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A Simple Shock Wave-Based Mechanism for Forward-Accelerated Fragment Generation from Anti-Satellite Impacts

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1. Introduction

The anti-satellite (ASAT) test conducted by the US in 1985, using the Solwind P78-1 satellite as a target and an F-15 fighter-launched missile as the interceptor, resulted in the generation of three fragments that had a significantly higher apogee than the original satellite. The fragments (size > 10 cm) had an apogee of 1800 km, compared to the original satellite altitude of 530 km. (Tan et al., 1996) Other fragments were reported to have reached a maximum altitude of 2800 km. (Chobotov & Spencer, 1991) These fragments must have been accelerated to a velocity 500 m/s greater than the original velocity of the satellite in order to have raised their apogee by this amount (their perigee remained approximately at the altitude of the original satellite at the time of impact). A reconstruction of the velocity vectors of the fragments after impact by T.S. Kelso indeed showed the maximum velocity fragment was accelerated forward in the direction of the original satellite orbit. (Remillard, 1990) The mechanism by which this occurred was the subject of considerable discussion in the post-mortem analysis of the test.

More recently, the Chinese ASAT test conducted on 11 January 2007, also resulted in fragments being lofted into orbits with apogees as great as 3500 km, compared to the original 860 km orbit of the Fengyun 1C satellite. Analysis of the tracking data by Forden (2008) showed that roughly half of the 40 debris fragments tracked by NORAD had an increased longitudinal velocity along the original orbit, with the increase in fragment velocity as great as 600 m/s compared to the original orbital velocity of the satellite. The increases in fragment velocity in the radial and transverse planes were not as significant, similar to the fragmentation of Solwind P78-1.

The planned intercept of the NRO satellite USA 193 by the US has again raised the issue of debris generation by ASAT events. In particular, since the intercept is planned to occur at a low altitude (240 km) just prior to the anticipated reentry of the satellite, only fragments that are accelerated in the prograde direction represent a significant threat to other satellites. Any other fragments generated are likely to have an even lower perigee than the original satellite and reenter promptly (within a few orbits to a few days). Fragments that could be generated with a significantly higher apogee while retaining the same perigee could last days to weeks and represent an impact hazard for other spacecraft.

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Since the interceptor in these types of ASAT tests are on ballistic trajectories with the intercept occurring near the maximum altitude of the interceptor, the kill vehicle's velocity is much less than orbital velocity. Thus, the interceptor is, in fact, impacted by the satellite. The mechanism by which fragments from this impact can significantly exceed the initial velocity of the satellite has not been clearly established. Traditional models of fragment generation by explosions and collisions on orbit are based on statistical correlations of fragment size and velocity distribution (Barrows et al., 1990; Chobotov & Spencer, 1991; Tan et al., 1996; Johnson et al., 2001). Empirical fits to fragment size distributions are used along with partitioning of the kinetic energy dissipated in a plastic collision to estimate the velocity of fragments, which are assumed to expand symmetrically away from the center of mass of the original satellite or the satellite/impactor system. These models do not incorporate any detailed mechanism deriving from the fundamental physics of hypervelocity impacts. These models work well when they are "pegged" by specifying the maximum and minimum sized fragments generated. While these models are calibrated with data from laboratory impact tests and actual on-orbit events, using these models for events such as ASAT tests involves extrapolating the correlations to conditions outside the range over which they have been calibrated. Further, these models cannot account for the apparently selective acceleration of fragments in the prograde direction along the original orbit, since they assume an isotropic distribution in the direction of fragment velocity vectors.

Detailed experimental investigations of hypervelocity impacts of projectiles on thick target plates have shown that ejecta can "splash back" or "ricochet" (in the case of highly oblique impacts) in the direction opposite to the impactor's original velocity. (Schonberg, 2001; Mandeville et al., 1999) Lateral jets generated in the impact can greatly exceed the original impactor velocity, however the mass and particle size of these jets is too small by orders of magnitude to account for the large fragments observed from ASAT tests. A debris cone is also observed to move backwards with a velocity and total mass approaching that of the impactor, but again the material is highly comminuted, with the smallest particles having the greatest velocity. While the existence of a backward-moving ejecta spray is a well-established fact, the mechanism of its generation should be explained in terms of wave interactions within the bodies involved in the impact. Since this phenomenon has only been studied in the lab using small projectiles (< 1 cm), is it not known if this mechanism is capable of launching 10-cm-sized fragments observed in the prior ASAT tests. Finally, material from the target plate adjacent to the impact site may spall and fly backward; however, the velocity of these fragments is typically on the order to 10-100 m/s, to slow to account for the faster fragments seen.

