Painting Asteroids for Planetary Defense

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Abstract
Asteroidal impact threats to the Earth may be predicted a century or more in advance. Several methods of mitigating these threats have been proposed. Here I evaluate changing an asteroid’s albedo to change the Solar radiation pressure force, and hence its orbit. Albedo may be increased to near-unity by applying a thin (~ 0.1 μm) reflective coat of alkali metal, dispensed as vapor by an orbiting spacecraft. A complete coat reduces the effective Solar gravity, changing the orbital period and displacing the asteroid by a distance proportional to elapsed time. A Tunguska-class (50 m diameter) asteroid in a nominal orbit with perihelion 1 AU and aphelion 3 AU (a = 2 AU, e = 0.5) may be displaced along its path by ~ 1000 km in 100 years, sufficient to avoid impact in a populated area, by application of one kg of lithium or sodium metal over its entire surface. Alternatively, coating one hemisphere of an asteroid in an elliptical orbit may produce a Solar radiation torque on its orbit, related to but distinct from the Yarkovsky effect, displacing it by an Earth radius in ~ 200 years. The acceleration is inversely proportional to the asteroid’s diameter and its displacement increases quadratically with time, so the time required for deflection scales as the square root of the diameter (the 1/6 power of its mass). Larger asteroids are difficult to deflect by other means, but deposition of 400 kg of alkali metal makes it possible to prevent the catastrophic impact with the Earth of a km-sized asteroid 200 years in the future.

Keywords Planetary defense · Asteroids · Radiation pressure

1 Introduction
The impact of a 10–15 km diameter asteroid or comet 66 million years ago made the majority of living plant and animal species extinct, and a similar event in the future might end human civilization [1]. The very much smaller Tunguska

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event, believed to be produced by impact of a rocky asteroid with diameter 50–60 m, had an airburst yield estimated (uncertainly) as \( \sim 10 \) megatons high-explosive equivalent [2] and blew down about \( 10^3 \) km\(^2\) of forest. Such events may occur every few hundred to a 1000 years [3, 4], and would be very destructive were they to occur over a city.

Preventing such impacts is the problem of “planetary defense”. An asteroidal orbit may be changed by imparting momentum. If warning times can be lengthened to a century or more by improvements in predictions of asteroidal orbits, even very small changes in the asteroidal velocity may be sufficient to prevent collision, provided the orbit is changed early enough. If there is no early warning (warning of cometary impacts is likely to occur only when the comet has a heliocentric distance \( \lesssim 5 \) AU, about a year before impact) ablation by a nearby nuclear explosion may be necessary.

A number of methods of deflecting threatening asteroids have been proposed. These include nuclear explosions [5–7], small steady forces exerted on the asteroid by an ion engine, a “gravity tractor” itself accelerated by an ion engine [8], the impact of a spacecraft [9, 10] or the radiation force on a tethered balloon [11]. Nuclear explosions are widely considered undesirable (see, however, [12]) and may also create fragments on unpredictable orbits that are themselves large enough to be threatening. Ion engines require large masses of propellant to deflect larger asteroids in acceptable times.

This technical note investigates the possibility of changing an asteroidal orbit by coating it with a reflective metal to change the force of Solar radiation pressure on it. This is analogous to the Yarkovsky effect, but differs in that it depends on the instantaneous force of radiation pressure rather than the delayed re-emission of absorbed energy. The effects of radiation pressure force and albedo variations on asteroidal orbits have been previously considered [13]. The radiation pressure force has the same inverse square dependence on distance as gravity, so the effect of changing the albedo over the entire asteroidal surface would be dynamically equivalent to a small change in the Solar mass and therefore changing the orbital period. Alternatively, changing the albedo of one hemisphere of an asteroid whose rotational axis is not aligned with its orbital axis and is in an eccentric orbit produces a systematic trend in its orbital angular momentum and a displacement proportional to the square of the elapsed time.

