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AUTHOR(S): Johndale Solem Theoretical Division

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Interception and Disruption

Johndale C. Solem
Los Alamos National Laboratory

Given sufficient warning we might try to avert a collision with a comet or asteroid by using beamed energy or by using the kinetic energy of an interceptor rocket. If motivated by the opportunity to convert the object into a space asset, perhaps a microgravity mine for construction materials or spacecraft fuels, we might try a rendezvous to implant a propulsion system of some sort. But the most cost-effective means of disruption (deflection or pulverization) is a nuclear explosive. In this paper, I discuss optimal tactics for terminal intercept, which can be extended to remote-interdiction scenarios as well. I show that the optimal mass ratio of an interceptor rocket carrying a nuclear explosive depends mainly on the ratio of the exhaust velocity to the assailant-object closing velocity. I compare the effectiveness of (1) stand-off detonation, (2) surface burst, and (3) penetration, for both deflection and pulverization, concluding that a penetrator has no clear advantage over a surface-burst device for deflection, but is a distinctly more capable pulverizer. The advantage of a stand-off device is to distribute the impulse more evenly over the surface of the object and to prevent fracture, an event which would greatly complicate the intercept problem. Finally, I present some results of a model for gravitationally bound objects and obtain the maximum non-fracturing deflection speed for a variety of object sizes and structures. For a single engagement, I conclude that the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. Furthermore, the non-fracturing deflection speed is somewhat dependent on the number of competent components of the object, the speed for a 13 component object being about twice that for a 135 component object. Generalizations indicate: (1) asteroids more than 3 km in diameter can be most efficiently deflected with a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected with a stand-off device; (3) smaller asteroids are best pulverized.

Introduction

Many schemes have been devised to deflect or pulverize comets and asteroids bent on colliding with our fair planet (Canavan and Solem, 1992; Canavan and Solem, 1993; Canavan *et al.*, 1994; Ahrens and Harris, 1994; (Simonenko *et al.*, 1994). Reaction devices have been proposed that require landing on the object quite some time before the impending collision and setting up a rather elaborate propulsion power plant. These include very-low-specific-impulse devices such as mass drivers (O' Neill, 1977), which are essentially electromagnetic bucket brigades that scoop up material from the object and expel it into space with physics reminiscent of a conveyor belt. They also include high-specific-impulse devices such as nuclear-reactor rocket engines that use volatiles from the object as a propellant (Willoughby, 1994). Albeit with exceedingly low thrust, solar sails (Friedman, 1988; Wright, 1992; Melosh *et al.*, 1994) have also been proposed to gently drag the threatening object off its course. Beamed energy has been suggested in the form of high-power laser or microwave sources to heat and blow-off material from the object's surface, thereby providing a high-specific-impulse rocket with a remote power source. Solar collectors have been designed to focus the sun's radiation onto the object and thereby produce a modest vapor blow-off during a protracted encounter (Melosh *et al.*, 1994), producing a gradual acceleration and deflection. Kinetic energy devices seem quite viable for both deflection and pulverization, (Solem, 1993a; Solem, 1993b; Solem, 1993c; Solem, 1994a; Solem, 1994b; Melosh *et al.*, 1994) because of the enormous energies involved in orbital collisions.

Exploration of the myriad alternatives is a wonderful stimulus to the imagination and makes an for an excellent set of exercises for undergraduates. I mean this only in a positive sense. In 1967, remarkably a dozen years before Alvarez's pronouncement on the cause of the Cretacious-Tertiary extinction, and inter-departmental student project at the Massachusetts Institute of Technology was addressed to intercepting a hypothetical collision with a one-kilometer asteroid, *Icarus* (Kleiman, 1968). The students solution, however, was to use nuclear explosives. Specifically, they proposed deploying six *Saturn V* carrying 100-MT warheads.

