ELECTROSTATIC TRACTOR FOR NEAR EARTH OBJECT DEFLECTION

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Abstract

This paper contains a preliminary analysis on the possibility of changing the orbit of an asteroid by means of what is here defined as an "Electrostatic Tractor". The Electrostatic Tractor is a spacecraft that controls a mutual electrostatic interaction with an asteroid and uses it to slowly accelerate the asteroid towards or away from the hovering spacecraft. This concept shares a number of features with the Gravity Tractor but the electrostatic interaction adds a further degree of freedom adding flexibility and controllability. Particular attention is here paid to the correct evaluation of the magnitudes of the forces involved. The turning point method is used to model the response of the plasma environment. The issues related to the possibility of maintaining a suitable voltage level on the asteroid are discussed briefly. We conclude that the Electrostatic Tractor can be an attractive option to change the orbit of small asteroids in the $100m$ diameter range should voltage levels of $20kV$ be maintained continuously in both the asteroid and the spacecraft.

INTRODUCTION

The possibility of altering the orbital elements of an asteroid has been discussed in recent years both in connection to Near Earth Object (NEO) hazard mitigation techniques (asteroid deflection) [1] and to the more far-fetched concept of capturing an asteroid into the Earth's gravity field [2][3] for exploitation purposes. Techniques such as kinetic impactors [4], nuclear blasts [5] or gravity tractors [6] seem to be options that have the technological maturity level to be implemented in the short term. The gravity tractor concept [6] has, in particular, been quite popular in recent literature [7][8][9] as it offers the possibility of obtaining a gradual and very controllable change of the asteroid orbit.

The concept of a Gravity Tractor was first introduced by Lu and Love [6]. In their work, the spacecraft would modify the asteroid trajectory by hovering alongside the asteroid, in static equilibrium, with its thrusters angled outwards preventing the exhaust plumes from impinging on the asteroid surface. In case of exahust impingement on the NEO surface no mass would escape and therefore no momentum would be transferred and the centre of mass of the system would be unaltered. In the original paper by Lu and Love [6] a deflection of a 200m asteroid using a 20 ton Gravitational Tractor is taken as a reference scenario and a lead time of 20 years is derived to be necessary.

Schweickart et al. [8] further considered the Gravity Tractor for the specific test cases of 99942 Apophis and 2004VD17. They found that a 1 metric ton Gravity Tractor powered by solar electric propulsion is capable of meeting the deflection challenge posed by these two NEOs. McInnes [9] demonstrated, from first principles, that displaced, highly non-Keplerian (halo) orbits could, in certain circumstances, provide a more effective use of the gravitational coupling to modify asteroid orbits. This is because there is not always a need to cant the spacecraft thrusters in a halo orbit and therefore the displaced non-Keplarian orbits can allow the same NEO deflection to be obtained with a smaller thrust magnitude. The gravitational coupling between the asteroid and the spacecraft allows for this deflection technique, but it also represents a limit as it constrains the choice of the hovering altitude or of the Halo orbit and ultimately of the spacecraft mass.

The idea behind the gravity tractor is that of establishing an invisible "tractor beam" between the spacecraft and the asteroid exploiting their mutual gravitational interaction. It turns out that, for a certain asteroid mass, this is just of the right order of magnitude to provide an effective deflection force. Being based on mutual gravity, such a technique is not very useful for small asteroids (gravitational field is not strong enough) or for high deflection efforts (force required is too high). To investigate how to remove these limitations, we consider the possibility of establishing such an invisible tractor beam artificially, using forces other than gravity and in particular electrostatic forces.

The outline of the paper is as follows. We start by introducing the deflection graphs as a tool to evaluate the danger of a given deflection scenario. From the deflection graphs we argue that the maximum force applicable to the asteroid by a given deflection strategy is a measure of its efficiency. Thus we concentrate, in the rest of the paper, in the evaluation of such a maximum force in case of the Electrostatic Tractor concept. Great care is taken to correctly model the plasma environment. Laplace and Debye-Hückel approximations are not used and are indeed shown to be unsuitable to evaluate Coulomb forces in an interplanetary space plasma.

