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EARTH DELIVERY OF A SMALL NEO WITH AN ION BEAM SHEPHERD

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The possibility of capturing a small Near Earth Asteroid (NEA) and delivering it to the vicinity of the Earth has been recently explored by different authors. The key advantage would be to allow a cheap and quick access to the NEA for science, resource utilization and other purposes. Among the different challenges related to this operation stands the difficulty of robotically capturing the object, whose composition and dynamical state could be problematic. In order to simplify the capture operation we propose the use of a collimated ion beam ejected from a hovering spacecraft in order to maneuver the object without direct physical contact. The feasibility of a possible asteroid retrieval mission is evaluated.

INTRODUCTION

The number of near Earth asteroids rises steeply with decreasing diameter, with a size distribution roughly following a power law. This implies that as ground-based observation capability improves the detected number of very small asteroids will rise sharply in the future providing more targets accessible from Earth with very low ΔV, hence allowing cheaper asteroid rendezvous missions. On the other hand, when the asteroid size goes down to a few meters in diameter another interesting possibility opens up: the asteroid itself, whose mass is large but not overwhelming, can be moved and delivered to Earth orbit for subsequent scientific exploration, resource utilization, and, possibly, human missions. Researchers from China[1] and the U.S.[2] have already started to assess the feasibility of such a concept.

The approach followed by the first reference[1] consists of impacting at very high relative velocity (~60 km/s) with a massive spacecraft (~26 tons) against a small 10-m size asteroid transiting inside the Sun-Earth Hill sphere in such a way to instantaneously modify the asteroid Jacobi constant and close the boundaries of the forbidden region around an oval surrounding the Earth. Apart from the formidable difficulty (and cost) of impacting a multi-ton spacecraft at such a high speed with such a small object a more basic problem is the fact that it is extremely unlikely such a small asteroid can survive even an order of magnitude smaller impact energy without being completely obliterated.[3] A much more realistic solution was recently put forward by Brophy et al.,[2] who propose to send a spacecraft to rendezvous with a hypothetical 2-m diameter object, place it in a large canister, despin it with hydrazine thrusters, and deliver it to Earth orbit following an optimized low-thrust interplanetary trajectory employing a lunar swing-by for the final capturing in high Earth orbit. A deorbit maneuver was proposed to subsequently deliver the "bagged" asteroid to the international space station. One of the major difficulty of this approach is perhaps the need to deploy a somewhat

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large canister and close it around the object in a safe manner before starting a despin maneuver. In addition, the attitude stabilization of the despun asteroid during the interplanetary trajectory may be problematic.

Recently, our group has explored the possibility of using a collimated ion beam to deflect the trajectory of an Earth-threatening asteroid.[4,5] The beam would be ejected from the electric propulsion system of a spacecraft (shepherd) hovering in the vicinity of the asteroid, and the momentum transmitted to the asteroid would be roughly equal to the thrust provided by the same propulsion system to the shepherd spacecraft. The advantage of the method comes from its "contactless" nature allowing to bypass all issues related to the interaction with an unknown object. Small asteroids are very often fast rotators and attaching any kind of artificial device to their surface can be a daunting task.

The present article explores the feasibility of using an IBS for the contactless delivery of very small objects in the Earth vicinity. The focus here is not much in the details of the IBS-asteroid interaction but rather on the trajectory design and the choice of an appropriate target. The idea is to pick an Arjuna asteroid, that is, a low-eccentricity low-inclination asteroid with semimajor axis close to one astronomical unit, and modify its trajectory in order to *induce a prolonged quasi-satellite motion.* Transitions to quasi-satellite states of horseshoe asteroids have occurred in the past and will in the future for the case of a few known asteroids.[6,7] Such transitions can last several years.

The advantage of having an asteroid enter such a state can be considerable. First of all it could allow cheaper and repeated visiting missions to the NEO with larger payload and possibly robots and humans. Launch windows constraints and flight duration issues, often decisive factors for human missions, could be relaxed substantially. In addition, because during such transition the asteroid can approach and occasionally enter the Sun-Earth Hill sphere with relatively small Earth binding energy, it may be possible to gently perturb its trajectory and finally capture it in a highly elliptical orbit around the Earth. More advanced low ΔV transfer methods exploiting weak stability boundaries may also employ a quasi-satellite phase as starting point.

After introducing the ion beam shepherd concept and giving an example of natural quasi-satellite motion we perform a survey of the population of very small NEOs (visual magnitude H>28) to select objects whose trajectory can be modified until Earth capture with a reasonable amount of propellant mass and total thrust duration. An extensive 3-dimensional search is performed considering a constant tangential thrust maneuver of varying magnitude and duration applied to a number of candidate objects and recording the duration of the asteroid motion in the vicinity of the Earth. The best results found are reported and discussed.