The purpose of the present analysis is to explain a simple shock wave mechanism by which fragments can be accelerated to velocities significantly greater than the original spacecraft velocity. The considerations here are only one-dimensional, meaning that only impacts occurring in the direction of the original satellite orbit are considered. It may be argued that only impacts occurring axially along the original spacecraft direction can result in fragments that have in increased apogee while retaining the original perigee of the spacecraft. However, limiting our examination to just one-dimensional impacts is mainly for simplicity and clarity of the explanation. The analysis is not intended to provide a realistic simulation of the details of an actual satellite impact. These types of models can be (and have been) extended to more realistic oblique impacts, see Schonberg (1999) for an example of how this is done.

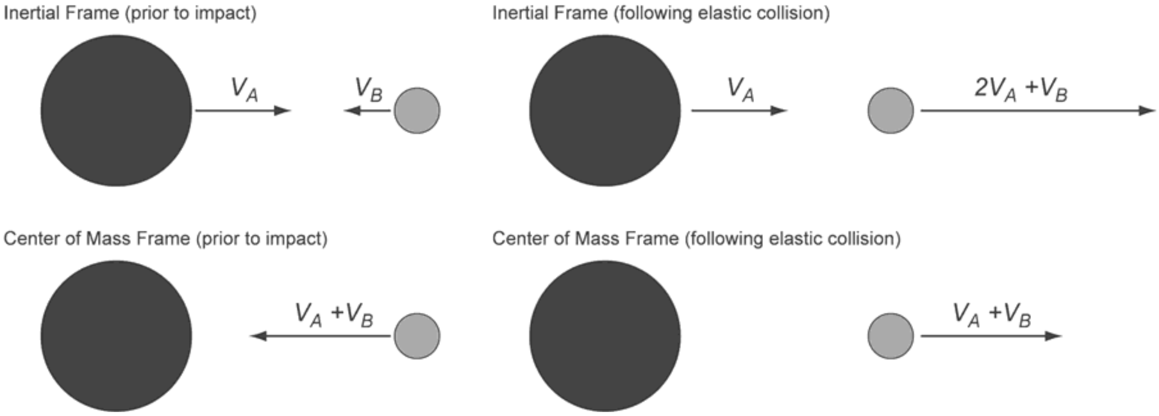

Figure 1: Model of elastic collision, conserving both mass and momentum, of a massive body *A* into a light body *B*.

2. Elastic Collision Model

A simple elastic collision model (the "ping-pong ball" model) was discussed by Forden (2008) in order to provide an explanation as to how the Fengyun 1C ASAT test could have resulted in higher velocity fragments. In this model, a heavy object (the satellite or dense "superball") impacts a light object (the impactor or light "ping-pong ball") resulting in an elastic collision that conserves kinetic energy. In the center of mass frame (essentially, the reference frame of the heavy object), the velocity of approach of the light object is reversed upon impact, as shown in Fig. 1. Transforming back to the original reference frame by adding the heavy object's velocity, the light object is seen to have been accelerated to a velocity greater than the original heavy object. In the limit of a large mass ratio between the two objects, an initially stationary, light object can be accelerated to twice the velocity of the heavy object, with the heavy object only decelerating incrementally, as given by the mass ratio. This mechanism would predict that fragment velocities of 15 km/s or greater can be produced by impacts in LEO.

While this model is illustrative of the possibility of fragment acceleration, the assumption of an elastic impact is highly idealized. No collision happening at hypervelocity is elastic. If the impact is assumed plastic (i.e., the two bodies collide and stick), no direct mechanism for fragment acceleration exists, although energy dissipated in the impact may result in fragments being ejected outward. This mechanism is incorporated into orbital debris simulation models discussed above.

3. Shock Wave Model

The actual mechanism by which hypervelocity impacts impart velocity to the fragments generated is via shock waves and subsequent wave dynamics within the bodies involved in the impact. A simple scenario where a thick body (corresponding to a satellite component) impacts a thin body (a piece of the interceptor)