We would like to find solutions other than nuclear explosives. Clearly, the arms-control, safety, and nonproliferation implications are horrendous. But a practical technology beyond nuclear explosives has yet to emerge. The most nearly competitive technology is the kinetic energy device. The specific energy of an interceptor spacecraft at typical orbital speeds is several hundred times that of high explosive. However, the specific energy of a nuclear explosive is several million times that of high explosive. The kinetic energy device to deflect a kilometer-size object is an unimaginable leviathan (Solem, 1993a; Solem, 1993c). At this time, and probably for decades to come, the only thing we have is a nuclear explosive.

This paper gives a cursory discussion of three subjects related to the deflection or pulverization of NEOs using nuclear explosives. First I discuss the problem of terminal intercept, the tactics that may be used when there is little warning and how those tactics may be optimized. Second, I present some conclusions concerning modes of engagement, the surface burst, the stand-off detonation, and the penetrator. The justification for these conclusions resides mainly in prior publications. Third, I show some limitations on the velocity increment that can be imparted in a single engagement, if the object is modeled as a gravitationally-bound agglomeration (flying rubble pile).

Terminal Intercept, Tactics, Optimization

The final velocity of an interceptor missile relative to the Earth, or the orbit in which it is stationed, is given by,

$$V = v_x \ln \frac{M_i}{M_f}, \tag{1}$$

where M_i and M_f are the initial and final mass of the interceptor and v_x is the rocket exhaust velocity. The time required to reach this relative velocity will be short compared to the total flight time. The time elapsed from launch to intercept is

$$\Delta t = \frac{R_l}{v+V}, \tag{2}$$

where R_l is the range when the interceptor is launched and v is the speed at which the object is closing on the Earth. So the range at intercept is

$$R_i = R_l \left(1 - \frac{v}{v+V}\right). \tag{3}$$

If the nuclear explosion gives the object a transverse velocity component $v_\perp$ then the threatening assailant will miss its target point by a distance

$$\varepsilon = R_l \frac{v_\perp}{v} \left(\frac{V}{v+V}\right), \tag{4}$$

where we have neglected the effect of the Earth's gravitational focussing and used a linear approximation to Keplerian motion. The nuclear explosive will blast a crater on the side of the object. The momentum of the ejecta would be balanced by the transverse momentum imparted to the object. From Glasstone's empirical fits (Glasstone 1962), the mass of material in the crater produced by a large explosion is

$$M_e = \alpha^2 E^\beta, \tag{5}$$

where α and β depend on the location of the explosion, the soil composition and density, gravity, and a myriad of other parameters. Clearly the *crater constant* α and the *crater exponent* β will vary depending on whether we are considering an assailant composed of nickel-iron, stony-nickel-iron, stone, chondrite, ice, or dirty snow. For almost every situation involving a surface explosion, however, we find $\beta \simeq 0.9$. This has now been extensively verified by numerical simulations (Solem and Snell, 1994).

Only a fraction of the nuclear explosive's energy is converted to kinetic energy of the ejected or "blow-off" material. Let this fraction be equal to $\frac{1}{2}\delta^2$ for algebraic convenience. Most of the weight after the rocket fuel is expended would be the nuclear explosive, which produces a yield of

$$E = \varphi M_f,. \tag{6}$$

where φ is the yield-to-weight ratio. Again, $\delta^2/2$ of this energy goes into the dirt ejected from the crater, so the transverse velocity imparted to the object is

$$v_\perp = \frac{\delta}{M_a}\sqrt{\varphi M_f M_e} = \frac{\alpha\delta}{M_a}\left(\varphi M_f\right)^{\frac{\beta+1}{2}}. \tag{7}$$

Although when the complete orbital mechanics is considered, we will want to impart a transverse velocity only when the object is very close to collision, the magnitudes obtained from this simplified calculation are effective over substantial distances. We can combine Eqs. (4), (5), and (7) to obtain

$$\varepsilon = \frac{\alpha\delta R_l}{M_a v}\frac{V(\varphi M_f)^{\frac{\beta+1}{2}}}{V+v} \tag{8}$$

for the displacement.