ASSESSING A DEFLECTION STRATEGY

All deflection strategies that do not aim at breaking up the asteroid are necessarily based on imparting, by any means, an acceleration to the asteroid center of mass. These types of strategies are here called "soft" to distinguish them from the "hard" deflection strategies aiming at the asteroid fragmentation. The acceleration imparted by soft deflection strategies can be impulsive, e.g. in the case of kinetic impactors, or continuous. In both cases, the amount of deflection achieved can be evaluated using the asteroid deflection formula [10] accounting for the induced asteroid phase shift:

$$\Delta\zeta = \frac{3a}{\mu} v_E \sin\theta \int_0^{t_p} (t_s - \tau)\mathbf{v}_{ast}(\tau) \cdot \mathbf{A}(\tau) d\tau$$

where $\Delta\zeta$ is the amount of deflection achieved in the b-plane, a is the asteroid semi-major axis, v_E is the velocity of the Earth at the encounter, θ is the angle between the asteroid velocity relative to the Earth at encounter and the Earth velocity at encounter, $\mathbf{A}(\tau)$ is the deflection action (i.e. the acceleration imparted to the asteroid by the deflection strategy), t_p is the push time (i.e. the duration of the deflection action), t_s is the lead-time, that is the time to encounter when the deflection start and $\mathbf{v}_{ast}(\tau)$ is the asteroid velocity. The coefficient $\frac{3a}{\mu} v_E \sin\theta$ accounts for the geometry of the asteroid encounter with the Earth. Such a coefficient, having the inverse dimensions of a velocity, is a first measure on how responsive a collision scenario is to soft deflection techniques aiming at changing the asteroid phase. Small magnitudes of the θ angle are, in particular, associated to head-on encounters between the Earth and an asteroid. A situation in which the phase shift of the asteroid represent an inefficient strategy. Note that neglecting the $\sin\theta$ term, as often done in back of the envelop calculations, may result in a significant overestimation of the deflection obtained. A straight forward use of the asteroid deflection formula helds the asteroid deflection charts introduced in [11], i.e. t_p, t_s plots of the maximum deflection achievable by continuously applying 1N force to the asteroid. Figures 1 and 2 show two of such deflection charts for two asteroids that had quite some attention in the recent past.

The asteroid 2007 VK184 close encounter with our planet in June 2048 is currently associated with a significant chance of impact, to the extent that, as of 27th August 2008, in the Torino risk scale [12] the asteroid is the only one in the entire NEO population rated 1. The relevant parameters used to plot the deflection chart for 2007 VK184 are $a_{VK} = 1.72AU$, $e_{VK} = 0.57$, $M_{VK} = 3.3e09$ kg and $\nu_{VK} = 4.93$ rad, where a is the semi-major axis, e the eccentricity, M the mass and ν the true anomaly along the asteroid orbit of the Earth encounter. Similarly, in the case of the 2029 Apophis encounter, we have

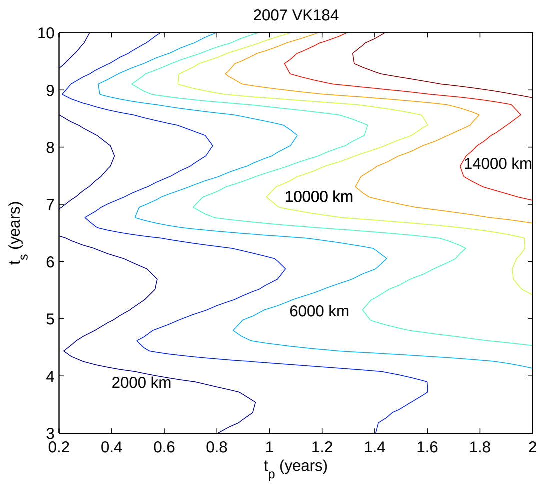

Figure 1: Deflection chart for the asteroid 2007 VK184 close encounter in June 2048

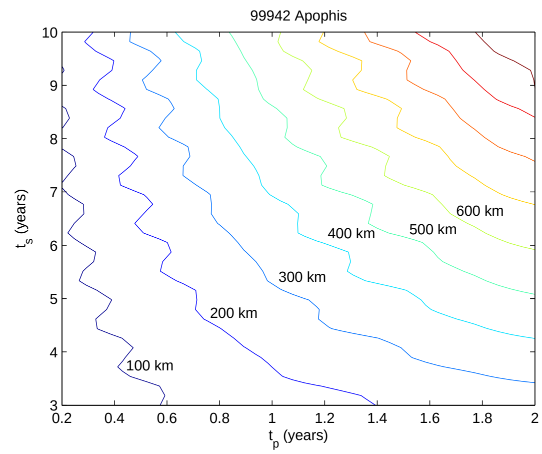

Figure 2: Deflection chart for the asteroid 99942 Apophis close encounter of 2029

$a_{AP} = 0.922AU$, $e_{AP} = 0.191$, $M_{AP} = 4.6e10$ kg and $\nu_{AP} = 5.43$ rad. The amount of deflection achievable is, in general, larger in the case of 2007 VK184 due to its smaller mass. Note that the other relevant quantity, the amount of deflection needed, depends on the accuracy of the observations and on whether we are considering a pre-keyhole deflection or not.