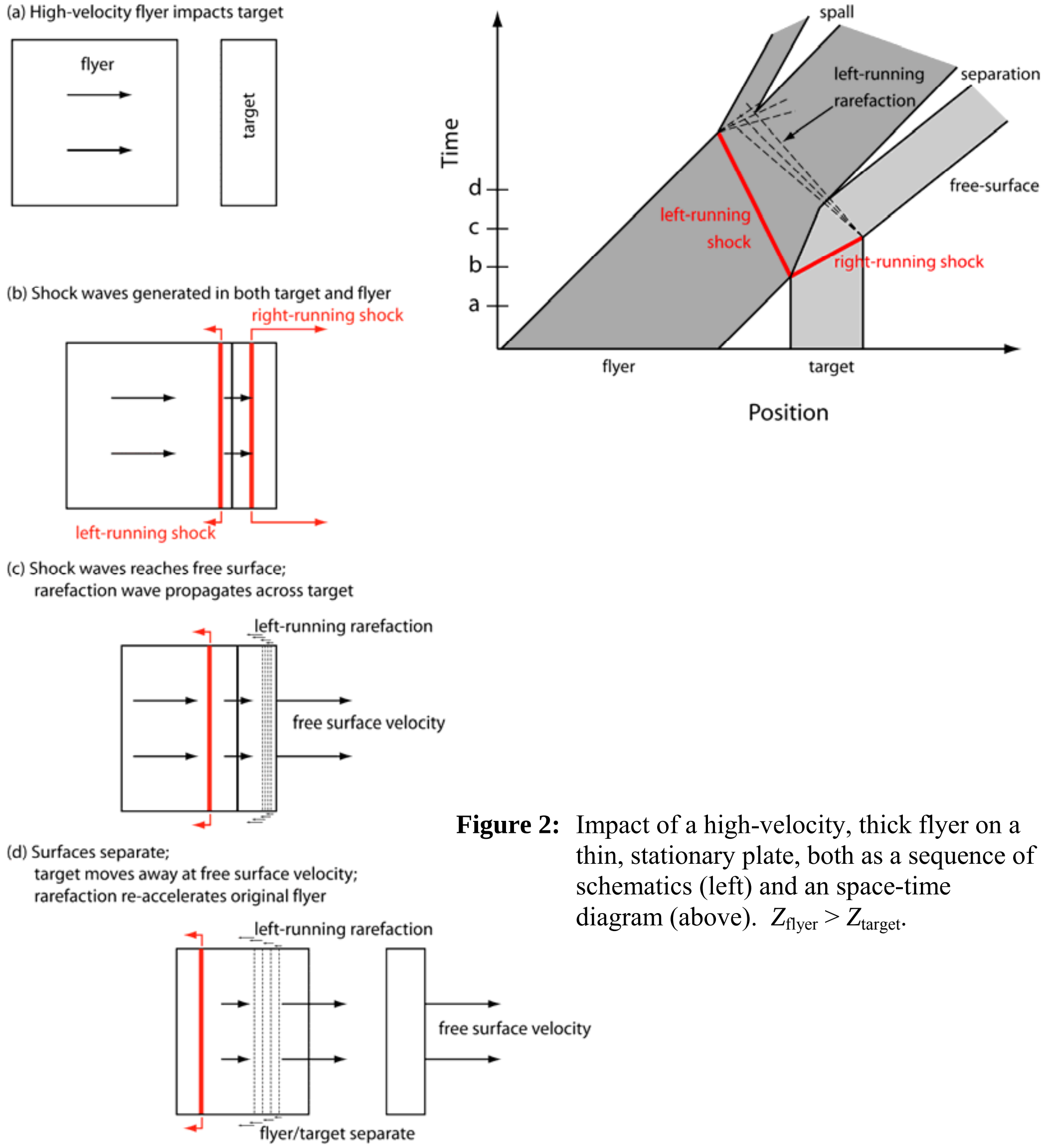

Figure 2: Impact of a high-velocity, thick flyer on a thin, stationary plate, both as a sequence of schematics (left) and an space-time diagram (above). $Z_{\text{flyer}} > Z_{\text{target}}$.

is shown in Fig. 2 as a sequence of cartoons and a space-time (*x*-*t*) diagram. This impact is assumed to be uniaxial (i.e., head-on with no transverse component). At the instant of impact, a shock wave is transmitted forward into the target (which, confusingly, is actually the interceptor) and a second shock is sent backward into the flyer (the original satellite). The forward shock will be referred to as the “right-running” shock and the shock sent back into the flyer is the “left-running” shock in Fig. 2. These shock waves act to accelerate the target and decelerate the flyer, with the interface of the two moving at the same velocity, since the two materials cannot mix or pass through one another on the timescale of the impact. This requirement provides the key condition to solve for the strength of the shock waves generated. The shock waves also increase the pressure of the material they pass through, typically to 10-100's of GPa's for orbital velocity impacts (100,000's to 1M's bar pressure). These pressures greatly exceed the yield strength of almost all materials, and as a result, the strength of materials is largely negligible in modeling impacts. Indeed, under these types of shock loadings, even metals flow almost as liquids, which is why computer codes that model hypervelocity impacts are referred to as "hydrocodes."

