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DEFLECTING ASTEROIDS BY MEANS OF STANDOFF NUCLEAR EXPLOSIONS

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A nuclear explosion at a distance can deflect an asteroid primarily because of energy transmitted to the surface by neutrons and X rays. If the surface material is nonporous, evaporation or spalling can produce the impulse. However, if the surface is porous, spalling caused by neutrons usually is not effective, so that the energy density must be great enough to produce evaporation. Based on some recently available information and some reasonable assumptions about the surface material, computed results are presented that show the impulse produced on a porous object as a function of total neutron energy, distance of the explosion, and diameter of the object. The deflection of an object by a sudden impulse such as that from an explosion may cause it to disperse, especially if the ratio of deflection velocity to escape velocity of the object is high. Although internal rubble may make the dispersion of an object more likely in some cases because it is already fractured, in other cases it may help to prevent dispersion because internal absorption of energy is aided by voids. Results are presented showing the maximum portion of fragments that would be expected to hit Earth, as a function of the amount of attempted deflection relative to Earth's radius, in case the object disperses. These indicate that it is fairly easy to keep this portion below 10% and in some cases below 1%. Publicly available information about some current nuclear bombs and reasonable assumptions about custom-made bombs are used to estimate total neutron energy and bomb mass for some possible warheads that could be used for deflection. By using all of the information described above, examples (based on the Defined Threat scenarios recommended for this conference) are given of threatening asteroids that could be deflected successfully with existing technology, and in some cases even with existing hardware, by means of standoff nuclear explosions.

INTRODUCTION

One of the methods that have been proposed for deflecting an object headed for Earth is the use of a standoff nuclear explosion,[1,2,3,4] which is defined here to mean that the bomb is not buried or on the surface, although in some cases it may be as close as 10 m or so. (Typically it would be considerably farther away.) This method has the advantage that the warhead can be detonated during a flyby or just before a collision, so that there is no need for a large spacecraft Δv to match velocities or for operations on the surface. Therefore, it is the method that would be easiest to implement if an object were to threaten Earth in the near future (except for the use of kinetic energy from impacts, which is practical only for small objects).

It sometimes has been said that this method would not be suitable for an asteroid that is a rubble pile. For example, this statement surfaced at the recent Mitigation workshop,[5] especially with regard to an object with a surface layer of finely divided regolith. The latter situation is apt to occur whether the asteroid otherwise is monolithic or is a rubble pile. Here it is argued that an object with finely divided surface material is only moderately harder to deflect than is a bare object when things are done optimally, and that whether or not the interior is rubble usually has little effect when a standoff nuclear explosion is used. In fact, in some cases the rubble pile actually might be easier, because of its lower density or because of its greater ability to absorb energy.

It also has been claimed that attempting to deflect an object by means of a sudden impulse (as from a nuclear explosion) risks dispersing the object (especially if the force is concentrated in a small area, such as from a close explosion) and that the resulting multiple pieces would pose a greater danger than the original object. Although in some cases this danger is real, it is shown here that in most realistic cases it is minimal or it can be overcome.

ENERGY FROM NEUTRONS AND X RAYS

A standoff nuclear explosion produces a change in the momentum of an asteroid primarily by means of material that is evaporated or spalled (by rapid thermal expansion) from its surface due to the deposition of energy. This energy is transmitted from the explosion mostly by means of neutrons and X rays.

For typical nuclear bombs, around 70% of the energy is delivered as X rays.[6] However, they are absorbed in a much thinner layer of material than are neutrons (roughly by a factor of 1000).[4,7] This fact can cause such high temperatures to be produced that most of the energy is reradiated. It also causes a smaller amount of mass to be ejected from the asteroid. When the energy density in the surface material is high (as it may well need to be if a large impulse must be given to an asteroid), this smaller amount of mass results in a lower momentum-to-energy ratio, because it tends to be inversely proportional to the square root of energy density at high levels. However, when the energy density is low, increasing it because of less mass may help by making it sufficiently high to cause evaporation, especially with porous material. Therefore, neutrons often are more effective in deflecting an asteroid than are X rays, in spite of the smaller energy that they deliver, although in some cases X rays can be important, especially when the standoff distance is large and the neutron yield of the bomb is very low. X rays have another complication, in that the evaporated layer is so thin that it has time to expand considerably during the pulse of X rays. Mostly neutrons will be considered here, not necessarily because they usually are more effective, but because one of the purposes of this paper is to show the feasibility of using nuclear explosions to deflect asteroids, and using one method suffices for that.