For any deflection strategy, the deflection chart returns an upper bound of the deflection achievable by multiplying the number obtained from the chart by the maximum force we can apply to the asteroid using the deflection strategy considered. This straight forward result allows us to consider the evaluation of this maximum force as the primary task in the assessment of any soft deflection strategy.

THE ELECTROSTATIC TRACTOR

Similarly to the gravity tractor [6], the Electrostatic Tractor introduced here exploits the mutual interaction between a hovering spacecraft and an asteroid to achieve the required deflection. The interaction is considered to be the sum of gravitational and electrostatic forces, the latter being relevant as some form of charge control is assumed on board the spacecraft and the asteroid is assumed to be charged to a given level. As shown in Figures 4 and 5, the total resulting force can be pushing or pulling the asteroid, depending on the charge polarities.

The efficacy of this deflection concept depends entirely on the amount of electrostatic force that can be established artificially between a spacecraft and an asteroid, therefore ultimately on the amount of charge we are able to maintain on both. We thus briefly discuss the issues connected with spacecraft and asteroid charging.

Charging a spacecraft

A conductive body in space, e.g. a spacecraft, becomes naturally charged as a result of the ambient space plasma and the solar extreme ultraviolet (EUV) [13] which causes the emission of photoelectrons via the photoelectric effect. Typically, a spacecraft operating in this environment will accumulate charge until an equilibrium is reached (floating potential, typically varying from -1 kV to +20 V on a geostationary or a polar orbiting spacecraft) in which the net current is zero. By artificially emitting ions or electrons from the spacecraft, such an equilibrium potential can be controlled as the unique

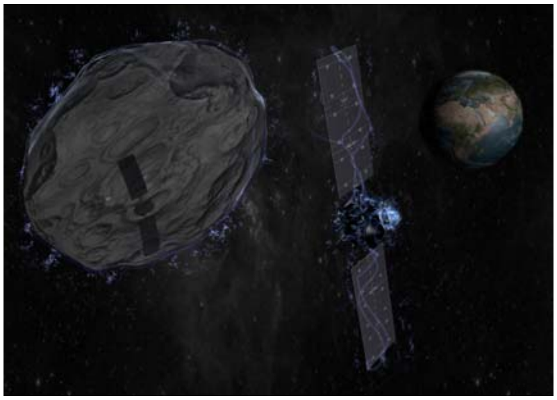

Figure 3: Artistic impression of the Electrostatic Tractor during an Earth encounter (Credits: Fabio Annecchini & Dario Izzo, ©2008 Advanced Concepts Team, ESA)

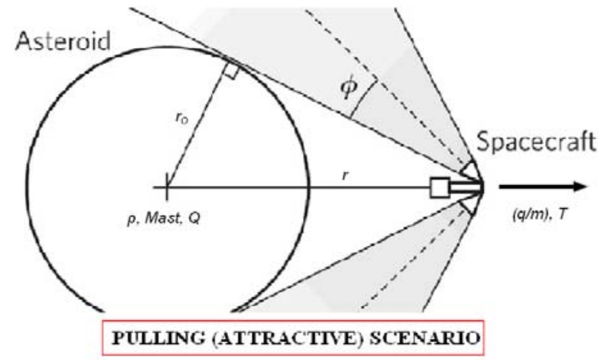

Figure 4: Spacecraft and asteroid are charged to opposite polarities. Figure adapted from [7]. The engines need to be canted.

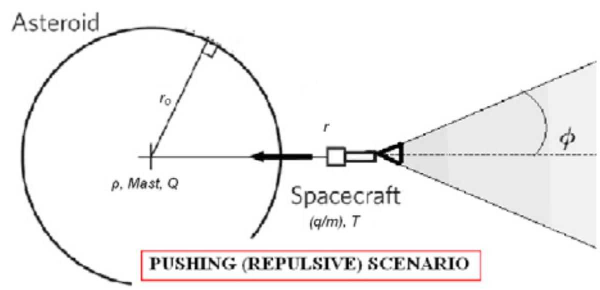

Figure 5: Spacecraft and asteroid are charged to the same polarity. Figure adapted from [7]. The engines do not need to be canted.

experiments on charge control performed on board the SCATHA satellite [14] proved. The primary interest for space engineers has always been to obtain a neutrally charged satellite, as a consequence little is known about situations in which high potentials are desirable on board the satellite. Only recently several authors concerned with Coulomb formation flying [15][16][17] argued that potentials as high as 20kV can be considered for standard spacecraft designs if care is taken to avoid differential discharging.