When the shock wave in the target reaches the front surface, the material is free to depressurize from the enormous shock pressure generated. The material does this by expanding forward as a "free surface" and a rarefaction (or expansion) wave is sent backward in the left-running direction into the target, pulling material to the right. When this expansion reaches the interface between the flyer and target, complex wave interactions may occur. As will be discussed below, for the scenario of interest for the generation of high-velocity debris, the surfaces will separate, and the target will move away from the flyer to the right. The key question this analysis seeks to answer is: ***Can the target move away from the impact at a greater velocity than the original flyer?***

To analyze this mechanism quantitatively, the conservation laws of mass, momentum, and energy as applied to a shock wave are used. These conservation laws provide relationships between the pressure, density, the shock wave velocity, and material velocity induced by the shock. In essence, for a given initial state of a material, once one parameter of a shock wave is fixed (say, the pressure generated), then all the other parameters (shock velocity, material velocity, density) are determined. These relations, as dictated by the conservation laws, are usually expressed as curves on the pressure-density (or pressure-specific volume P-v) plane called *Hugoniots*. The Hugoniot of a given material is the relation between pressure and density for a shock wave. The curves are material-depended and, in general, must be measured experimentally.

The most reliable technique to measure the Hugoniot of a material is to perform an actually hypervelocity impact in the laboratory, just as shown in Fig. 2. Measuring pressure and density in a dynamic shock wave experiment lasting only microseonds is very challenging, so usually the shock velocity and material velocity induced in the target are measured instead. For most materials, the relationship between these two (shock velocity U_s and particle velocity u_p) is nearly linear. The Los Alamos National Laboratory has compiled a large database of these type of measurements made over the last 50 years (Marsh, 1980), and a Web-based database of similar Russian data is now available (Bushman et al., 2003). This data can be trusted with a very high degree of confidence. Indeed, shock Hugoniots are used to calibrate almost all other types of high dynamic pressure instrumentation. The U_s–u_p Hugoniots of several materials of interest in modeling spacecraft structures are shown in Fig. 3 (aluminum, titanium, beryllium, magnesium), along with simple linear fits to the data that will be used in the analysis here.

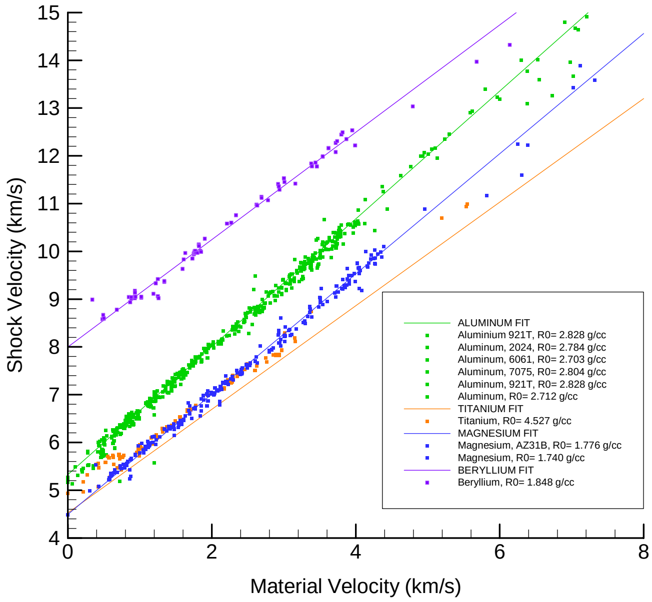

Figure 3: Measurements of shock velocity vs. material velocity (U_s-u_p) for various materials used on spacecraft. Each point represent a flyer plate-driven shock experiment (Marsh, 1980, Bushman et al., 2003). Lines are linear fits used in this analysis.

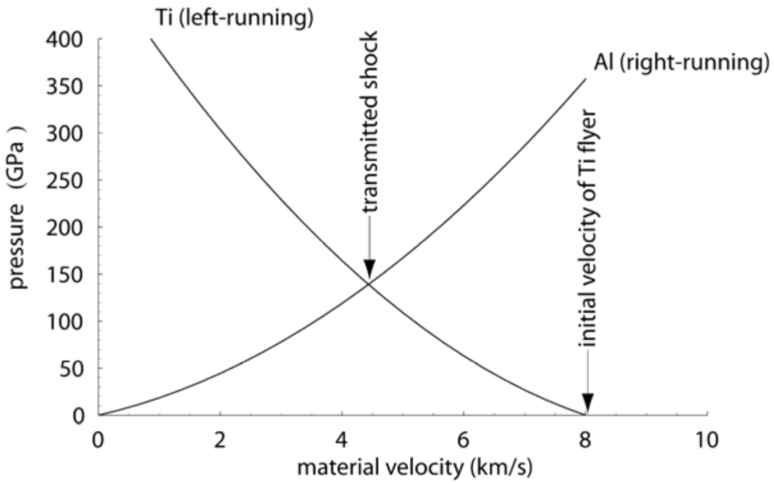

Figure 4: Shock waves in aluminum (initially at rest) and titanium (initially at 8 km/s), represented by Hugoniots on the P–u_p plane, derived from the data of Fig. 3.

