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Research Article

Low-cost debris deorbiting plus planetary protection

Abstract

Space debris can be deorbited by a coating of volatile material that evaporates in sunlight. Consider a roque CubeSat that gets splashed with black gel while on the night side of its orbit. As it emerges into the rays of the Sun, kinetic evaporation provides a retro force relative to the orbital velocity, causing speed to diminish. At midpoint of orbital dayside, the net force is downward, towards the Earth's atmosphere, where drag increases. If sufficient gel remains unevaporated during the transition back to nightside, there could be acceleration, but the dose of gel is limited to avoid this. Gel balls can be delivered from a standoff distance such that orbital matching need not be perfect, saving time and fuel for the debris-hunter. Larger chunks of debris can be shot with multiple gel balls designed that rupture and wet the surface, similar to a paint marking capsule ("paintball"), to provide more retroforce. For very large objects, such as earth orbit-crossing asteroids, judicious application of volatile material can provide a net force away from the Sun, altering the trajectory sufficiently to avoid impact. This work considers the velocity distribution in a liquid assuming the Maxwell-Boltzmann equation, the vapor pressure using the Clausius-Clapeyron equation, and the evaporative flux using the explicit Schrage equation to model vapor kinetics from the Knudsen layer under direct solar irradiation. A concept of operations for a notional debris-hunter satellite design allows an estimate of debris mass that can be deorbited in a given period of time. From this, and an estimate of launch mass, the number and mass of space junk that can be removed from a higher low-earth orbit (LEO) can be calculated. These expenses are sufficiently smaller than the consequence of a Kessler syndrome to compel spacefaring nations to implement this proactive approach without delay.

Keywords: orbital debris, Kessler syndrome, space junk, evaporative gels

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Introduction

The importance of removing orbital debris is universally recognized. Until now, there has not been a cost-effective solution. The default assumption seems to be that spacefaring nations will react only after the onset of Kessler syndrome. If such a chain-reaction occurs, new satellites to remove debris risk becoming more debris themselves. The result could be a death-spiral for any orbital operations, precluding safe launches for decades.

Existing proposals for debris removal generally involve soft-mating that is expensive in terms of time and fuel. Once connected, any number of deorbiting technologies is envisioned. Once the offending body has been dispatched, the debris removal craft must now accelerate to a new target, and then match orbits again. The on-board fuel reserves for successive rendezvous severely limits the number of pieces of space junk that can be removed.

Other concepts involve ground-based lasers or masers, with ablation on the earth-facing side of the debris. This adds altitude without reducing orbital speed, making the orbit more elliptical in hopes that the lower perigee will "catch" in the atmosphere and increase drag. Lasers from satellites at higher orbit can be more effective but must contend with downrange risks of unintended terrestrial targets. Other objections to coherent radiation include potential weaponization.

Method

Figure 1 shows an illustration of a debris-hunter satellite with a reservoir of gelatinous, dye-filled balls that are fired at a piece of space junk.

The preferred timing for gel ball impact is when the part to be deorbited is within the Earth's umbra. When the body is in quadrature to the Sun-Earth line, sunlight heats the gel ball material, which has ideally spread itself over a portion of the debris surface. The dye materials are chosen so that AM0 sunlight causes evaporation, which will be in opposition to its orbital velocity when at quadrature. As the dye-splattered body is in conjunction with the Sun, the net force of evaporation will be downward towards the Earth. Ideally, the quantity of volatile material will have fully evaporated by the time the body is moving away from the Sun, so that the net force vector is both retro and down relative to the original orbital velocity. The space debris is now moving more slowly and at a lower altitude, sending it deeper into the rarified atmosphere where drag can finish the job of deorbiting.

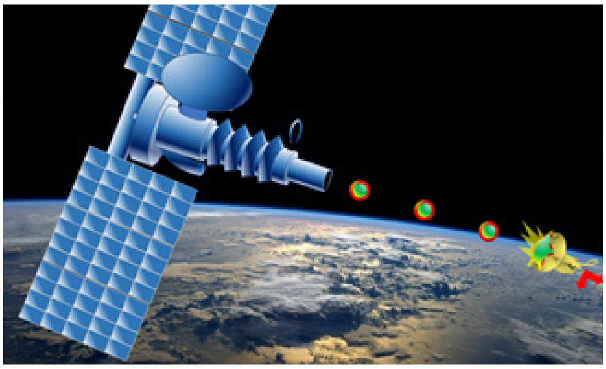

Figure 1 Notional design for debris-hunter equipped with gel balls. Red arrows show net force backward and downward from evaporation.