Extensive surveys [14] are conducted to find and catalogue asteroids whose orbits bring them [15, 16] close enough to the Earth (Potentially Hazardous Objects (PHO), a subcategory of near-Earth objects (NEO) whose orbits approach Earth’s orbit) to present a threat of collision. In the foreseeable future, such surveys are expected [17] to be complete to sizes smaller than the Tunguska impactor, and the progress of observational technology will extend them to yet smaller asteroids. Orbital prediction may be made more accurate, for example, by emplacing a transponder or transmitter on or in orbit around the small number of asteroids previously identified as possible threats. A combination of more accurate measurement of present orbital elements and improved modeling of non-gravitational forces (such as the radiation pressure force that is here proposed to be modified) may enable the prediction of collisions far into the future, depending on the improvement of methods to calculate the several small but significant
perturbations accurately, including the force of radiation pressure on irregularly shaped bodies.

It may not be necessary to avoid collision entirely; deflecting an asteroid of the size that produced the Tunguska event to the ocean or to an impact point hundreds of km from any population may be sufficient. If asteroidal orbits are in the future accurately calculated centuries in advance, the area around the impact point could be used as farmland or nature reserve with minimal infrastructure, and completely evacuated when impact is imminent.

The present state of the art is indicated by the calculations [18, 19] of the orbit of 101955 Bennu, a 500 m diameter asteroid predicted to pose a small risk of collision in 2178–2290, and especially in 2182, more than 150 years in the future. Extant optical observations are only accurate enough to establish the possibility (with small probability) of collision. In order for the proposed method to be feasible, it will be necessary to predict asteroidal orbits to an accuracy less than the size of the Earth a century or more into the future. This capability does not now exist.

However, it is within present technical capability to land on or place in orbit around an asteroid, as well as other Solar System objects, a transponder or transmitter (such has already been done for Bennu). An interplanetary equivalent of GPS might be feasible, with orbits determined to cm accuracy, enabling much more accurate evaluation of possible collision risk.

A related proposal [20, 21] has suggested changing the albedo of 99942 Apophis to modify its Yarkovsky effect and deflect its trajectory. Although this shares with the present work its dependence on radiation pressure forces, the orbital mechanics differ. Apophis and 65803 Didymos, (Dimorphos, the smaller component of the binary Didymos, is the target of the Double Asteroid Redirection Test (DART) experiment [9, 10]) are easier targets to reach and their orbits can be influenced more readily than those of most asteroids because they have smaller semimajor axes, bringing them close to Earth, but the principles are the same.

2 Angular Momentum Conserving Forces

2.1 Reducing the Effective Solar Mass

The magnitude of the fractional change in effective Solar mass is given by the ratio of the radiation pressure force to the gravitational force:

\[
\epsilon = \frac{f (L_\odot / 4 \pi R^2 c) \pi D^2 / 4}{GM_\odot \pi D^3 \rho_{ast} / (6R^2)} \approx \frac{3f}{8} \frac{L_\odot}{GM_\odot c D \rho_{ast}}
\]

where \(L_\odot\) is the Solar luminosity, \(M_\odot\) the Solar mass, \(f\) the difference in momentum albedo between the bare asteroid and its reflective coat, averaged over its surface, \(R\) the distance from the Sun, \(D\) the diameter of the asteroid, \(\rho_{ast}\) its density, \(G\)
the constant of gravity and $c$ the speed of light. The momentum albedo is defined as the fraction of the incident radiation momentum that is reflected opposite to the direction of the incident illumination, in analogy with the usual energy albedo, but because momentum is a vector quantity only its component opposite to the direction of illumination is considered. The momentum albedo depends on the angular distribution the scattered light, here taken to be specular.

In steady state, absorbed Solar energy is reradiated as thermal infrared radiation. If the asteroid is spherical and its surface is a Lambertian scatterer and emitter at all wavelengths, then the force of radiation pressure

$$F = \frac{L_\odot}{4\pi R^2 c} \frac{\pi D^2}{4} \frac{11}{9}. \quad (2)$$

In steady state this is independent of the visible albedo because an increase of scattered visible radiation implies a decrease, by the same amount, of re-emitted infrared radiation, and vice versa. The thermal infrared emissivity (or albedo) affects the surface temperature, but not the energy and momentum radiated because they are determined by energy balance.