MOVING AN ASTEROID WITH AN IBS

The ion beam shepherd concept (IBS) proposes a novel use of space electric propulsion in which the plasma accelerated by an ion thruster (or similar plasma propulsion device) is directed against the surface of a target object to exert a force (and a torque) upon the target from a distance of a few times its size. One of the its most promising applications is the deflection of Earth-threatening asteroids (Fig.1) as recently proposed.[4,5] In a typical asteroid deflection mission employing this technology a "shepherd spacecraft" rendezvous with the target asteroid sufficiently early in time before a predicted impact, and position itself at a safe hovering distance from the asteroid surface towards which one (or multiple) electric propulsion thruster(s) are aimed. Ideally the shepherd

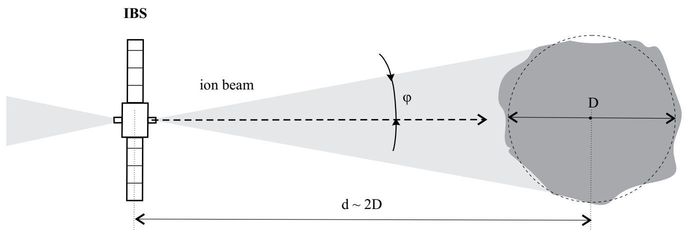

Figure 1. Asteroid ion beam shepherd concept (IBS)

should be placed as further away as possible from the surface (to avoid the unstable interaction with the asteroid gravitational field as well as reduce collision risks) but without exceeding a limit distance at which a considerable fraction of the thruster plasma plume misses the asteroid (due to plume divergence effects). As long as the ion beam emitted by the thruster(s) is correctly pointed at the target a deflection force arises from the variation of momentum of the plasma ions (typically xenon) impacting against the surface of the object and penetrating its outermost layers before being stopped. An essential element of the IBS is then the presence of a secondary propulsion system that compensates for the reaction force that the ion beam exerts on the shepherd and that would make it accelerate away from the asteroid.

This simple idea can be used to remotely maneuver objects in space without physical contact (docking) and has also been proposed for the active removal of space debris.[8] Similarly to space debris, asteroids can be problematic to attach to as they are typically in a spin state which, in addition to complicate a docking maneuver, constraints the direction of the thrust hence diminishing its effectiveness in deflecting the celestial body. Furthermore, many asteroids, even relatively small ones, are unconsolidated bodies (rubble piles) held together only by gravity and friction, which complicates the mechanical transmission of even a tiny deflection force.

As far as deflection performance the IBS has been compared to the gravity tractor concept (GT), a well known "contactless" deflection technique exploiting the spacecraft-asteroid gravitational interaction. It has been shown that, in the case of sub-kilometer asteroids, more than an order of magnitude decrease in required spacecraft wet mass at rendezvous can be obtained with an IBS of equal deflection capability.[4,5] IBS deflection simulations with real asteroids have also be carried out showing that an IBS of reasonable mass (<5 tons) could deflect a typical 140-m diameter Earth-approaching asteroid (e.g. $2009\mathrm{AG}_5$) by more than 2 Earth radii when the deflection maneuver is initiated ten years before the predicted impact.[5]

NATURAL EARTH QUASI-SATELLITES

A number of asteroids has experienced or will enter a quasi-satellite (QS) phase in the future. Apart from the known cases listed in the literature[6] such as $2002\mathrm{AA}_{29}$ and $2003\mathrm{YN}_{107}$, going through a relatively large QS motion, other cases can be found. We have performed extended simulations with a high-fidelity in-house propagator* focusing on small NEOs (visual magnitude H>28) to detect quasi-satellite motion in the next 50 years. A few cases were detected. Remarkably,

*We have employed a 14th order Runge-Kutta integrator including the gravitational perturbation from all planets, Pluto and the three major asteroids, as well as relativistic effects and the solar gravitational J2 term. JPL ephemerides DE405 were employed.

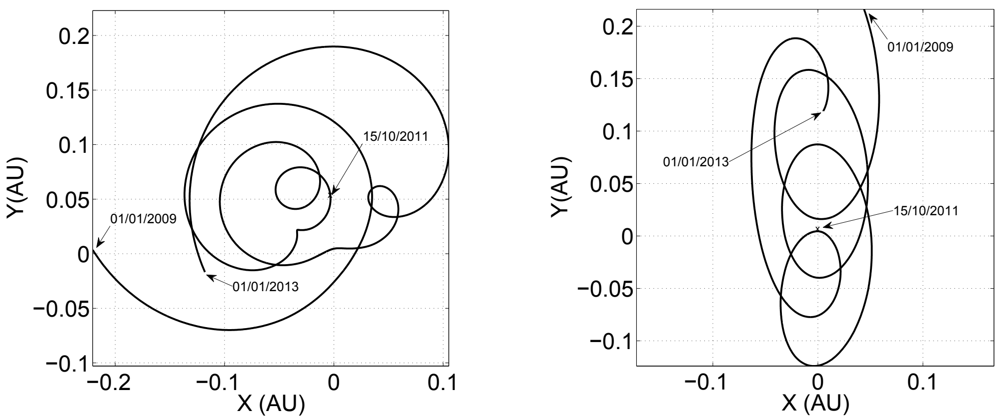

Figure 2. Quasi-satellite motion of asteroid $2011\mathrm{UD}_{21}$ in the years 2009-2013 plotted in Earth-centered inertial (left) and synodic axes(right).