To obtain the optimum mass ratio for nuclear explosive deflection, we substitute Eq. (1) into Eq. (8) and solve

$$\frac{d\varepsilon}{d(M_i/M_f)} = 0. \tag{9}$$

The logarithm of the mass ratio that produces the largest value of ε,

$$Q = Q \equiv \ln\frac{M_i}{M_f} = -\frac{v}{2v_x}\left(1-\sqrt{1+\frac{2v_x}{(1+\beta)v}}\right). \tag{10}$$

This is an interesting, although not profound, result. Despite the many parameters that come into the problem, the optimal mass ratio depends only on the quotient of the *closing velocity* and the *exhaust velocity*. The *crater exponent* is well established at 0.9. A substantial advantage accrues to a higher-specific-impulse rocket(Solem, 1993b; Solem, 1994a). The maximum displacement of the impact location on Earth is then given by

$$\varepsilon = \frac{\alpha\delta R_l}{M_a v}\frac{v_x Q(\varphi M_i e^{-Q})^{\frac{\beta+1}{2}}}{v_x Q+v}. \tag{11}$$

For a surface burst, Glasstone uses $\beta = 0.9$, but takes $\alpha \simeq 1.6\times10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\sec^{\beta}$. He describes the material as dry soil. Medium strength rock would be more consistent with $\alpha \simeq 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\sec^{\beta}$, and, in the 20-kt range, would roughly agree with Cooper (1976). If about 5% of the nuclear explosive energy goes into kinetic energy of the blow-off, then $\delta = 1/\sqrt{10} \simeq 0.316$. bigskip Equation (11) can be rearranged to give the required initial mass of the interceptor,

$$M_i = \frac{e^Q}{\varphi}\left[\frac{M_a v\varepsilon}{\alpha\delta R_l}\left(1+\frac{v}{v_x Q}\right)\right]^{\frac{2}{\beta+1}}, \tag{12}$$

where Q is given by Eq. (10). bigskip It is generally known that the yield of nuclear warheads can be a few kilotons per kilogram if they weigh more than about a hundred kilograms. For the purpose of these estimates, we will take a conservative value of $\varphi = 1$ kiloton $\cdot$ kilogram^{-1}. Figure 1 shows the initial mass of the interceptor required to deflect an object by 10 Mm, as a function of the assailant's diameter d and its range R_I when the interceptor is launched. Figure 1 assumes an object density of $\rho = 3.4$ gm $\cdot$ cm^{-3}, an assailant velocity of $v = 25$ km $\cdot$ sec^{-1}. The deflection is conservative for missing the planet entirely ($R_{\odot} = 6.378$ Mm), partially compensating for the neglect of gravitational focusing. From the graph, it is clear that threatening objects as large as a kilometer can be deflected, even if the are only one astronomical unit away when the interceptor is launched. A Russian *Energia* rocket could easily boost the 100-ton interceptor int Earth orbit.

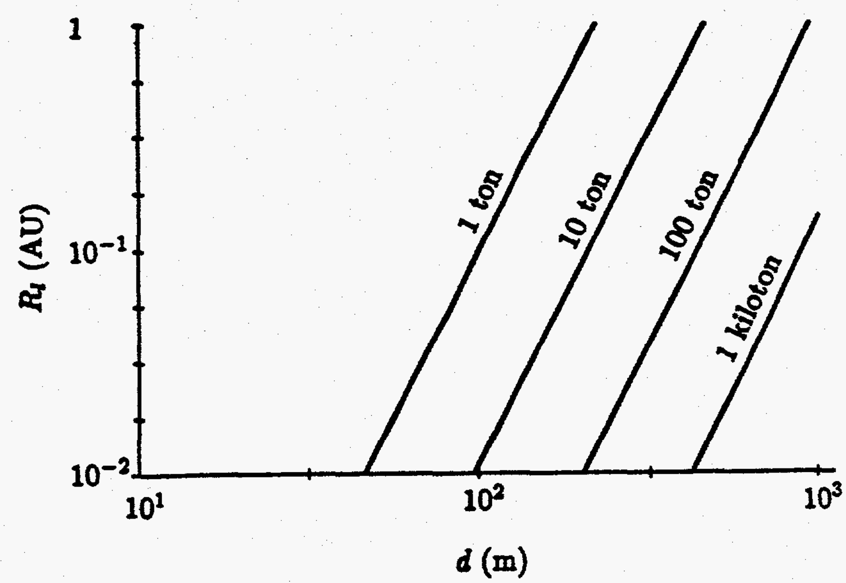

Figure 1. Initial masses of optimally designed interceptor rockets to obtain 10-Mm deflection.