Increasing the visible albedo by coating with reflective metal does not immediately reduce the recoil force of thermal infrared emission because the asteroidal interior remains warm for a thermal relaxation time of many years; a $0.1 \mu m$ metallic layer is sufficient to reflect visible light but is transparent to thermal infrared radiation. If the albedo increases by $\Delta A$ the net radiation pressure force becomes

$$F' = \frac{L_\odot}{4\pi R^2 c} \frac{\pi D^2}{4} \left( \frac{11}{9} + \frac{2}{9} \Delta A \right). \quad (3)$$

Asteroids are generally dark, with visible energy albedos in the range $0.03–0.2$, while alkali metals are reflective, with visible energy albedos in the range $0.90–0.95$ [22]. Their difference $\Delta A \approx 0.8$ and $2(A' - A)/9 \approx 0.2$.

The fact that changing the reflectivity of an asteroid changes the Solar radiation force on it offers the opportunity to change its path by applying a very thin coat of reflective material. The effective mass of the Sun would then be

$$M' = (1 - \varepsilon)M_\odot. \quad (4)$$

### 2.2 Orbital Mechanics

A complete treatment is complex, so we consider only simple limiting cases.

#### 2.2.1 Adiabatic Change of Reflectivity

The asteroid moves in a central force field, so its orbital angular momentum $\ell$ is conserved. If the change in effective mass occurs adiabatically (over many orbits) then the orbital eccentricity
where \( E \) is the orbital energy per unit mass of the asteroid, would be conserved. From Eq. 5,

\[
\frac{E'}{E} = \left( \frac{M'}{M_\odot} \right)^2 \approx 1 - 2\epsilon. \tag{6}
\]

From the general relation

\[
a = -\frac{GM_\odot}{2E} \tag{7}
\]

we find

\[
\frac{a'}{a} = \frac{M'}{M_\odot} \frac{E}{E'} \approx 1 + \epsilon. \tag{8}
\]

The orbital period

\[
P = 2\pi \sqrt{\frac{a^3}{GM_\odot}} \tag{9}
\]

becomes \( P' \):

\[
\frac{P'}{P} = \left( \frac{a'}{a} \right)^{3/2} \left( \frac{M'}{M_\odot} \right)^{-1/2} \approx 1 + 2\epsilon. \tag{10}
\]

### 2.2.2 Instantaneous Change of Reflectivity

An impulsive (on a time scale \( \ll P \)) change in reflectivity changes both \( a \) and \( e \), but \( \ell' \) is still conserved because the force is central. If this occurs at perihelion

\[
\ell' = vr = va(1 - e), \tag{11}
\]

where \( v \) is the asteroid’s velocity, perpendicular to the radius vector at perihelion. This velocity may be found from the condition that changing its reflectivity does not change its energy:

\[
E = \frac{v^2}{2} - \frac{GM_\odot}{a(1 - e)} = -\frac{GM_\odot}{2a} \tag{12}
\]

or

\[
v^2 = \frac{GM_\odot}{a} \frac{1 + e}{1 - e}. \tag{13}
\]
Following the instantaneous reduction in effective Solar mass to $M'$, the new energy (per unit mass of the asteroid)

$$E' = \frac{v^2}{2} - \frac{GM'}{a(1-e)} = \frac{GM\odot}{2a} \left( \frac{1 + e - 2M'}{1 - e} \right)$$

$$= \frac{GM\odot}{2a} \left( \frac{1 + e - 2(1 - e)}{1 - e} \right) = \frac{GM\odot}{2a} \left( -1 + \frac{2e}{1 - e} \right)$$

(14)

Then

$$a' = -\frac{GM'}{2E'} = a \frac{(1 - e)(1 - e)}{1 - e - 2e} = a \left( 1 + \frac{e + 1}{1 - e} \right).$$

(15)

Because the change in effective mass does not affect the perihelion (the velocity remains perpendicular to the radius vector)

$$a(1 - e) = a'(1 - e')$$

(16)

and

$$e' = e \left( 1 + \frac{e + 1}{e} \right).$$

(17)

The ratio of new to former period

$$\frac{P'}{P} = \left( \frac{a'}{a} \right)^{3/2} \left( \frac{M'}{M\odot} \right)^{-1/2} = \left( \frac{(1 - e)(1 - e)}{1 - e - 2e} \right)^{3/2} (1 - e)^{-1/2}$$

$$\approx 1 + \frac{2 + e}{1 - e}.$$  

(18)

If the change in albedo occurs instantaneously at aphelion $e$ is replaced by $-e$ and the period ratio

$$\frac{P'}{P} \approx 1 + \frac{2 - e}{1 + e}.$$  

(19)

### 2.3 Avoiding Collision

The preceding results may be summarized:

$$\frac{P'}{P} = 1 + \alpha$$

(20)

where
and the numerical factors were evaluated for a nominal $e = 0.5$.