For two concentric spheres in a vacuum the capacitance C can be given by:

$$C = 4\pi\epsilon_0 \frac{R+\delta}{\delta} R$$

In this paper we imagine a spacecraft of mass M_0 surrounded by a charged sphere of radius R and surface density, ρ_s such as described in [15]. The mass of the spacecraft and charged sphere can be expressed with the following equation:

$$m = M_o + 4\pi R^2 \rho_s$$

The charge to mass ratio will then be given by the following equation assuming that the charged sphere-plasma system acts as a capacitor with the distance between the two shells having a finite distance equal to the plasma sheath thickness, δ:

$$\frac{q}{m} = 4\pi\epsilon_0 \frac{\frac{R+\delta}{\delta} R}{M_0 + 4\pi\rho_s R^2} V$$

The sheath thickness, δ, can be modelled by the Child Law for potentials up to 40 kV [18]:

$$\delta = \frac{\sqrt{2}}{3}\lambda \left(\frac{2V}{T_e}\right)^{3/4}$$

where V is the spacecraft's potential and T_e is the electron temperature. Assuming $M_0 = 500$ kg, $R = 4$ m, $\rho_s = 0.0355$ kg / m^2, $T_e = 1.0 \cdot 10^5 K$ and $\lambda = 7.4$ m (data consistent with interplanetary medium at 1

AU), the spacecraft can hold a charge of $12.51\mu C$. Similarly charging the same spacecraft to a level of 40 kV produces an overall charge of $22.10\mu C$. The relations here derived will be used later to evaluate the electrostatic charge and thus the resulting forces from the potential levels.

Charging an asteroid

If little information on spacecraft charge control is available in the literature, even less can be found on the electrostatic charge of asteroids. It is known that electrostatic fields develop at the surface of resistive asteroids exposed directly to solar radiation and the solar wind [19]. This process, thought to be the result of triboelectric charging [20], is expected to lead to the levitation and transport of charged grains. We will assume here that the asteroid is a cohesive, conductive, spherical solid body. This is a large simplification, however asteroids with a high cohesive strength, i.e. not rubble-pile asteroids, are unlikely to break apart due to the electrostatic forces even if they are irregulary shaped. We also assume that no large volume of charge will be lost to the surrounding space as a result of the electrostatic repulsion between loose particles on the asteroid surface. Any dust on the surface will become charged and may be ejected but it is assumed that this will have little impact. M-type objects are almost certainly good conductors and the C-type asteroids may be reasonably good conductors even at typical asteroidal surface temperatures [21]. However, the hypothesis that all asteroids will behave as a conductive body is probably quite weak and the electric charges will most probably not move freely through the asteroid volume, a complex charge diffusion will instead take place.

We start by evaluating the power required to maintain a given surface voltage on the asteroid. We will then propose three concepts to meet such a requirement.

Power requirements

The current density of charged species with mass m, charge q, and with temperature T, assuming a Maxwellian distribution of velocities is given by:

$$J_0 = \left(\frac{qn}{2}\right)\left(\frac{2kT}{\pi m}\right)^{1/2}$$

where k is the Boltzmann constant and n is the charged species density. A body with a potential V immersed in such a plasma attracts particles with opposite charges. If the space charge of the plasma can be neglected (thick sheath approximation) the current produced due to the species attracted to a spherical body of radius r is limited by the orbital motion of the particles and can be expressed as [22]:

$$I = 4\pi r^2 J_0 \left(1 - \frac{qV}{kT}\right)$$

In the other limiting case, when the sheath thickness is much smaller than the central body radius, (thin sheath approximation), then the current due to the attracted species is only limited by the thermal flux of attracted species entering the sheath and can be expressed as:

$$I = 4\pi r^2 J_0$$

The actual real situation is obviously somewhere in between these two limiting scenarios. The "turning point method" of [23] and the software developed by Thiebault et al. [24] is here used to evaluate a more accurate value for this type of current. To maintain the asteroid at a given voltage, the current due to the attracted species must be counter-acted by an equal current of repelled species or emitted particles. Active control of the voltage is thus performed through emission of particles. Such particles must have sufficient energy to escape the potential of the central body, the power required being $P = VI$.