Note that high angular rates of spin of the unwanted debris body are not necessarily a problem. Depending on the relative velocity of the gel ball upon impact, the worst scenario is that the duty cycle of retroforces is reduced and does not finish in a single orbit. Because there will always be less material as the debris enters the nightside, the net result is backwards and downwards. This is a significant advantage over soft-docking concepts which may not be effective at all for debris with high rates of yaw, pitch, or roll.

The gel ball design in Figure 2 includes an exterior shell that is relatively inert in space, and may be a thin polymer, possibly with laser-inscribed scoring to encourage uniform rupture upon impact with a piece of space debris. The shell should be non-volatile in order to provide longevity in the vacuum of space as the debris-hunter navigates from one quarry to the next. The gel inside should have a low surface tension so that it wets the (likely metal) surface of the target and makes a substantially flat, uniform layer. If the ideal gel material is not dark, a dye or suspension of particles (e.g. lampblack) can be added to increase absorption of sunlight.

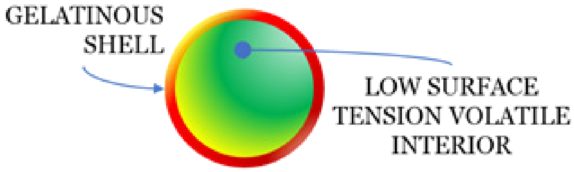

Figure 2 Cross section of gel ball. Interior may be dyed black to minimize albedo.

A method of propulsion for the gel ball is depicted in Figure 3, keeping in mind that the debris-hunter satellite will experience momentum transfer upon discharge, so the aiming must be accurate. An integrated optics package is depicted schematically at the bottom of the figure. A compressed gas cylinder modulated by a controllable valve is one means by which to provide a low-jerk launch of the gel ball. Shown in cross section as red circles are (optional) radio-frequency heating coils that can warm and soften the gel if needed after lingering in shadow. Alternate embodiments for launch are certainly possible, such as a mechanical trebuchet or a rotary centrifuge. The optimization of mass efficiency is left to a later study.

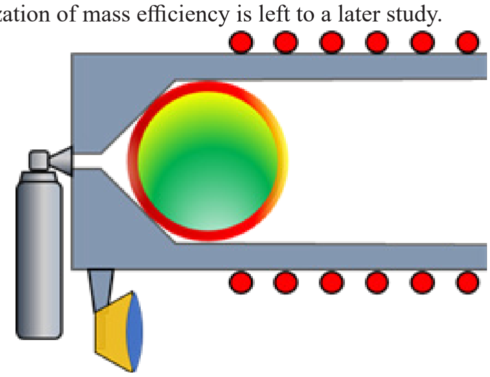

Figure 3 Propulsion methods for gel ball aiming and delivery.

Mathematical treatment

First-order modeling

An ultra-black (albedo < 0.005) object 1 AU from the sun has an equilibrium temperature determined by the Stefan-Boltzmann law of 394 K.[1] The retroforce from evaporation has complex physics, especially in outer space, as described below. However, a starting point can be obtained with several simplifying approximations.

Consider dyed, gelatinized water splashed onto a flat object 10x10 cm and 3 mm thickness (metal plate) such that the liquid is 1 mm thick (10 grams). Assuming similar thermodynamics with pure water, the heat of vaporization is taken as 2.23E3 joules/gm. Geometrically, an integral of cosine-squared over the hemisphere means that only about 31% (π2/32) of the energy is directed normal to the surface. With aluminum having specific density of 2.7, and assuming perpendicular (best case) sunlight, the velocity change imparted to the metal plate is Δv=412 m/s. This can be considered an upper limit because of the simplifications but provides a reference point to validate more-detailed calculations.