Multiplying the orbital period by a factor $1 + \alpha$ changes the mean anomaly $n$ after $N$ orbits by $\Delta n \approx 2\pi a N$ radians and displaces the asteroid after a time $T$ by a distance

$$\Delta X \sim a \Delta n \approx 2\pi a a N \approx 2\pi a a \frac{T}{P}, \quad (22)$$

that necessarily varies (Eq. 22 is not an equality unless $e = 0$) along its orbit. Because the paths of Earth and asteroid intersect obliquely, delaying the asteroid $(P' > P)$ moves the impact point on the Earth’s surface by $\sim \Delta X$. To avert collision entirely would require

$$\Delta X \gtrsim R_E, \quad (23)$$

where $R_E$ is the radius of the Earth (for a typical asteroidal relative velocity $\sim 20$ km/s gravitational focusing by the Earth is not large); this relation would be an equality if the undeflected asteroidal trajectory were through the center of the Earth.

This leads to a condition on $\alpha$ (and on $\epsilon$ from Eq. 21)

$$\alpha > \frac{\Delta XP}{2\pi a T} \approx 2 \times 10^{-8} \left( \frac{\Delta X}{1000 \text{ km}} \right) \left( \frac{100 \text{ y}}{T} \right) \left( \frac{P}{3 \text{ y}} \right) \left( \frac{1 \text{ AU}}{R} \right). \quad (24)$$

Comparison to Eqs. 1 and 21 indicates that a 50 m diameter asteroid may be deflected by $\sim 3000$ km in a century or 1000 km in $\sim 30$ years. Tunguska-class asteroids may be deflected enough to miss cities and directed into a depopulated area, perhaps an ocean. Because there would be many years of warning, that area could be used for any purpose, such as agriculture or a nature reserve, that did not require major permanent infrastructure, and evacuated when impact is imminent. If the initial trajectory were through the center of the Earth it would require 200–300 years to avoid collision entirely.

### 3 Angular Momentum Non-conserving Forces

If the perturbation conserves orbital angular momentum (Sect. 2) the displacement of the asteroid is proportional to the time elapsed (Eq. 22). However, if the perturbation produces a non-zero mean torque the displacement would be quadratic in the time elapsed. It may exceed the Earth’s radius in the characteristic warning times of a century or two, enabling impact to be avoided entirely, and also allow for uncertainty in the predicted trajectory.

For simplicity, consider the rotational angular momentum to lie in the orbital plane. Suppose reflecting material be applied to a hemisphere containing one
rotational pole of the asteroid, but not to the other hemisphere, and that the rotational angular momentum have a component in the asteroid’s orbital plane. If the rotational period is short compared to the orbital period the reflectivity may be averaged over longitude so that it depends only on latitude. In a circular orbit the radiation torque increases the orbital angular momentum during half of the orbit and decreases it during the other half, the two effects cancelling.

However, asteroidal orbits are significantly eccentric; a nominal PHO with perihelion of 1 AU and aphelion of 3 AU, perhaps representative, has an eccentricity $e = 0.5$. The ratio of the radiation pressure torque at aphelion to that at perihelion is $(1 - e)/(1 + e) = 1/3$ while the ratio of times spent near these points is $[(1 - e)/(1 + e)]^{-3/2} = 3^{3/2}$. If the rotation axis were parallel to the semimajor axis of the orbit no torque would be exerted around perihelion or aphelion and orbital angular momenta imparted between aphelion and perihelion would cancel that imparted between perihelion and aphelion, so no cumulative orbital angular momentum would be imparted. In contrast, if the rotational angular velocity has a component parallel to the semiminor axis of the orbit the orbital angular momentum imparted by radiation pressure around aphelion may be nearly twice that imparted (in the opposite direction) around perihelion; there would be a net change of orbital angular momentum each orbit.