In Figure 6 we show the results from the turning point method (results based on the thin and thick sheath approximations are also shown for completeness, but only the "turning point" curve needs to be considered) to evaluate the total power required to keep a $r = 100m$ asteroid at a given potential. Average values at 1AU have been used for $n_e = 8.7cm^{-3}$, $T_e = 1.0{\cdot}10^5K$, $T_i = 1.2{\cdot}10^5K$. The power due to the drift velocity and the photoemissions is also evaluated (photoemission contribution is included only for the

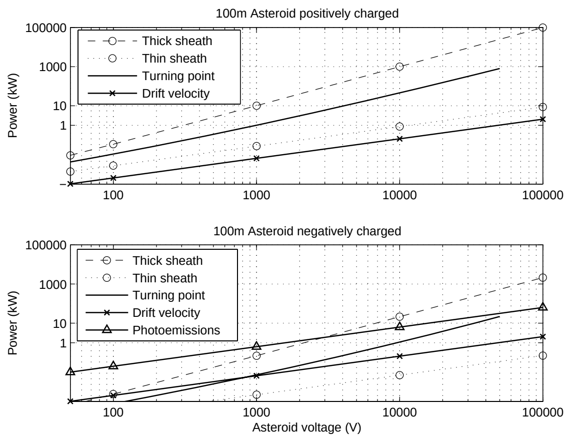

Figure 6: Power contributions for a 100m radius asteroid

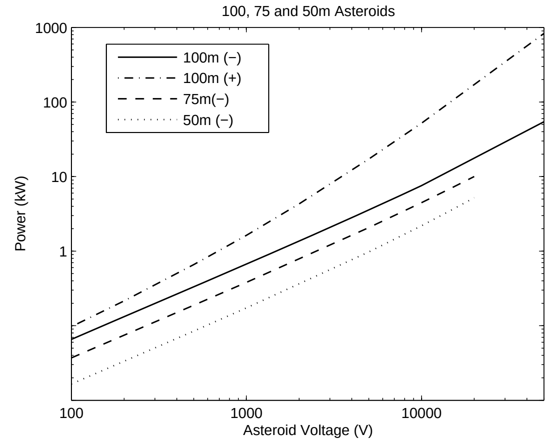

Figure 7: Total power required to maintain different sized asteroids at a given voltage. Negatively charged asteroids are mainly considered as this is more efficient.

r_o (m)	Power (kW)
10	0.61
50	5.21
75	10.05
100	16.61

Table 1: Power required to maintain $-20kV$ on an asteroid at 1AU

negatively charged case as for a positively charged asteroid, all the photoemission electrons are recollected and thus this factor does not play an important role in the power considerations). When accounting for the ion drift velocity current contribution we considered an average value of $468km/s$ for the solar wind velocity, corresponding to 1AU. Such a value is assumed to be approximately constant at this distance from the Sun whereas the solar wind density is expected to scale with approximately a $1/r^2$ dependence on solar distance. A typical photoemission yield of $2.0 \cdot 10^5 A/m^2$ has been used in accounting for the photoemission contribution.

In terms of power requirements, it is more efficient, at high voltages, to charge the asteroid negatively, even taking into account the non negligible photoemission contribution. In Figure 7 we report the total power (sum of the power to maintain the turning point value, accounting for the drift velocity and the photoemission curve) for a number of different sized asteroids.

Asteroid charging concepts

Maintaining the asteroid voltage costs power. We may consider several ways to keep an electrical charge on the asteroid and with different overheads for the overall mission design. We introduce three ideas and briefly discuss them.

1. Using an alpha emitter: in this concept the required charge level is maintained on the asteroid by a small quantity of a radioactive alpha emitter material such as Polonium [15]. By giving careful consideration to the design, shape and choice of the material the power levels needed can be efficiently achieved passively by small radioactive masses. The asteroid would thus constantly emit a current and no additional power sources would be required on board the spacecraft or on the asteroid surface. The control of the emitted current would be a great challenge for this concept, even if one could assume to leave the asteroid potential uncontrolled and adjust the deflection

force by controlling only the spacecraft potential.

2. Landing on the asteroid: an electron or ion gun placed on the asteroid surface can emit charged particles thus leaving the asteroid charged. Such a device could achieve a finer charge control at the expense of requiring an appropriate power source anchored to the asteroid surface

3. Shooting charges: we could envisage shooting charges from the spacecraft to the asteroid, which would leave both the spacecraft and the asteroid charged. In this case we would have only one system, on board the spacecraft, able to provide the voltage levels. Controlling independently the spacececraft charge and the asteroid charge would though be impossible. The power required by this device would need to be evaluated using different arguments than those discussed above.