the small asteroid $2011\mathrm{UD}_{21}$ is currently a quasi-satellite of the Earth and will remain as such until the end of this year (Fig.2).

INDUCING QUASI-SATELLITE MOTION

An extended numerical simulation campaign has been carried out to verify the possibility of extending the duration of an existing quasi-satellite state or inducing a new one. For this preliminary study, simulations were carried out considering a constant tangential thrust strategy applied continuously over an interval of variable length starting on January 1st 2020. Different thrust magnitudes were also considered and ranging from -1 to +1 N. Finally a number of selected small NEOs, typically less than 10 meters in diameter, were taken as candidate targets.

A relatively large set of QS encounters could be obtained. However, only in a reduced number of cases the QS phase was seen to be robust enough against small numerical integration or initial condition errors. The best solutions in this regard are reported below.

1991VG

With a visual magnitude H=28.39 and assuming a geometric albedo of 0.16 and a density of 2.0 $\mathrm{kg/cm}^3$ asteroid 1991 VG can be modeled as a sphere of 7 m diameter and weighting 360 tons. By applying a constant tangential thrust of -430.6 mN from Julian date JD=2458849.5 (January 1 2020) until JD=2460019.5 (March 16 2023) the asteroid can be trapped in a quasi-satellite state during the years 2042-49. Figures 3-5 describe the asteroid QS motion in both synodic and inertial axes. The QS behavior could be reproduced with two different integration tolerances differing by 4 orders of magnitudes, which confirms that the solution is robust and reproducible.

$2010\mathrm{VQ}_{98}$

Asteroid $2010\mathrm{VQ}_{98}$ is characterized by a visual magnitude H=28.2. Taking the same geometric albedo and density values of the previous case this corresponds to a 7.6-meter 460-ton asteroid . By applying a constant tangential thrust of -587.6 mN from Julian date JD=2458849.5 (January 1

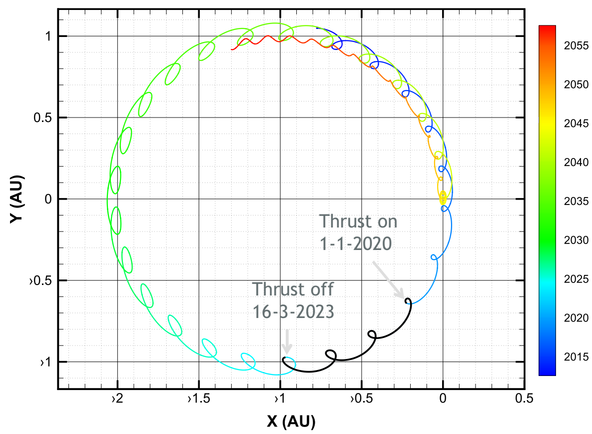

Figure 3. Induced quasi-satellite motion of asteroid 1991VG **in synodic axes.**

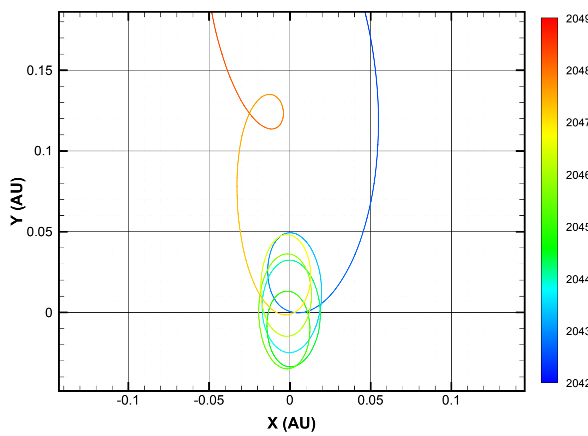

Figure 4. Close-up of figure 3.

2020) until JD=2459959.5 (January 15 2023) the asteroid can be trapped in a quasi-satellite state during the years 2042-49. Figures 6-8 describe the asteroid QS motion in both synodic and inertial axes. As in the previous case The QS behavior could be reproduced with two different integration tolerances.