In the latter case, any anti-symmetric (about the rotational equator), longitudinally averaged, distribution of reflectivity would produce a cumulative change of orbital angular momentum, semi-major axis and period, and a displacement increasing quadratically with time. Such an effect may occur naturally, and should be included in the orbital solutions of small bodies. It is distinct from the classical Yarkovsky effect because it occurs only in elliptic orbits, requires a non-zero component of rotational angular momentum in the orbital plane, and does not depend on a delay between absorption and reradiation of energy. Coating one hemisphere around the axis of rotation with reflective material can change the orbital angular momentum an order of magnitude more rapidly than the change resulting from any natural asymmetry of the reflectivity; that natural asymmetry would be included in the calculated ephemeris that predicts impact while the change could displace the asteroid from an impact trajectory to a close approach without collision.

The orbital parameters of the threat object (if search is extended to sufficiently small objects an impactor will be found [3, 4]) are not known prior to its discovery, so only a parametrized estimate can be made. The change in orbital angular momentum in one orbit may be described by an equivalent impulsive change in velocity at perihelion

\[ \Delta v = g \frac{\pi}{4} D^2 \frac{L_\odot}{4\pi R^2 c} \frac{\sqrt{R^3/GM_\odot}}{\pi \rho_{\text{ast}} D^3/6} = \frac{3g}{8\pi} \frac{L_\odot}{\rho_{\text{ast}} D c \sqrt{GM_\odot R}} \]

\[ = 0.023 g \frac{50 \text{ m}}{D} \sqrt{\frac{1 \text{ AU}}{R}} \frac{3 \text{ g/cm}^3}{\rho_{\text{ast}}} \text{ cm/s,} \]

where the dimensionless parameter $g < 1$ accounts for the difference in reflectivity between the coated and uncoated hemispheres, the integration of the component of
the radiation pressure force perpendicular to the radius vector along the elliptic orbit, the projection of the spin angular momentum direction onto the orbital plane and along the semiminor axis and the variation of $R$ along the orbit (reducing the radiation intensity away from perihelion). Each of these factors is uncertain, and depends on the spin and orbit of an as-yet-unidentified threat object. For numerical estimates I adopt a nominal $g = 0.4$, but this can only be an order-of-magnitude estimate.

In a single perihelion passage the speed $v$ (Eq. 13) is replaced by $v + \Delta v$ and the energy $E$ is replaced by

$$E' \approx E + v\Delta v = v^2 \left( \frac{1}{2} - \frac{1}{1+e} + \delta \right),$$

(26)

to lowest order in

$$\delta \equiv \frac{\Delta v}{v} \approx \frac{g}{0.4} \frac{3 \times 10^{-9} \frac{g}{cm^3}}{\rho_{ast}} \frac{50 m}{D}.$$ 

(27)

Using Eq. 13 for $E$,

$$\frac{E'}{E} \approx 1 - 2\delta \frac{1+e}{1-e},$$

(28)

$$\frac{a'}{a} = \frac{E'}{E} \approx 1 + 2\delta \frac{1+e}{1-e},$$

(29)

and the mean angular motion $n$ becomes $n'$:

$$n' = \left( \frac{a'}{a} \right)^{-3/2} \approx 1 - 3\delta \frac{1+e}{1-e}.$$ 

(30)

After $t/P$ orbits,

$$n(t) \approx n(0) \left( 1 - 3\delta \frac{1+e}{1-e} \frac{t}{P} \right).$$ 

(31)

The mean anomaly $M$ advances at a rate $dM/dt = n(t) = 2\pi/P(t)$ and drifts from the unperturbed motion

$$\frac{d(M' - M)}{dt} = n' - n \approx 3n\delta \frac{1+e}{1-e} \frac{t}{P}.$$ 

(32)

After a time $T$ the cumulative drift

$$M' - M \approx \frac{3}{2} n\delta \frac{1+e}{1-e} \frac{T^2}{P}.$$ 

(33)