Here we do not provide any detailed analysis on these three concepts and it may well be that other more convenient ways could be identified to provide the necessary voltages to both the spacecraft and the asteroid.

THE POTENTIAL FIELD AROUND AN ASTEROID

The evaluation of the electrostatic force between the asteroid and the spacecraft is a highly complex task. It needs to account for the complex plasma interactions that tend to shield the electric field created. To evaluate the magnitude of the force we will assume a perfectly spherical and conductive asteroid immersed in the space plasma. We will derive potential field it generates using the “turning point method” [24], the Debye-Hückel potential and the Laplace potential approximations. We will thus discuss the possibility of introducing an “effective shielding length” in the Debye-Huckel expression to fit the turning point method results and we will eventually obtain the force on the satellite modelling it as a point charge immersed in the evaluated potential field.

Laplace and Debye-Hückel potentials

The solution to the electric field for our geometry is quite straight forward should we ignore the presence of the plasma right away. It is given by the well known Laplace expression:

$$\varphi = k_c \frac{Q}{r}$$

expressing the potential at a distance r from a point charge Q. Where the electrostatic constant, k_c, is given by:

$$k_c = \frac{1}{4\pi\varepsilon_o}$$

and ε_o is the permittivity of free space. If r_0 is the radius of the asteroid and φ_0 the surface potential, we get:

$$\frac{\varphi}{\varphi_0} = \frac{r_0}{r} \qquad (1)$$

If we consider the plasma environment, we may compute the potential, in the limiting case of small potential perturbations, using the Debye-Hückel expression:

$$\varphi = k_c \frac{Q}{r} \exp^{-\frac{r}{\lambda}}$$

where λ is the Debye length. Expressing the above formula in terms of the asteroid surface potential we get:

$$\frac{\varphi}{\varphi_0} = \frac{r_0}{r} \exp^{-\frac{r-r_0}{\lambda}} \qquad (2)$$

In Figure 8 we report different curves for φ/φ_0 evaluated using the Laplace potential and the Debye-Hückel expression.

The turning point method

Reality lies somewhere in between Eq.(1) and Eq.(2). The electrostatic potential around a spherical and conductive charged asteroid immersed in a plasma can be better modelled exploiting the “turning point method” of [23]. The turning point method is based on the analysis of the possible particle orbits to solve

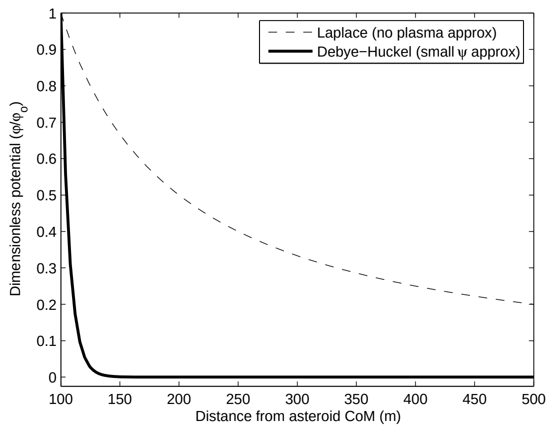

Figure 8: Dimensionless Laplace and Debye-Hückel potentials

the Vlasov equation [25] for a given potential distribution with spherical symmetry. The Poisson-Vlasov system of equations is then solved by iteration. Here the implementation of Thiebault et al. [24] has been used.

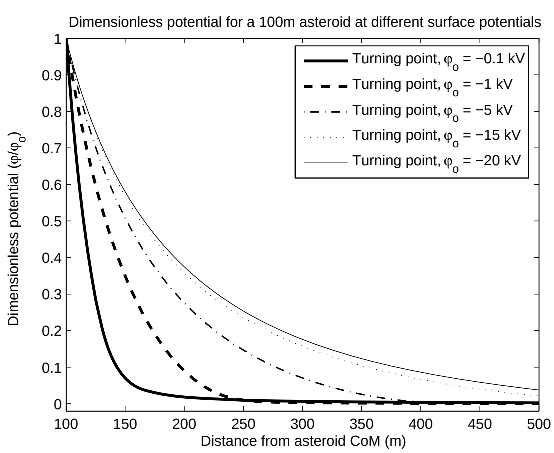

Figure 9: Dimensionless potential

In Figure 9 we report different curves for φ/φ_0 evaluated at different asteroid surface potentials using the turning point method. The asteroid radius has been assumed to be 100m, the Debye length 7.4m (interplanetary medium) and the asteroid surface potentials considered are -0.1, 1, 5, 15 and 20 kV.