Statistical mechanics modeling

The study of evaporation kinetics is not fully mature. The velocity distribution of liquids is commonly assumed to follow the Maxwell-Boltzmann distribution function f(v) even though that was derived for gases assuming they are ideal. A graph of equation (1) has an exponentially decreasing tail of fast-moving molecules, which are those capable of escaping the surface (k is the Boltzmann constant).

$$f(v)\,d^3v = \left[\frac{m}{2\pi kT}\right]^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT}\right) d^3v \tag{1}$$

The mean-free path of molecules in liquid are on the order of molecular diameters. The explicit Schrage improvement of the Hertz-Knudsen equation predicts flux density J across the surface (valid for low Mach numbers).[2,3]

$$J = \frac{2\sigma}{2-\sigma}(2\pi R)^{-1/2}\left(\frac{p_e}{\sqrt{T_L}} - \frac{p_v}{\sqrt{T_v}}\right) \tag{2}$$

Where σ is the evaporation coefficient (assumed equal to the condensation coefficient and both equal to unity) and pe is the equilibrium saturated vapor pressure at the liquidus temperature TL, and subscript v applies to the vapor in the continuum region adjacent to the liquid-vapor interface (Knudsen layer). R is the gas constant. The pressures can be estimated from the Clausius-Clapeyron equation if values are known at either (T,P) point 1 or point 2:

$$ln\left(\frac{P_1}{P_2}\right) = \frac{ÄH_{evap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{3}$$

Substitute (3) into (2) to obtain:

$$J = \sqrt{\frac{2}{\pi R}}\,p_e\left[\frac{1}{\sqrt{T_L}} - \frac{\exp\left(\frac{ÄH_{evap}}{R}\left(\frac{1}{T_v} - \frac{1}{T_L}\right)\right)}{\sqrt{T_v}}\right] \tag{4}$$

Using the vapor pressure of water at the triple point as 0.611 kPa, and enthalpy of 40.65 kJ/mol, and with the vapor temperature taken as 3.1 K, the flux from the surface of the liquid in the example above is -7.8E-9 kg each second. The average velocity of the Maxwell-Boltzmann distribution of a molecule having molar mass M is 481 m/s from:

$$v_{mean} = \sqrt{\frac{2}{\pi}}\sqrt{\frac{2RT}{M}} \tag{5}$$

Those energetic water molecules at the high end of the velocity distribution function are assumed to leave the surface substantially perpendicular. Molecules with lesser speed and off-normal velocity may not escape surface tension. Under this assumption the cosine of the angle is approximately unity. When the duration of this flux is applied over one-quarter of a typical MEO orbital period (12 hours),

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the total change in velocity of the metal plate is Δv=382.6 m/s. This is about 7% lower than the first-order calculation, and is likely a more accurate value.

Results

Using the Omni orbital velocity calculator, a reverse iterative solution can be obtained for the changes in orbital parameters. For the representative piece of debris, having a mass of 0.081 kg, in a lower-end MEO altitude of 10,000 km above the Earth, this velocity change will lower the perigee by 1,150 km. The eccentricity of a formerly circular orbit is increased to 0.07.[4]

This is a modest change. However, the mass flux computed from equation (4) amounts to evaporation of a layer just 0.01mm in thickness. Given the assumption of a relatively thick layer of gel, this amounts to a bit under 1% of the total. Thus, the 1 mm layer assumed above would be sufficient for 100 such orbits. For a plate that retains its orientation relative to the Earth's center, these successive orbits will continue to reduce the perigee. Once it enters higher-drag regions of LEO, the atmosphere will finish the deorbiting process. For a less favorable, and probably less likely, situation in which the debris plate faces the Sun at all times, these successive orbits will continue increasing the eccentricity. This will also have the effect of bringing the undesired object down to altitudes where atmospheric drag can further slow the object through drag and cause it to deorbit.

A gel ball of this volume has a diameter of 7 cm and a mass of 10 grams, or 100 such balls per kilogram of launch mass. The aiming and delivery apparatus of Figure 3, plus a hopper and feeder mechanism may require several of kilograms, including a cold gas reservoir. This is similar in size and mass to a 3U CubeSat. A debris-hunter satellite mass will be dominated by fuel mass to navigate between targets. This task is common to all in situ debris mitigation strategies; however, gel ball delivery can reduce delta-v slightly, and maneuvering time significantly, providing an advantage in debris items served in a given time period. For large objects, such as spent rocket stages or fairings, the debris-hunter can simply pepper the surface with a large number of gel balls.