Near Earth encounter at a distance $R \approx 1$ AU this corresponds to a displacement
\[ \Delta X \sim (M' - M)R \approx \frac{3}{2} \frac{1 + e}{1 - e} n \delta RT^2 \]
\[ \approx 3\pi R \frac{g}{0.4} 3 \times 10^{-9} \sqrt{\frac{1 + e}{1 - e}} \left( \frac{T}{P} \right)^2 \frac{3 \text{ g/cm}^3}{\rho_{\text{ast}}} \frac{50 \text{ m}}{D} \]
\[ \approx \frac{g}{0.4} 1.2 \times 10^9 \left( \frac{T}{100 \text{ y}} \right)^2 \left( \frac{3 \text{ g/cm}^3}{\rho_{\text{ast}}} \frac{50 \text{ m}}{D} \right) \text{ cm}, \]  

where the numerical result takes \( e = 0.5 \). A complete miss (\( \Delta X > R_{\text{E}} \)) occurs at

\[ T > 75 \sqrt{\frac{0.4}{g} \frac{\rho_{\text{ast}}}{3 \text{ g/cm}^3} \frac{D}{50 \text{ m}} \frac{P}{3 \text{ y}}}. \]  

4 Material Requirements

Measurements \([22]\) of the reflectivity of alkali metals describe bulk metal. The intensity skin depth in Li and Na is \( \approx 180\text{Å} \) at the visible and near-infrared wavelengths at which nearly all the Solar energy is radiated \([23]\). As a result, a layer \( h = 0.1\mu\text{m} \) thick has, to better than 1% accuracy, the same reflectivity as a half-space even at normal incidence (and more accurately as other angles of incidence). The mass required to coat a sphere of diameter \( D \) with metal of density \( \rho_m \)

\[ M_{\text{metal}} = \pi D^2 \rho_m h \approx \begin{cases} 
426 \left( \frac{D}{50 \text{ m}} \right)^2 & \text{g Li} \\
763 \left( \frac{D}{50 \text{ m}} \right)^2 & \text{g Na.} 
\end{cases} \]  

It would be necessary to deposit this material as an atomic vapor from a spacecraft orbiting the asteroid because impact with relative velocity \( > 10\text{km/s} \) of metal droplets released in a flyby would produce micro-fireballs, and essentially all the metal would be lost in their expansion. Atomic vapor would be deposited efficiently, even at this (or higher) relative speed, but it would be difficult to produce a vapor cloud confined so that a significant fraction of it would strike the asteroid, unless dispensed from a platform with low relative velocity. A platform in polar orbit close to the asteroid could dispense vapor and coat any desired portion of the surface.

Evaporative deposition of thin films is a mature technology, widely used in industry and the laboratory \([24]\). Atoms evaporated from a heated surface travel ballistically until they strike the cold asteroid, where they deposit with nearly unit efficiency; this vapor deposition is a familiar laboratory process. The atoms do not condense into droplets because their density is too low (they strike the asteroidal surface first). Instead, they attach to the surface as individual atoms, which have insufficient energy and momentum to disturb the surface. The very thin film conforms to the surface, however rough it may be, just as it does in the laboratory. Some fraction of the surface may be shadowed from ballistic deposition, but this can be
mitigated by depositing vapor from different angles in repeated passages of the dispensing orbiter. If the orbiter is in a low orbit then the asteroid would fill nearly \(2\pi\) steradian from it; the majority of the atoms evaporated from hot metal facing the asteroid would strike it; sticking probabilities approach unity. The film would be subject to “impact gardening” by micrometeoids and chemical erosion by the Solar wind, but the experience of the Lunar retroreflectors over several decades indicates that these processes are not likely to be destructive on the time scale of a century.

Solar energy could be used to evaporate the metal. If this is to occur in a time \(\Delta t \ll P\), the required power would be

\[
P = \frac{\pi D^2 \Delta H_v \rho_m h}{\mu \Delta t} = \begin{cases} 88 \left( \frac{D}{50 \text{ m}} \right)^2 \left( \frac{10^5 \text{s}}{\Delta t} \right)^2 \text{ W Li} \\
32 \left( \frac{D}{50 \text{ m}} \right)^2 \left( \frac{10^5 \text{s}}{\Delta t} \right) \text{ W Na,} \end{cases}
\]

where \(\Delta H_v\) is the latent heat of evaporation (145 kJ/mole for Li and 97 kJ/mole for Na) and \(\rho_m\) is the density of the metal (0.54 g/cm\(^3\) for Li and 0.97 g/cm\(^3\) for Na) and \(\mu\) its molecular weight.