To solve for the impact scenario shown in Fig. 2, it is convenient to plot the Hugoniot relations representing mass, momentum, and energy conservation in the P–u_p plane (pressure vs. material velocity). These curves represent the pressure generated by a shock versus the velocity of the material that has been shocked. For a given initial condition, there are two such curves: one for the right-running shock that induces material motion in the positive direction, and another for a left-running shock that induces motion in the negative direction. For example, if a thick titanium flyer (satellite component) at 8 km/s impacts a stationary thin aluminum plate initially at rest, the right-running shock in aluminum must have a pressure and induced material velocity that lies along the "Al" curve in Fig. 4. Likewise, the left-running shock that propagates back into the titanium moving initially at 8 km/s must lie along the "Ti" curve. Recall that the interface between the two materials must have the same velocity. Further, the interface must be at the same pressure, since an interface between two materials cannot support a pressure difference. In other words, once shocked, the material must behave hydrostatically. These two conditions are satisfied by the intersection of the "Al" and "Ti" Hugoniot curves on the P–u_p plane, and this determines the strength of the shock waves generated. Thus, for this example, we can say that a 139 GPa shock wave is generated that accelerates the aluminum target to 4.43 km/s and also decelerates the titanium flyer to the same velocity.

The relations to generate these curves and basic Hugoniot data can be found in a number of textbooks on shock waves or explosives. (Zukas, 1990l; Zukas & Williams, 2003; Cooper, 1996) The textbook by Cooper (1996) is particularly recommended for its clear development of this type of analysis and step-by-step worked-out examples.

When the shock wave reaches the free surface, the material is now free to expand and depressurize. This occurs via a rarefaction (also called expansion) wave that propagates back into the aluminum. This is not a shock wave (an expansion shock would violate the Second Law of Thermodynamics) and does not obey the Hugoniot relations. The rarefaction wave is a smooth, continuous wave that is very nearly isentropic, and the thermodynamic path for a rarefaction follows the isentope. However, for the purpose of engineering calculations, for many materials (including those considered here) the isentrope can be shown to be very closely approximated by using the shock Hugoniot. This assumption is routinely made in simple shock wave calculations and usually gives results in acceptable agreement with experiment. More accurate models require using sophisticated equations of state (e.g., the Grüneisen equation of state) for which simple analytic solutions are no longer possible.

Using the Hugoniot to solve for the rarefaction wave that occurs when the shock reaches the free surface is equivalent to "mirroring" the original Hugoniot about the point at which the interaction occurs. Thus, if we mirror the aluminum Hugoniot about the shock point in Fig. 4, we obtain the curve for the left-running expansion wave (see thick dashed curve in Fig. 5). Since this wave is expanding the material to vacuum, it must bring the pressure on the free surface to zero. Thus, the solution for the expansion wave is the point where the dashed line reaches zero pressure (i.e., where it intercepts the x-axis). This point determines the velocity of the material of the surface that is expanding to zero pressure. Note that, in this example, the velocity of the aluminum is 8.870 km/s, or 870 m/s *faster* than the original titanium flyer. This provides a mechanism for the generation of higher velocity fragments via impact.

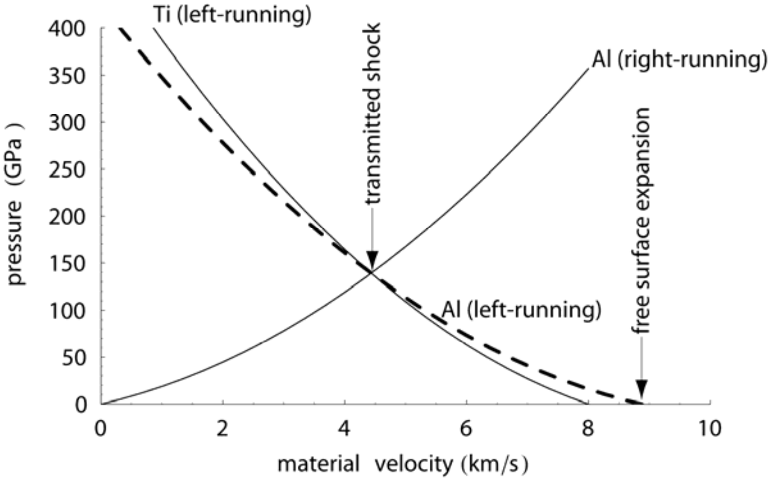

Figure 5: Rarefaction wave in aluminum (dashed line) releasing pressure to zero and accelerating plate to 8.87 km/s.