Fitting the turning point curves

To obtain an analytical expression out of the numerical simulations performed using the turning point method we propose to fit the simulated curves of the non dimensional potential curve to the expression:

$$\frac{\varphi}{\varphi_0} = \frac{r_0}{r} \exp^{-\frac{r-r_0}{\alpha\lambda}} \tag{3}$$

introducing de facto an "effective shielding length" $\tilde{\lambda} = \alpha\lambda$ in the Debye-Hückel expression. The effective shielding length $\tilde{\lambda} = \alpha\lambda$ is now dependant on the surface potential of the sphere and represents only an approximation to the turning point solution of the electric potential field. The advantage of knowing α is in the possibility of using analytical, rather than numerical, expressions to express the force between the spacecraft and the asteroid. This facilitates the preliminary study of possible charge control systems and of the stability of the overall system.

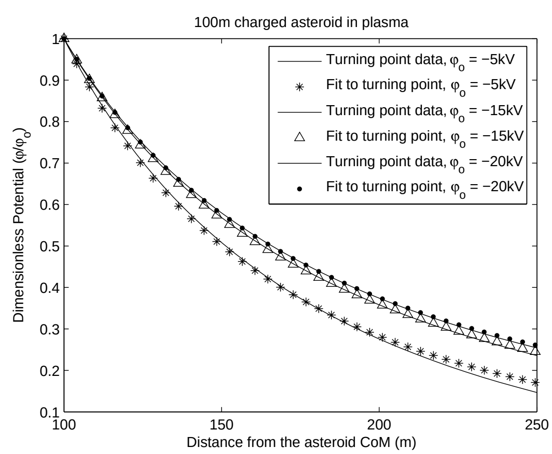

Figure 10: Fit to turning point dimensionless potential

In Figure 10 we report the results of the fit in the near asteroid surface space, for a $r_0 = 100m$ asteroid charged to -5kV, -15kV and -20kV. Note that the effective shielding length is 20-50 times larger than

φ_o (kV)	α	$\tilde{\lambda} = \alpha\lambda$
-0.1	3.36	24.87
-1	10.00	74.00
-5	23.70	175.38
-15	41.14	304.44
-20	47.16	348.98

Table 2: Effective shielding lengths for a $100m$ asteroid

r_o (m)	α	$\tilde{\lambda} = \alpha\lambda$
10	17.77	131.50
50	36.17	267.66
75	42.15	311.91
100	47.16	348.98

Table 3: Effective shielding lengths for asteroids charged to $-20kV$

the Debye length. The effective shielding lengths for a 100m radius spherical asteroid charged to different surface potentials is given in Table 2. The effective shielding lengths found for spherical asteroids of varying sizes charged to $20kV$ and immersed in plane with a Debye length of $7.40m$ are given in Table 3.

THE AVAILABLE DEFLECTION FORCE

At this point we may evaluate the deflection acceleration $\mathbf{A}$ due to a spacecraft carrying a charge q hovering at a distance r from the center of mass of an asteroid having a surface potential φ_0. To do this we first evaluate the effective shielding length $\tilde{\lambda}$ fitting the turning point method numerical simulation, and we then write:

$$\mathbf{A} = \frac{\mathbf{f}}{M_{ast}} = \frac{Gm}{r^2}\hat{\mathbf{r}} - \frac{q\varphi_0 r_0}{rM_{ast}} \exp\left(-\frac{r-r_0}{\tilde{\lambda}}\right)\left[\frac{1}{r} + \frac{1}{\tilde{\lambda}}\right]\hat{\mathbf{r}}$$

Assuming that we have a spherical asteroid of typical density $2g/cm^3$, and a $500kg$ spacecraft charged to $20kV$ which will produce a spacecraft charge of $12.51\mu C$ immersed in a plasma with a Debye length of $7.40m$. The forces that will be exchanged between the asteroid and the spacecraft hovering at a distance r from the asteroid center of mass are shown in Figures 11-13 for different asteroid radii. From these curves we see that, already at these potential levels, the electrostatic force established between the spacecraft and the asteroid has an order of magnitude that is comparable with the gravitational term for an asteroid radius of 100 m thus allowing a form of "gravity control".