Modes of Engagement

There are three qualitatively different ways in which a nuclear-explosive-carrying interceptor can engage a comet or asteroid, either for the purpose of deflection or pulverization. The engagement can deploy (1) a surface-burst, which is detonated at or very near the surface of the object; (2) a stand-off device, which is detonated at considerable distance from the surface; or (3) a penetrator device, which buries the nuclear explosive at an optimum depth. These modes have been discussed extensively in prior publications, I will present here a brief description of what we believe we have learned.

Surface-Burst Device

The optimization calculations of the previous section, which led to Fig. 1, were based on a surface-burst engagement. The surface burst is highly efficient for transferring momentum to the target object. If the same *optomization procedure is applied to the kinetic energy device, the nuclear-explosive and interceptor system can be shown to be three orders of magnitude lighter. A problem with the surface burst is that it creates a crater to provide blow-off material. This introduces a great deal of stress and a fairly high probability of fracture. It is also somewhat difficult to time the surface-burst detonation at high rates of closure. If the relative velocity of the interceptor is 50 km $\cdot$ s^{-1} and the acceptable error in altitude of the detonation is 10 cm, as it might be for a typical surface explosion, then the timing jitter must be less than 2 μsec.

Stand-Off Device

The fracture problem can be much mitigated by detonating the nuclear explosive some distance from the astral assailant. Rather than forming a crater, the neutrons, x-rays, γ-rays, and some highly ionized debris from the nuclear explosion will blow-off a thin layer of the object's surface. This will spread the impulse over a larger area and lessen the shear stress to which the object is subjected. Of these four energy transfer mechanisms, by far the most effective (at reasonable heights of burst) is neutron energy deposition, suggesting that primarily-fusion explosives would be most effective (Shafer *et al.*, 1994).

complete description requires computer simulations. However some general statements can be made. At an optimal height of burst, I find about 2 to 8% of the explosive's energy is coupled to the assailant's surface, again depending on the object's actual composition and the neutron spectrum and total neutron energy output of the explosive. Most of the energy is deposited within 10 cm of the surface. The blow-off fraction will be about a factor of 35 times smaller than the surface burst and the initial mass of the interceptor would have to be about 40 times as large.

Penetrator Device

A greater momentum can be imparted for the same yield if the detonation is below the surface. The relative velocity will provide adequate kinetic energy the bury the nuclear explosive at significant depths. In order to penetrate into the assailant, the nuclear explosive must be fitted with a weighty billet: a cylinder of material that will erode during penetration. The billet will add weight to the package that must be delivered. Analytic studies have shown that a penetrator has no value in enhancing deflection, but may be of great value if we choose to pulverize the object (Solem, 1995).

Surface and subsurface detonations make a crater that is small compared to the characteristic dimension of the object. The linear momentum impulse will be imparted along a line connecting that crater and the center of mass — with corrections for local geology and topography. An aspheric object will also receive some angular momentum, depending on the location of the crater and the object's inertial tensor. The size of the impulse will depend on material properties, geology, and topography. bigskip Thus, it will be necessary to characterize the geology and mechanical properties of the object when using the *cratering* deflection techniques. Such characterization might be accomplished by a vanguard spacecraft. Stand-off deflection is much less sensitive to these details. In general, linear momentum will be imparted along the line connecting the detonation point with the center of mass — a large lever arm. Little angular momentum will be imparted, and this will depend on relative projected areas of various topographical features compared with components of the inertial tensor. Thus, besides its inherent fracture-mitigation virtues, the stand-off deflector demands substantially less information about the object it is deflecting.