When the rarefaction wave reaches the titanium-aluminum interface, it is reflected as another rarefaction that now propagates to the right as well as transmitting a rarefaction into the titanium. These two rarefactions pull in opposite directions, and will pull the aluminum/titanium interface apart. The rarefaction that continues into the titanium acts to re-accelerate it. If the flyer is very thick, it can be shown that the ensuing wave reflections will eventually reaccelerate the flyer to near its original 8 km/s, although the original flyer cannot go faster.

If the original flyer was thin, then another rarefaction can occur when the first left running shock encounters the free surface on the back of the flyer. This right-running rarefaction can interact with the left-running rarefaction from the front free surface, resulting in material being pulled in opposite directions inside the target (or flyer). If this tension exceeds the strength of the material, it can be ripped in two (or more) pieces. This is the well-known phenomenon of “spall” which can be important in hypervelocity impacts. In Fig. 2, the flyer was sufficiently thick that the interaction of rarefaction waves resulting in spall occurred in the flyer, after the target had been launched by the impact. The fragments generated by spall are in general slower than the free-surface material moving at 8.870 km/s discussed above. Their velocity can be estimated by an analysis found in Kanel et al. (1996). Thus, the free surface velocity represents the greatest velocities that can likely be generated from an impact.

If we return to the original example (Fig. 2) and reverse the materials by having an aluminum flyer (i.e., satellite component) impact a titanium target (i.e., impactor), the resulting shock interaction is shown in Fig. 6. Note that the denser, stiffer titanium target resists the impact of aluminum better than the converse, such that the titanium free surface velocity is only 7.13 km/s. Thus, any titanium fragment generated will be 870 m/s slower compared to the original orbital velocity. It can further be shown that the flyer and

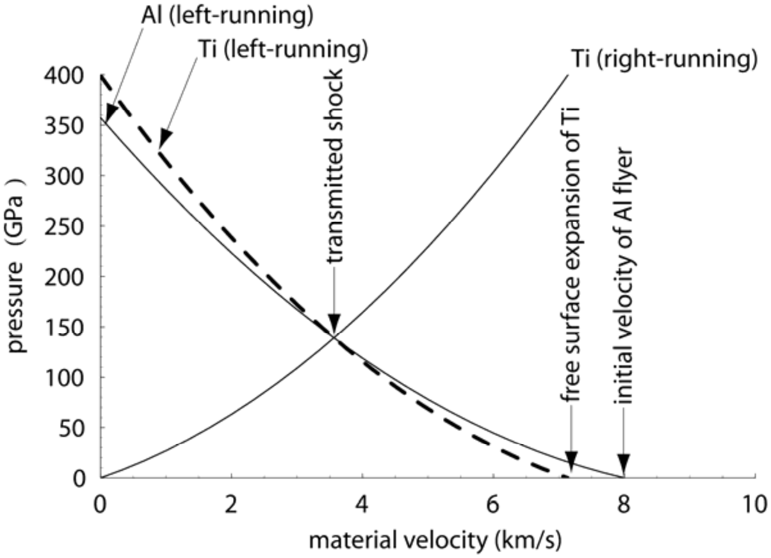

Figure 6: Aluminum flyer impacting titanium plate. Note that titanium is only accelerated to 7.13 km/s.

target do not separate in this case. (Cooper, 1996) This is similar to the "ping-pong ball" model where the roles are reversed and a light ping-pong ball impacts a heavier ball; the heavier ball will hardly be accelerated.

For shock wave interactions, the key parameter that determines whether a faster or slower fragment is generated is the shock impedance Z, which is given by the product of the shock velocity and the density of the material. If the flyer has a greater shock impedance than the target, a faster fragment will be generated. If the flyer is a low impedance material, then only slower fragments will be generated. For quick estimate purposes, the acoustic impedance (sound speed times density) can be used instead of the shock impedance. Thus, an aluminum satellite piece ($c_o\,\rho = 5100$ m/s × 2700 kg/m^3 = 13.8 × 10^6 kg/m^2-s) hitting a magnesium interceptor ($c_o\,\rho = 8.0 \times 10^6$ kg/m^2-s) will generate a fragment faster than the original satellite, but the same aluminum satellite piece hitting a titanium ($c_o\,\rho = 18.7 \times 10^6$ kg/m^2-s) will only generate slower fragments.