CONCLUSIONS AND RECOMMENDATIONS

A new strategy to allow the delivery of small asteroids in the vicinity of the Earth based on the ion beam shepherd concept has been proposed. It is seen that some small Arjuna asteroids can be forced into a quasi-satellite state of a few years with a continuous low thrust maneuver of relatively small magnitude (<500 mN) and reasonable duration (~3 years). It should be underlined that no attempts were made so far to optimize the asteroid deflection strategy in order to bring it to a QS state with minimum fuel expenditures, something that will need to be look at in future studies. Moreover,

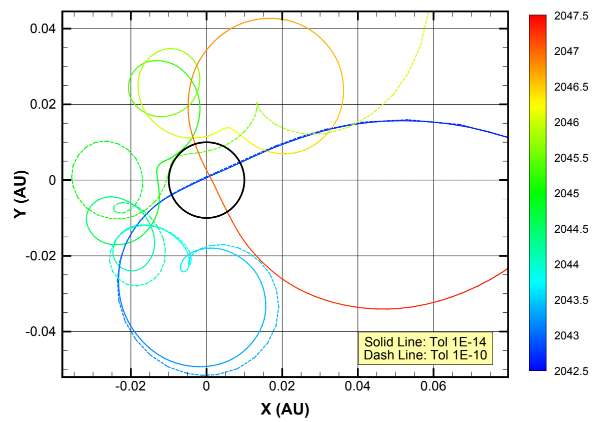

Figure 5. Induced quasi-satellite motion of asteroid 1991VG **in inertial axes. The trajectory propagation has been performed with two different numerical tolerances to check its robustness. Hill's sphere (dark) is added for comparison.**

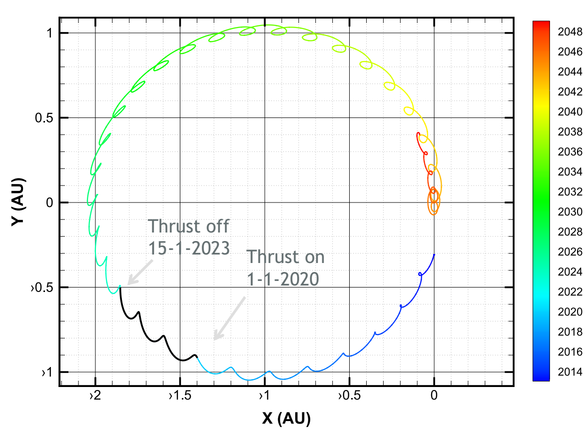

Figure 6. Induced quasi-satellite motion of asteroid $2010VQ_{98}$ **in synodic axes.**

before investigating possible ways to transfer the asteroid to a high Earth orbit, more work will be required to address the sensitivity of the quasi-satellite state duration to small variations in the nominal thrust level.

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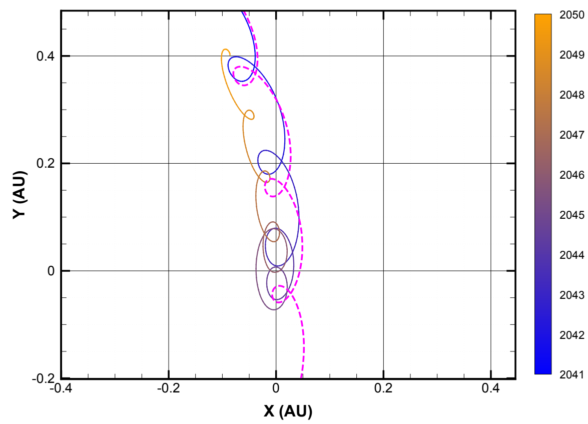

Figure 7. Close-up of figure 6. The dash-line represents the unperturbed asteroid trajectory.

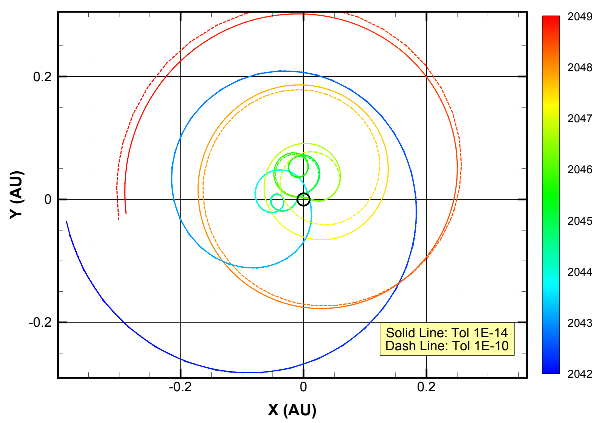

Figure 8. Induced quasi-satellite motion of asteroid $2010\mathrm{VQ}_{98}$ in inertial axes. The trajectory propagation has been performed with two different numerical tolerances to check its robustness.

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