Multicomponent Gravitationally-Bound Objects

Energetically, it is always preferable to deflect the object, particularly when it can be intercepted early, perhaps several orbital periods before it would impact our planet. More friable objects, however, might be susceptible to fracture, which may make the problem of deflection more difficult as several resulting objects would have to be deflected or pulverized by nuclear explosives, probably delivered by subsequent interception vehicles. bigskip Here, I address the problem of fracture by modeling objects as conglomerates of competent rocks bound together by gravitation and subjecting them to various impulses imparted by nuclear explosives. Simulations can never substitute for the deep understanding provided by analytic formulations, but a series carefully analyzed can supply some insight into this exceedingly complex problem.

Model for Asteroid Fracture

The model of an asteroid as a agglomeration of competent rocks bound together by mutual gravitational attraction is surely a great simplification. We have little knowledge of how asteroids are held together. There are certainly other cohesive forces between components, but the model may be adequate for many objects, particularly the larger ones. bigskip The goal is to ascertain under what conditions the asteroid will: (1) hold together as a single body, but change its trajectory; (2) fracture into dangerous shards, some of which are on nearly the original trajectory; or (3) be pulverized into harmless smithereens that will burn-out in the Earth's atmosphere if their departure from the original trajectory is insufficient to miss the Earth entirely. bigskip For these simulations, I model the rocks or snowballs comprising the asteroid or comet as uniform spheres, which interact gravitationally except when they touch. The touching, or collision, of two rocks is handled a scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved. The scattering approximation, as well as the lack of cohesive strength between the component rocks, favors shattering the asteroid over moving it as a unit. Thus we are bounding the problem from the conservative end. The objects are modeled as more friable than they probably are. bigskip The depiction of comets as "flying rubble piles" has enjoyed increasing support (Solem, 1994b; Asphaug and Benz, 1994; Scotti and Melosh, 1993; Weissman, 1986; Weidenschilling, 1994) and comets with multiple nuclei, probably owing to tidal disruption, are not uncommon (Sekanina and Yeomans, 1985; Sekanina, 1993; Whipple, 1985). Asteroids may well be similar agglomerations.

Sketch of the Simulation Algorithm

During the calculation, the spherical components interact gravitationally except when they touch. The touching, or collision, of two components is handled as a non-adhesive frictionless scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved, but some of the kinetic energy may be converted to heat. Because the components are frictionless, no spin is imparted in a collision. The simulation is a detailed calculation of the gravitational interaction and collisions of the components — it is not a hydrodynamic calculation. bigskip A further simplification, which greatly accelerates computation, is to assume the radius r_0 and density ρ of each component to be the same. Under this assumption, the equation of motion in the vicinity of the comet's center of mass is well approximated by

$$\ddot{\vec{r}}_j = Gm_0 \sum_{i \neq j} \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|^3}, \tag{13}$$

where $G = 6.672 \times 10^{-8}$ dyn $\cdot$ cm^2 $\cdot$ gm^{-2} is the universal gravitation constant, $m_0 = \frac{4}{3}\pi\rho r_0^3$ is the component mass, $\vec{r}_i$ is the radius vector of the ith component from the comet's center of mass. bigskip As long as all the components remain separated by at least two radii, the motion is found by straightforward integration of Eq. (13). A "collision" occurs whenever $|\vec{r}_i - \vec{r}_j| < 2r_0$ and the emergent velocities are given by

$$\dot{\vec{r}}_i{}' = \dot{\vec{r}}_i - \frac{\delta(\dot{\vec{r}}_i - \dot{\vec{r}}_j)\cdot(\vec{r}_i - \vec{r}_j)}{8r_0^2}(\vec{r}_i - \vec{r}_j). \tag{14}$$

