($< 56\,\mathrm{m/s}$), this simulated example of capture of an existing NEO may be considered as a proof of the feasibility of the capture phase. Moreover, considering the supposedly high number of small size NEO with a diameter lower than 50 m, there is a high probability that bodies even easier to capture may orbit on trajectories close to the one of 2000SG344. With an estimated diameter of 20–70 m, 2000SG344 is an acceptable, but probably slightly oversized David. We are currently refining the scenario of capture [9].

3.2. The station keeping phase

The station keeping phase does not seem to be critical from an astrodynamical point of view [10]. Indeed, considering the well known "escape direction" method, the station keeping in the vicinity of L1 or L2 would cost a few m/s per year as long as manoeuvres are performed with an accuracy of 1 cm/s to a tenth of cm/s and these two majors constraints of the method are largely fulfilled by the foreseen robot in charge of David management.

3.3. The shield management phase

On station at L1 or L2, David would ensure a high protection capability thanks to the large area it can patrol. Indeed, as it is shown on Fig. 5, thanks to heteroclinic connections between the unstable manifold of a Lagrangian point and the stable one of the other [11], David could switch from a periodic orbit around L1 to a periodic orbit around L2 in several month (roughly 8 months) and access all around the Earth through the manifolds. In the orthogonal direction of the ecliptic plane the manifold can get to an amplitude bigger than 200 000 km. With a typical half width of 500 000 km in the ecliptic plane the connected four manifolds of L1 and L2 points deploy a donut shaped shield all around the Earth in the ecliptic plane and up to 21.8° of declination on each side of the ecliptic plane. Except around the ecliptic poles, the Earth would be protected from incoming threatening bodies with a reaction time of about 8 months. With such a short time response the critical impacting trajectory accuracy requirements are lowered.

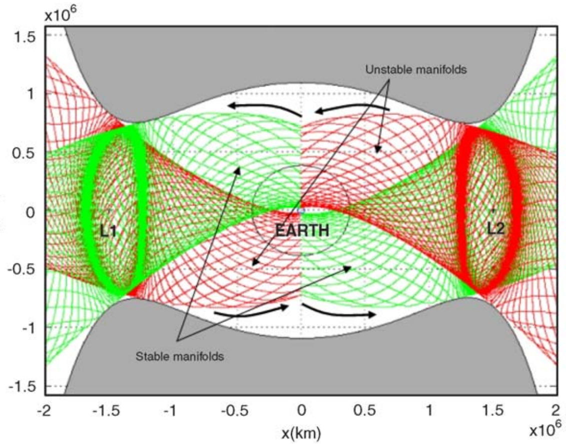

Fig. 5. Illustration of the manifold. Scales are in million km.

4. Synergetic use for space exploration

The concept of asteroid capture may contribute to exploratory missions. Such missions require the launch of a large mass, mainly made of propellants, into trajectories whose first step is the liberation from earth gravity. The idea of producing part of this propellant mass in situ is very attractive. The Moon is a very natural target for in situ production because the cost of putting Moon-produced material into Earth escape trajectories (EET) corresponds to a ΔV of roughly 2.8 km/s against 11.2 km/s in the case of Earth. Similarly, the surface of Mars or the surface of Phobos can be envisioned as in situ sources of propellant or other materials. However, even the moderate ΔV required to lift the material from the Moon into an EET is a serious limitation to the usefulness of the process. Even using advanced propellants such as (H_2–O_2) leads to a significant cost as shown be this numerical example: Lifting 10 ton of Moon-produced O_2 into an EET typically requires 1 ton of dry mass plus 9 ton of (H_2–O_2), of which 1 ton of H_2. Therefore, in the most optimistic scheme, 2 ton coming from the Earth (the dry mass and the amount of H_2) will be combined to 18 ton of Moon-produced liquid oxygen and will result in 10 ton of it placed into an EET. The effort of landing 2 ton to the surface of the Moon corresponds roughly to bringing 4 ton directly onto an EET without lunar insertion and landing. Therefore, the advantage of the process is on the order of a factor two at best. The same applies for materials aimed at other purposes, such as mass used for shielding astronauts against cosmic radiations.

An asteroid placed on a Lagrange parking orbit is virtually on an EET. If a proper apparatus is placed in the vicinity of the asteroid, it could produce a large mass of liquid oxygen in a few years time frame assuming reasonably that most of the asteroid is made of oxides.

This oxygen could then be loaded into the tanks of a planetary mission which would first reach an EET toward this Lagrangian gas station and then come back close to the Earth, still on an EET, in the proper position for its final acceleration to a planetary trajectory. If a chemical propulsion is used for the exploration of Mars, up to 80% of the mass of the mission could be liquid oxygen, thus offering a similar gain in heavy lifting requirements. The 240-day or so detour to the asteroid does not necessarily apply to the exploration crew which could join the spacecraft when it grazes Earth again on its way back. If necessary, a different crew could manage the refill and enter the earth atmosphere directly on the way back from the asteroid. The cost in ΔV would virtually be zero.

Finally, the initial investment of bringing the apparatus required for such a production from Earth is half the effort required for putting the same apparatus on the Moon in terms of mass, just because there is no need of lunar insertion nor landing.

5. Advantages and drawbacks, conclusion

We expect a number of advantages and drawbacks to result from the proposed concept. Among the drawbacks we have the severe requirement on the accuracy in the knowledge of the impact parameters. This is somewhat attenuated by the step by step procedure which can start with a relatively modest accuracy leading to a rough correction parameters, to be refined as the collision time nears. Another drawback is in the principle of prior collision, which may not prevent some debris of Goliath from hitting the Earth. Finally, using the "throwing pebble catapult" might generate space debris, although few in Earth orbit.

The advantages clearly outweigh the drawbacks: there is no need for deep space, high energy missions: the selected asteroid can be reached in a few months with a modest payload and uses conventional launchers and mature solar arrays for energy. Most importantly, the features of the incoming body may remain uncertain for a long time as the preparation is independent. If the final analysis shows that the threat will miss the Earth, we just cancel the collision. If the asteroid is positioned in advance, the reaction time might be as short as 6 or 8 months. Our scenario is probably the only one that could deal with a short notice threat such as brought by a comet nucleus. Some complex tasks for engineering the asteroid might also be envisioned using manned missions with a typical duration of less than a year, for using the captured asteroid to other purposes, such as contributing to more than 80% of mass required for a mission to Mars based on chemical propellants. Of course once we have succeeded in capturing an asteroid, we can continue and capture more asteroids, multiplying the possibilities of interception and increasing the amount of available materials.

Nothing in the scenario is really far fetched. The main points to be developed is our capacity to spot smaller threatening bodies in the solar system and even smaller bodies in the vicinity of Earth. Progress in our knowledge of the mechanical properties of the material of asteroid are expected in the coming years. A specific effort in space robotics as well as a specific development for the catapult have to be undertaken.

Such an asteroid capture would be one of the most remarkable achievements of mankind. It would provide us with a David's stone against the potentially destructive giants which cruise above our heads. It could also be a very effective help in the design of exploratory missions.

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