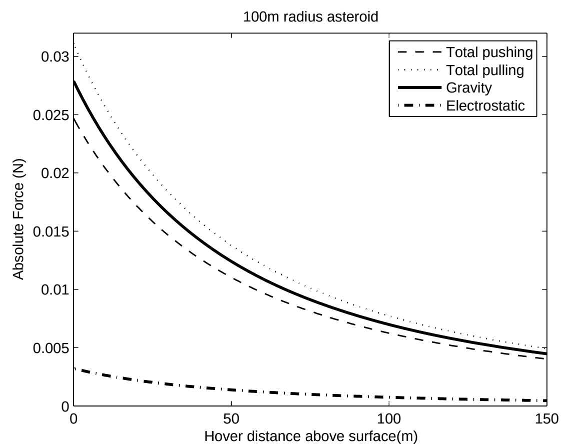

Figure 11: 100 m asteroid radius. Both asteroid and spacecraft charged to 20kV

With decreasing asteroid radii, the gravity becomes very feeble, while the electrostatic force (keeping the same surface potential) increases. Establishing a "tractor beam " between an asteroid and a spacecraft for small asteroid masses is then better achieved by artificially inducing an electrostatic field. The relative magnitude between gravity and the electric force is strongly dependant on the surface potential we are able to induce and maintain both in the spacecraft and on the asteroid. These are critical numbers that need further research efforts to be understood. In particular, the spacecraft design suggested by Peck [15], a spacecraft surrounded with a charged sphere of a light material, needs to be further examined to see if it can really deliver the very high voltages claimed. For the asteroid charging, the idea of leaving an alpha emmiter on its surface needs to be studied to check its feasibility and its implications on the as-

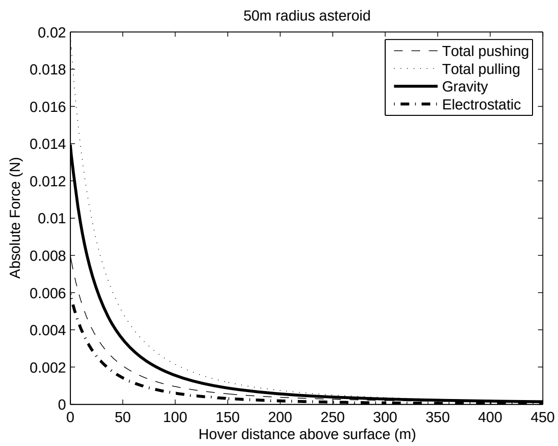

Figure 12: 50 m asteroid radius. Both asteroid and spacecraft charged to 20kV

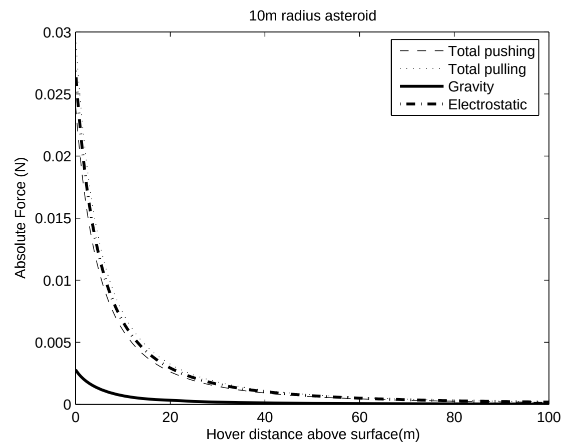

Figure 13: 10 m asteroid radius. Both asteroid and spacecraft charged to 20kV

teroid structural integrity. Concerns on the asteroid conductivity also need to be cleared and the charge distribution mechanisms understood before the Electrostatic Tractor concept can be considered as "feasible". We may though conclude that the magnitude of the forces that would be involved already at a 20kV surface potential levels are interesting, especially for small asteroid in the range of $r < 100m$, and can be used to "control", to different extents, the asteroid gravity.

CONCLUSIONS

The Electrostatic Tractor can be used to control the asteroid gravity fields of small sized asteroids. Depending on the voltage level applied to the spacecraft and to the asteroid, the electrostatic force will in fact dominate or be dominated by gravity. At 20 kV levels the electrostatic force goes from dominating gravity (10m radius asteroids) to being dominated (100m radius asteroids). A gravity control system can thus actually be achieved and used to control the spacecraft-asteroid interaction. Higher voltage levels would allow this concept to be applied to even larger asteroids, but it is not clear what the maximum voltage is one could achieve on an asteroid surface or on a spacecraft.

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