A frictionless collision can only alter the normal component of the relative velocity. If $\delta = 2$, the normal component of the relative velocity simply reverses direction and the collision is perfectly elastic. If $\delta = 1$, the normal component is reduced to zero in the collision. It is easy to see that the only allowed values are $1 \leq \delta \leq 2$. bigskip We have little knowledge of how components of this sort might lose kinetic energy in collisions. For this calculation, the details are not very important. It can be shown that for completely random impact parameters, the selection of $\delta = 1$ causes the average collision between components to lose <u>half</u> its relative kinetic energy to heat. This seems realistic. Because the gravitational orbital dynamics favors grazing collisions over random impact parameters, $\delta = 1$ will result in slightly less than half energy loss on average. bigskip The model embodied in Eqs. (13) and (14) enjoys a remarkable scaling relationship: all distances scale with simple similarity. Locations are described by the dimensionless vector $\vec{r}_i/r_0$. If we increase the diameter of the object by a factor of 2, the geometrical arrangement of all components at any time after disruption will be exactly the same, with the distance scale increased by a factor of 2. The energetics enjoy a similarly simple scaling relation. A factor of 2 increase in component radius increases all energies (kinetic energy, gravitational potential energy, and heat generated in component collisions) by a factor of $2^5 = 32$. As a result of these scaling properties, we can cover objects of all sizes with a single calculation. bigskip For the initial geometrical arrangement, I place one component at the center of mass with either 12 or 134 components packed around it in a face-centered cubic (FCC) array, which results in a model that is close to a gravitational potential minimum. The time step for the dynamical calculation is adjusted so only binary collisions occur, although there may be many binary collisions among separate pairs within that time step. The lattice spacing for the spheres to just touch is $r_0\sqrt{2}$, but this contact packing would cause the binary-collision condition to be violated on the first time step. So I use an initial lattice spacing of $r_0(\sqrt{2} + 0.0001)$ — the spheres are very close together, but not actually touching.

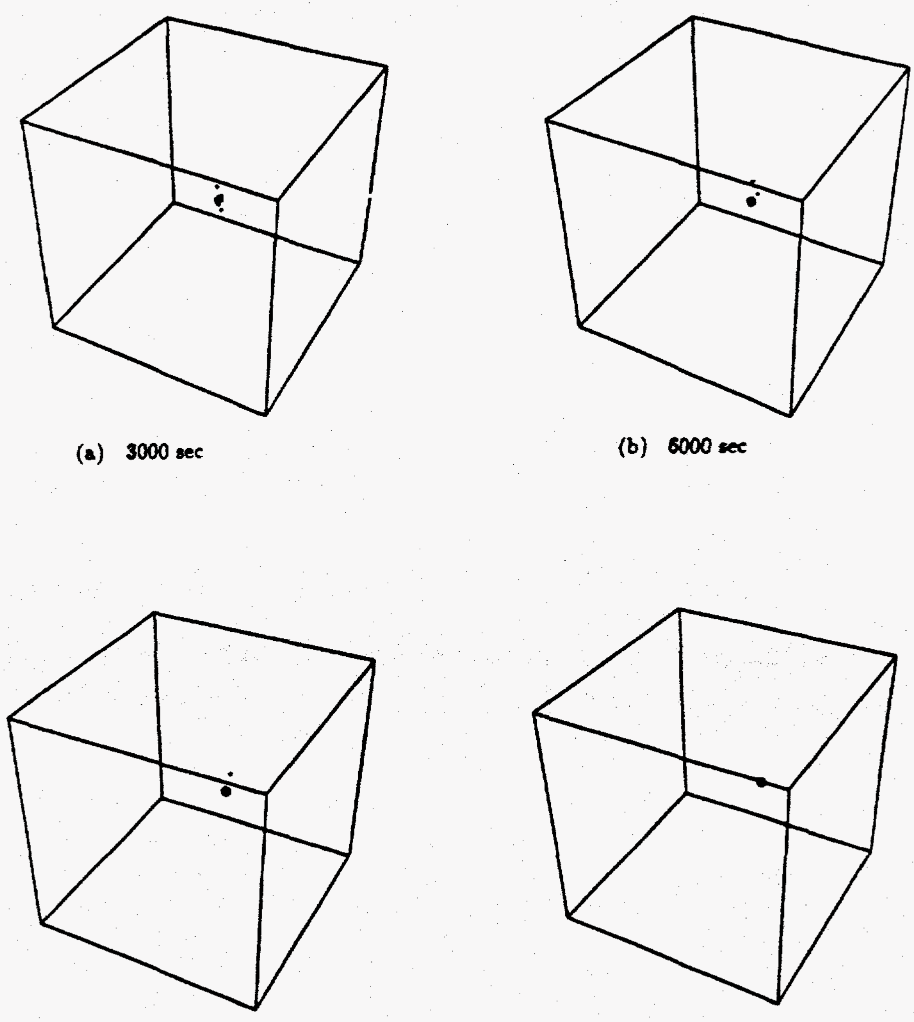

Figure 2. Incipient fragmentation of a gravitationally-bound asteroid consisting of 13 components, when subjected to a surface burst corresponding to a single outer component velocity of 1 $\mathrm{m \cdot sec^{-1}}$.