If photocells are used to make electricity to heat the metal resistively the required collecting area would be tiny:

\[
A = \frac{P}{I_\odot \varepsilon} \left( \frac{R}{1 \text{ AU}} \right)^2 = \begin{cases} 0.06 \left( \frac{R}{1 \text{ AU}} \right)^2 \left( \frac{D}{50 \text{ m}} \right)^2 \left( \frac{10^5 \text{s}}{\Delta t} \right) \text{ m}^2 \text{ Li} \\
0.02 \left( \frac{R}{1 \text{ AU}} \right)^2 \left( \frac{D}{50 \text{ m}} \right)^2 \left( \frac{10^5 \text{s}}{\Delta t} \right) \text{ m}^2 \text{ Na,} \end{cases}
\]

where \(\varepsilon\) is the efficiency of conversion of the Solar intensity \(I_\odot\) to latent heat of evaporation of the metal. For Solar cells \(\varepsilon \approx 0.2\). Alternatively, sunlight could be focussed on an exposed alkali metal surface. For a reflector focussing Solar radiation (a Solar furnace) \(\varepsilon\) may approach unity. Using Solar energy to evaporate enough metal to coat a threatening asteroid is feasible.

5 Discussion

If there is a century of warning of a Tunguska-class (50 m diameter) asteroidal threat, it may be feasible to change its Solar reflectivity and radiation pressure force to move its impact to locations where it would do little harm, or to avoid impact entirely. This may be done by coating the asteroid with a sub-micron layer of reflective alkali metal that would reduce the effective force of Solar gravity on it, or provide a torque that would systematically increase or decrease its orbital angular momentum.

In comparison to impact or an ion engine, the method is particularly advantageous against larger (km-class) asteroids that are rarer but whose impact would be catastrophic. For an asteroid with diameter of 1 km a few hundred kg of metal would suffice to provide a reflective coat. Such larger asteroids would take longer to deflect, but with a systematic torque the time required to avoid impact would be proportional.
to the square root of the asteroidal diameter (the sixth root of its mass), and would be $< 1000$ years for km-class asteroids.

Deflection of an asteroid of mass $M_{ast}$ by impact or by an attached ion engine would require a mass $\Delta M$ of impactor or ionic propellant proportional to that of the asteroid, and to the cube of its diameter. This mass may be estimated

$$\frac{\Delta M}{M_{ast}} \approx \frac{R_E}{AU} \frac{P_{ast}}{2\pi T} \frac{v_{ast}}{\Delta v} \approx 5 \times 10^{-8},$$

(39)

where $P_{ast} = 2\sqrt{2}y$ is a nominal asteroidal orbital period (semimajor axis 3 AU, semiminor axis 1 AU), $T = 200$ y is the time to deflect the asteroid’s path by the Earth’s radius $R_E$, $v_{ast}$ is a mean asteroidal orbital velocity and $\Delta v$ is either the impactor’s relative velocity or the ion engine exhaust velocity; $v_{ast}/(\Delta v) = 0.5$ is assumed (realistic for an ion engine, optimistic for impact). For an asteroid of diameter $D$ and density $\rho = 3000$ kg/m$^3$

$$\Delta M \approx 5 \times 10^{-8} \frac{\pi}{6} D^3 \rho \approx 80 \left(\frac{D}{100 \text{ m}}\right)^3 \text{ kg.}$$

(40)

This is modest for a 100 m diameter asteroid, but would require delivery of 80 tons to deep space if $D = 1$ km.

Like a nuclear explosion, the effects of impact are uncertain, and may include the creation of additional smaller but threatening debris. The gravity tractor was invented to avoid this and the uncertainty of attaching a thruster and its Solar cells to a threat object that may be a loose pile of debris, but its mass is also not negligible [8] and is in addition to the propellant mass. Painting with alkali metals may be an attractive alternative for larger threats in the more distant future.

The proposed method has the disadvantage, shared, with gravity tractors and landed thrusters, or requiring rendezvous, at significant cost in $\Delta v$. Nuclear explosions and impactors do not have this burden. However, the comparatively small mass of alkali metal required to coat even km-scale asteroids (hundreds of kg, comparable to the masses that have been landed on asteroids) mitigates this disadvantage.

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Declarations

Conflict of interest The author states that there is no conflict of interest.

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