Planetary defense

These methods of deorbiting can scale, and even be applied to asteroid deflection. Instead of small gel balls aimed precisely from small relative velocities, a large bag of dyed water can be impinged onto the surface of an earth-crossing asteroid at modest speeds (avoiding impact vaporization). A container of water, or other volatile conveniently provided in situ, will need to be heated so that it remains liquid. This can be accomplished through a mesh of resistive elements through which current is passed to avoid freezing into a solid. Concentrated sunlight could also be used to maintain a liquid state until impact.

The sunlit side of the asteroid should be the target, but in general, an asteroid will have some rate of tumble. The liquid, once splashed, will freeze quickly when not exposed to sunlight. In this way, an asteroid is made into a temporary comet. As the ice-coated surfaces swing into sunlight the evaporative pressure applies a thrust that is directed away from the sun regardless of the point in the orbit. Similar to a comet the "tail" will always point toward the Sun. The net effect is to change the orbital trajectory. The precise orbital dynamics are less important in this situation because the primary concern is missing the Earth. Earth is a relatively small target, assuming the asteroid is detected sufficiently early, so even a modest change in orbital parameters can be adequate to protect the planet.

Using the simplistic assumptions of first-order modeling, a spherical bolus of 180 meters diameter, having a relative density of 2.3, and coated with 1000 kg (1MT) of water, the phase change into vapor imparts an energy of 2.23E9 joules. The near-earth object (NEO) mass of 10.5E9 kg will experience a total velocity change of 65 cm per second. Relative to other methods of deflection for an intact NEO, this is a reasonable change. A non-rotating body of this size at AM0 illumination would release this energy in 32 minutes. If the NEO is detected late, a series of one-ton water bags can be peppered into the surface to effect the needed change.[5]

Discussion

Debris mitigation is a looming crisis for all spacefaring nations and companies with ambitions for the resources of outer space. Humanity has a poor history of prevention and will probably wait until a cure is desperately needed the current climate crisis being evidence of this. The only hope to avert disaster is to make prevention sufficiently inexpensive that nation-states will (grudgingly) accept the cost. This remarkably simple method of deorbiting hazardous space junk has the potential to fill that need.

Advantages of this approach include the following:

1. It is low-cost.
2. Effective on tumbling debris, albeit more slowly.
3. It does not add new space junk. Gel balls that miss their target are designed to splatter, not scatter.
4. Gel balls can be aimed such that misses are directed towards the atmosphere.
5. No precise docking is required, so it is faster than other approaches that require close contact.
6. A debris-hunter satellite could be refueled and resupplied with gel balls and go back out on-mission. It might even refuel from defunct satellites!
7. This method can apply to LEO and MEO orbits, and highly inclined orbits.
8. The gel ball impact itself imparts a small amount of delta-v. In fact, this could be used for satellite self-protection.
9. This method scales easily, with multiple gel ball strikes, or to large balls (1.6 m dia.) for asteroids.

As experience grows with this new method of orbital control, the technology may reach sufficient maturity to be used for asteroid capture. A great boon to Earth's economy could be realized by retrieving a resource-rich asteroid for processing, although other method of orbital manipulation may also be required. With sufficient time, and a fortuitous initial trajectory, splashes of water could be used to bring vast wealth in catalyst metals, rocket fuel, and habitat requirements to the convenience of Earth's neighborhood.

This introductory work covers the basic concept and a simplistic assessment of orbital parameters. Further work can beneficially focus on details of specific orbits, debris sizes, and degrees of tumble. A multi-physics model may be required for on-orbit calculation of the timing and number of gel balls to direct to a given target. Further research is also warranted in gel ball materials selection, as they must survive launch and the consequence of broken capsules would be dire. For planetary protection, testing this concept with a cubic meter bag of black gel impacted into a remote asteroid would seem to be a low-risk, relatively low-cost validation of how to save the Earth.

Conclusions

A low-cost method of expeditiously removing space junk has been presented here for the first time. The beauty of the concept is its simplicity, using technology that already exists, and that can be deployed rapidly at relatively low launch mass. The prospects for cleaning up Earth orbit to protect the assets currently deployed, and for the ambitious plans for the future can be realized with this innovative approach. A mathematical treatment of the deorbiting capability for a representative piece of debris shows that this simple method can be highly effective. With all these advantages, responsible spacefaring nations should aggressively cooperate to implement this straightforward method to clean up the messes they have left in orbit, and prevent a Kessler syndrome from ever happening.

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Conflicts of interest

The author asserts no conflicts of interest.

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