Fragmentation Studies

I have performed a large number of calculations with this model, and it is possible to give only a few to provide some flavor for the behavior of these objects. Figure 2 shows the response of an object consisting of 13 components when one outer component is driven toward the center with a velocity of 1 $\mathrm{m \cdot sec^{-1}}$, corresponding to a kinetic energy of 6.28×10^{16} erg, which is somewhat less than the total binding energy of the asteroid. This imparted velocity would result from a nuclear-explosive yield of 10.2 kilotons (4.29×10^{20} ergs). I take the density to be $\rho = 3\ \mathrm{gm \cdot cm^{-3}}$, so the mass of each sphere is $m_0 = \frac{4}{3}\pi\rho r_0^3 = 1.26 \times 10^7$ tons. The box is 15 km on a side, and the component rocks are shown to scale. The total mass of the asteroid is 1.63×10^8 tons and its greatest diameter is 600 m.

It is a case of *incipient fragmentation.* The object comes apart but then coalesces owing to mutual gravitational attraction. Just a little bit more energy will cause the object to remain fragmented.

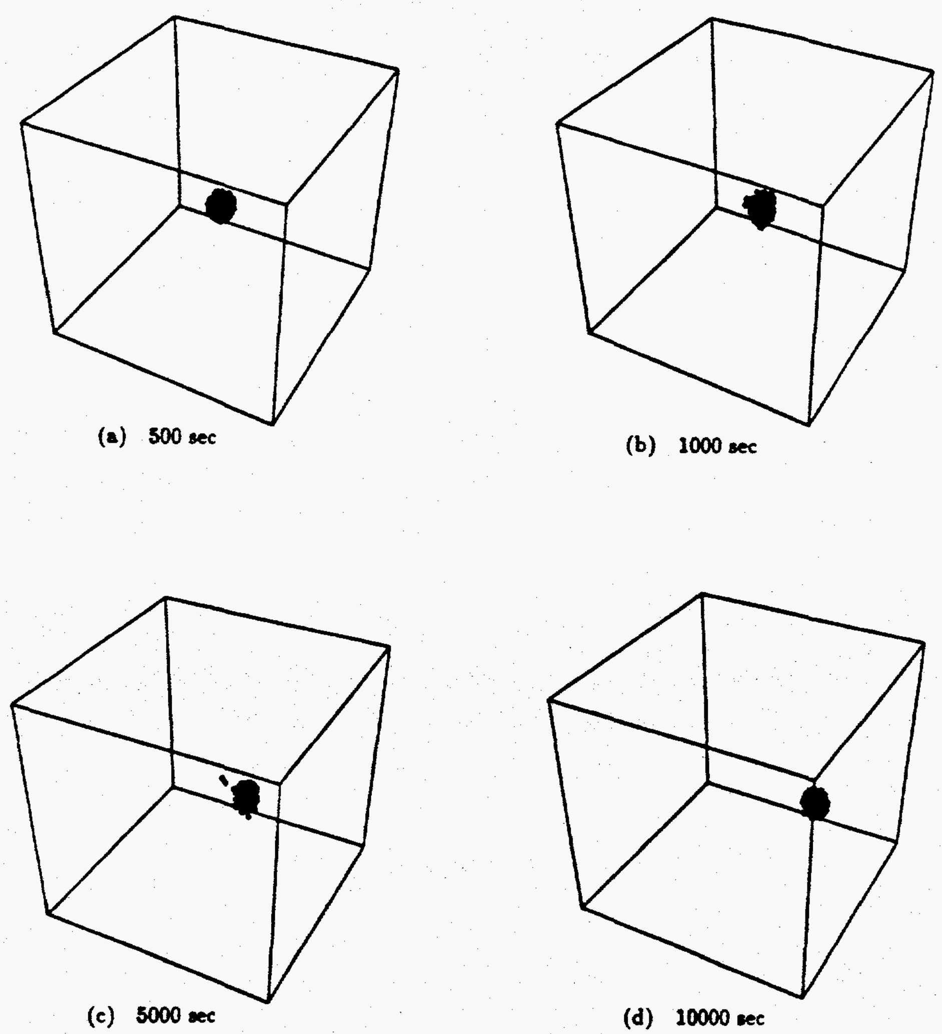

Figure 3. Incipient fragmentation of a gravitationally-bound asteroid consisting of 135 components, when subjected to a stand-off detonation corresponding to an average outer component velocity of 30 $\mathrm{cm \cdot sec^{-1}}$.

Figure 3 shows the response of an object consisting of 135 components where the components on one side are driven with the velocity distribution appropriate to a stand-off nuclear explosion. The total mass of the object is 1.70×10^9 tons and its greatest diameter is 1258 m. The total binding energy of the asteroid is 3.86×10^{18} erg. The average velocity given to the outer components is 30 $\text{cm} \cdot \text{sec}^{-1}$ This is another example of *incipient fragmentation*, and a little more energy will leave the object permanently fragmented.

Summary of Results