It is interesting to consider the highest possible velocity that can be generated in such an impact. For example, tungsten has a very high impedance ($c_o\,\rho = 100 \times 10^6$ kg/m^2-s), which is why it is use from armor penetration in military projectiles. The impact of an 8 km/s tungsten flyer on a stationary magnesium target is shown in Fig. 7. Note that since tungsten is very dense and stiff, its P–u_p Hugoniot is very steep, such that the magnesium Hugoniot upon expansion is nearly mirrored about the flyer's initial velocity. This results in a very high material velocity of the free surface expansion (13.3 km/s). In the limit of infinite impedance (vertical P–u_p Hugoniot), the free surface velocity will be twice the flyer's initial velocity

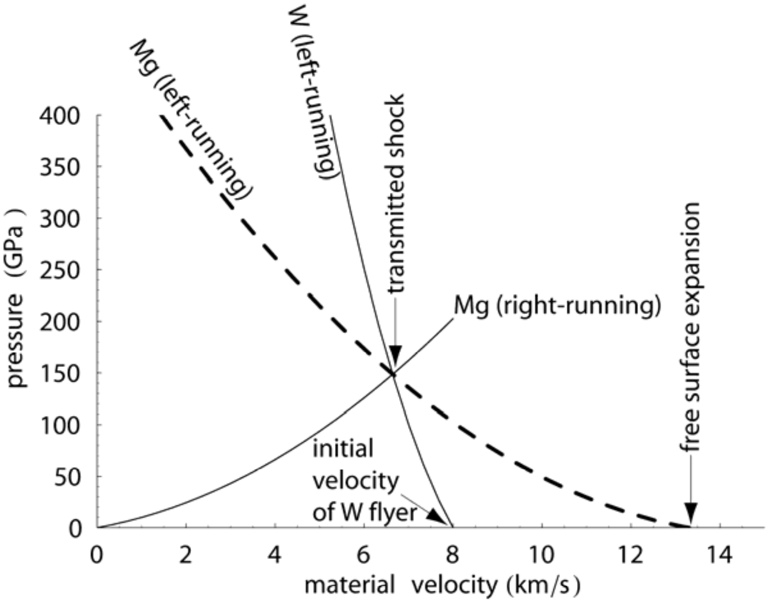

Figure 7: A tungsten flyer impacting a magnesium plate. Note the density and stiffness of tungsten result in a large acceleration of the light magnesium.

(16 km/s, in this example). Interestingly, this limiting case recovers the elastic "ping-pong" ball results, in which the relative velocity of approach equals the relative velocity of departure, and an initially stationary body can be accelerated to twice the velocity of the body impacting it. For the rest of this analysis, only these types of impacts (i.e., those that generate faster fragments) are considered, although we limit our attention to realistic spacecraft materials.

It might be argued that this analysis is overly idealized, with perfectly flat impactors being struck by perfectly flat satellites head-on. It is possible to extend this analysis to examine impacts with transverse components, as done by Schonberg & Ebrahim (1999). In fact, the calculations remain essentially the same, only with a transverse velocity component added onto the axial velocity vectors of Fig. 2. Further, even the very complex dynamics of a complete spacecraft colliding with another body at hypervelocity consists of a superposition of local collisions that follow the scenario outlined here (shock wave transmission followed by free surface expansion). Again, material strength is largely negligible at these speeds, so a complex assembly like a spacecraft can be thought of as an ensemble of unconnected parts. To the authors' knowledge, more complex, multidimensional impacts cannot result in fragments being launched to speeds significantly exceeding those calculated here, although we have not rigorously proven this to be the case. Further, it is possible for multibody impacts to generate even greater velocities (i.e., a heavy object striking an intermediate object, which then strikes a light object). Indeed, this technique has even been used in the laboratory to generate very fast projectiles. (Bat'kov et al., 1997, for example) However, utilizing this technique requires very carefully designed impactors and precise experimental conditions that would be unlikely to occur in an unorganized satellite collision. In other words, the estimate of free surface expansion is already an idealized scenario in which a thick satellite component hits a thin impactor component face-on. Thus, these calculations likely represent the maximum fragment velocity that can realistically be generated.