Accurate information on the fraction of the energy from specific nuclear bombs that is delivered by neutrons generally is not readily available. However, some general approximate statements can be made.

A neutron bomb (enhanced-radiation device) uses a mixture of deuterium (hydrogen 2) and tritium (hydrogen 3) as the thermonuclear material. This combination releases 80% of its fusion energy as neutrons. For the tamper and other surrounding material, substances low in neutron absorption are chosen, but some neutrons still are absorbed, so perhaps around 40% of the fusion energy could be carried away by neutrons. (Some of the total energy is supplied by the fission trigger, which would be significant in a small bomb.) However, tritium is very radioactive and is expensive, and deuterium and tritium are gases at ordinary temperature. Therefore, true neutron bombs probably are practical only in small sizes, which is what their application as weapons called for but which would not be effective for deflection purposes, so they will not be considered here, at least in the pure form stated above.

Ordinary thermonuclear bombs usually use lithium-6 deuteride. This combination produces a series of fusion reactions that, depending on which reactions predominate, probably yield more than 20% of their energy as neutrons. By using materials low in neutron absorption, it should be practical to achieve around 10% of the total energy from a large bomb as neutrons external to the bomb. (If it turns out that this is too difficult with pure lithium-6 deuteride, perhaps enhancements could be made to increase the neutron yield, such as replacing a portion of the deuterium by tritium.)

However, generating neutrons is not the purpose of existing bombs, so the tamper material usually is not very transparent to neutrons. In fact, often fission-fusion-fission bombs are used, in which the tamper is made of uranium 238. The high-energy neutrons from the fusion reactions cause fission of the uranium, which roughly doubles the energy yield of the bomb. Unlike U-235, U-238 does not produce a chain reaction; the neutrons from the fusion get used up, and the neutrons from the fission do not have enough energy to cause fission of U-238. (Around 3% of the energy produced by the fission of a nucleus is carried by the neutrons produced.[6]) As a result of these facts, typical existing bombs produce only about 1% of their energy as neutrons external to the bomb,[6] although it varies according to the individual bomb design. This value is assumed here.

There is a strategy that could make it easier to achieve the above assumed neutron-energy yields of 10% for a custom bomb and 1% for existing bombs, in terms of the effective yield as determined by the neutron dose on the target instead of the actual total yield. This strategy is to orient the bomb properly, in order to take advantage of the fact that the neutron radiation from a nuclear explosion is not isotropic, because of asymmetry in the design of the bomb.

Table 1 shows data on two actual bombs and two hypothetical bombs that could be built in a size to fit an individual need. Three of these will be used in later examples.

The largest U.S. bomb currently in service is the B83.[8,9] It has a mass of 1100 kg and a selectable energy yield, the maximum of which sometimes is stated as 1.2 MtTNT.[9] (The symbol tTNT is used here to denote the nominal energy released by the explosion of a ton of TNT, which by convention usually is defined to be exactly 10^9 thermochemical calories = 4.184×10^9 J.) A larger U.S. bomb no longer in service

TABLE 1

Warhead example	Based on	Mass (kg)	Total yield (MtTNT)	~ Energy of neutrons (J)	~ Energy of X rays (J)	Availability
A	B83 bomb	1100	1.2	5.0×10^{13}	3.5×10^{15}	Currently in service
B	B53 bomb	4000	9	3.8×10^{14}	2.6×10^{16}	Possibly still in storage
C	Optimum for neutrons	$840\,Y^{0.85}$	Y	$4.2\times10^{14}\,Y$	$2.7\times10^{15}\,Y$	Assumed custom design
D	Optimum for X rays	$460\,Y^{0.85}$	Y	$4.2\times10^{13}\,Y$	$2.9\times10^{15}\,Y$	Assumed custom design

is the B53,[8,9] some of which may still exist in storage. It has a mass of 4000 kg and a yield of 9 MtTNT. These two bombs are listed in Table 1, where they are denoted as A and B, respectively. In each case the neutron energy is computed based on the above 1% assumption and is converted to joules. Similarly, the X-ray energy is computed based on the above 70% value.