Table 1 shows the maximum velocity that can be imparted to gravitationally bound asteroids while maintaining their overall integrity. The comparison is for surface detonation and stand-off detonation with 13- and 135-component asteroids. Component density is 3 $\text{gm} \cdot \text{sec}^{-1}$. For the stand-off detonation, the nuclear explosive is placed $\sqrt{2} \times$ the asteroid radius from the asteroid surface. For the surface burst, a single component is accelerated into the body of the asteroid. The single component's crater parameters correspond to medium strength rock: $\beta = 0.9$, $\alpha = 10^{-4}\ \text{gm}^{\frac{1}{3}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$, and δ=0.316. The stand-off detonation corresponds to $\beta = 0.97$, $\alpha = 1.5 \times 10^{-6}\ \text{gm}^{\frac{1}{3}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$, and δ=0.3.

Table 1. maximum non-fracturing deflection speeds

Asteroid Diameter	13 Components				135 Components			
	Stand-Off		**Surface**		**Stand-Off**		**Surface**	
(km)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)
20.	1000	9×10^8	256.	3×10^7	477.	5×10^8	118.	1×10^7
10.	500.	5×10^7	129.	1×10^6	239.	3×10^7	58.9	7×10^5
6.	300.	6×10^6	76.9	2×10^5	143.	3×10^6	35.3	8×10^4
3.	150.	4×10^5	38.5	9×10^3	71.5	2×10^5	17.7	4×10^3
2.	100.	7×10^4	25.6	2×10^3	47.7	4×10^4	11.8	8×10^2
1.	50.0	4×10^3	12.8	9×10^1	23.9	2×10^3	5.89	4×10^1
0.6	30.0	6×10^2	7.69	1×10^1	14.3	3×10^2	3.53	5×10^0
0.3	15.0	3×10^1	3.85	5×10^{-1}	7.15	2×10^1	1.77	3×10^{-1}

Implications of Table 1

The calculations presented in Table 1 are, of course, for a single engagement. Multiple engagements will impart the vector sum of the velocity increments from each explosion. However, when approaching the level of incipient fracture, the time interval between successive explosions musty be great enough to allow the asteroid to settle down — to convert gravitational kinetic energy from the disturbance into heat energy.

From Table 1 we could conclude that, for a single engagement, the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. We also see that the non-fracturing deflection speed depends on the number of components, the speed for a 13 component object being about twice that for a 135 component object. The calulations given in the table lead us to the following tentative conclusions: (1) asteroids more than 3 km in diameter can be most efficiently deflected using a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected using a stand-off device; (3) smaller asteroids are best pulverized.

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