4. Results for Possible Impact Scenarios

In order to get a feel for the type of high velocity fragments that can be generated by the shock wave mechanism, three different scenarios are considered. The interceptor is assumed to be a missile in ballistic flight, near its apogee. The velocity of the interceptor with respect to the inertial frame is assumed to be as fast as 1 km/s, which is consistent with estimates of the kill vehicle velocity at the time of the 1985 Solwind satellite ASAT test. (Tan, 1996) In the first scenario, a retrograde interceptor (i.e., an interceptor that moves in the direction opposite to the prograde satellite) is assumed to be moving at 1 km/s and is impacted by a satellite with an orbital velocity of 8 km/s for a relative velocity at impact of 9 km/s. In the second scenario, the interceptor is at rest and is impacted by an 8 km/s satellite. In the third scenario, the interceptor is in prograde motion at 1 km/s when it is overtaken by an 8 km/s satellite, resulting in a relative velocity at impact of 7 km/s.

The materials considered are a titanium satellite component impacting an aluminum impactor.

The resulting free surface velocity following impact is shown in Table 1, giving the ΔV increase in fragment velocity above the initial velocity of the satellite. Also shown in Table 1 are the ΔV's as predicted by the elastic collision "ping-pong ball" model discussed in Section 2. The shock wave/free expansion mechanism described here predicts fragments having a ΔV of as much as 1 km/s above the satellite's original velocity for a prograde intercept. The more likely case (Scenario 2, with interceptor essentially at rest) results in a ΔV of 870 m/s, a result that is quite consistent with the ΔV's observed with the 1985 Solwind and 2007 Fengyun 1C ASAT events.

Table 1: Fragment Velocities for Titanium Impacting Aluminum [km/s]

Flyer (satellite) velocity	Target (interceptor) velocity	$(\Delta V)_{\text{shock model}}$	$(\Delta V)_{\text{elastic model}}$
8.0	−1.0	0.95	9.0
8.0	0.0	0.87	8.0
8.0	1.0	0.79	7.0

5. Discussion

The mechanism of fragment generation proposed here (shock wave transmission followed by free surface expansion) undoubtedly occurs in actual impacts on satellites. It is the fundamental wave interaction that occurs in all hypervelocity impacts, and it in turn is the mechanism underlying phenomena such as spall, ejecta, jetting, etc.

By considering a highly idealized case, the likely maximum fragment velocity that can be generated was found to be around 1.8 km/s. More realistically, this mechanism predicts fragment velocities of 600-800 m/s, consistent with those observed in prior ASAT tests.

While the elastic "ping-pong" ball model is very instructive in explaining how faster fragments can be generated, it is worth pointing out some of the similarities and differences with the more detailed shock wave mechanism described here.

Similarities:

- Only the initially slower body (the impactor) can be accelerated to speeds greater than the originally faster body (the satellite). The faster body (satellite) is always decelerated.
- Only lighter (lower impedance) impactor components can be accelerated by impact of heavier (higher impedance) satellite components.
- The maximum theoretical increase in velocity of the accelerated body is twice the relative velocity between the two bodies, which occurs in the limit of an infinite mass ratio for the elastic collision model and with an impactor of infinite impedance for the shock wave model.

Differences:

- The elastic impact model predicts the greatest velocity fragments will occur when impactor is retrograde, since this scenario has the greatest relative velocity between the two bodies. In the shock wave model, the velocity of the fragment does increase with relative velocity, but not as quickly.
- In the elastic model, the masses of the body are the governing parameter. In the shock wave model, it is their impedance (density times shock/sound speed).

6. Implications for the Intercept of USA 193

The results of this shock wave mechanism for fragment acceleration, like that of the "ping-pong ball" model, suggests that *only the mass of the impactor can generate fragments with a significantly greater velocity than the original satellite*. More complex mechanisms for forward-accelerated material, such as the ejecta from an impact, also scale with the impactor mass. Since the impactor for the planned USA 193 intercept is only 20 kg in mass, this would place an upper bound on the amount of material that can be significantly accelerated to high velocity and, thereby, into a higher apogee orbit. The satellite itself is always decelerated in any uniaxial shock wave interaction.

Predictions that this event could generate substantially more threatening orbital debris than the Chinese ASAT test due to USA 193's greater mass appear overly pessimistic. (Than, 2008; *Physics Today*, 2008) In comparing this planned intercept to the Fengyun 1C event, it should be pointed out that the interceptor in that case was estimated to be 600 kg in comparison to the 800 kg target satellite. (Forden, 2008) Thus, the Fengyun 1C event represented a one to two orders of magnitude greater potential for the generation of higher velocity debris.

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