If there is time to develop a custom bomb to deflect a threatening object, a bomb that could deliver much more energy in neutrons than the above two could be built, in principle. Sykes and Davis[10] provided a graph (which goes up to 10 MtTNT) with a straight line on a logarithmic plot that shows the U. S. state of the art as of 1980. According to this line, the mass is proportional to the 0.85 power of the energy yield, and this relationship is shown in Table 1 for warheads C and D. The latter uses a coefficient of 460 when the mass is in kilograms and the yield is in megatons of TNT, in accordance with the graph from Sykes and Davis. However, in order to maximize the neutron output, we are restricted here to using a thermonuclear bomb without the fission boost from a U-238 tamper. Therefore, the yield from the graph is divided by 2 as an approximate adjustment for this fact, and the result is a coefficient of 840 for warhead C. Then a 10% yield of neutron energy is assumed as stated above and is converted to joules to produce the value for warhead C in Table 1. (Note that this represents only a 5% neutron yield relative to the energies in Sykes and Davis, since presumably these were optimized for total energy output, not neutrons, and thus probably assumed a boost from U-238.) For warhead D, the usual 1% yield of neutrons and 70% yield of X rays are assumed. For warhead C, the yield of X rays is slightly reduced, because of the greater portion of energy going into neutrons. (Warhead D and the X-ray information for warhead C are included for completeness. Whereas X rays can be useful with warheads A and B because of their low neutron yields, X rays are less apt to be important in a custom device, because of the ability to increase neutron yield there.)

THE EFFECT OF SURFACE POROSITY

Ahrens and Harris[3] considered the case where the surface energy deposition is low enough to avoid melting or vaporizing the material. Instead, rapid thermal expansion causes a layer of material to be spalled off. However, Holsapple[11,12] has shown that such a method is not effective if there is a surface layer of regolith that is more finely divided than the absorption depth of the energy. Upon heating, the particles can expand into the empty spaces by being partially crushed. Therefore, if they remain in the solid state, there is very little tendency for the expansion to cause a layer to spall off, unless they expand enough to fill the voids. The remedy for this problem is to increase the energy density (e.g. by moving the explosion closer) so that the layer of material evaporates, even though for a solid object the higher energy density possibly would reduce the momentum-to-energy ratio. (There is apt to be less of a problem for X rays than for neutrons, since the energy density would be higher and the absorption depth for X rays may well be less than the size of the regolith particles.)

Holsapple's computer simulations[11,12] used the equation of state for silicon dioxide and the common assumption of uniform deposition of neutron energy over a constant straight-line distance.[3,4] His simulations showed that, for both nonporous and porous material, a maximum of the momentum-to-energy ratio (locally orthogonal to the surface) occurs at a value of specific energy (energy-to-mass ratio) absorption between 10 and 100 MJ/kg, the maximum value being about 1.2×10^{-4} s/m for nonporous material and 9×10^{-5} s/m with 50% porosity. (He plans to present similar material at this conference.[13]) Above this range, the momentum-to-energy ratio approaches being inversely proportional to the square root of specific energy. The values for porous and nonporous material are almost equal above 100 MJ/kg, but the value for porous material falls off sharply below about 5 MJ/kg.

An approximate fit of an empirical function to Holsapple's data for 50% porosity produced the following for specific momentum p_m (average blow-off velocity) as a function of specific energy E_m:

$$p_m(E_m) \;=$$

$$\frac{E_m}{4.6\text{ MJ/kg}} + \left(\frac{E_m}{2.87\text{ MJ/kg}}\right)^{10} \quad \text{if } E_m \le 4.904\text{ MJ/kg},$$

$$\text{or } 1.00\sqrt{E_m}\,\exp\left\{-2.38\left[1+\left(\frac{E_m}{9.55\text{ MJ/kg}}\right)^{4}\right]^{-1/4}\right\} \quad \text{if } E_m > 4.904\text{ MJ/kg} \qquad (1)$$

The dividing line between the two functions at 4.904 MJ/kg simply serves to select whichever is less. (Thus the discontinuity is in the first derivative and not in the function itself.) This transition occurs in the region between 2.6 MJ/kg and 10 MJ/kg where vaporization is beginning to occur, and Holsapple says that the code calculations in this regime are very difficult and that the curve thus is not well determined. For E_m > 6 MJ/kg, the above function agrees with Holsapple's numerical data within 5% at all computed points (1% above 600 MJ/kg, and 10% below 6 MJ/kg). Below 1 MJ/kg, Holsapple doesn't provide data of this nature; the above function probably falls off much too rapidly at these lower values, but the correct values are so small anyway as to be negligible in practical cases. (Note that the theoretical maximum that could be achieved is $p_m = \sqrt{2E_m}$. As $E_m \to \infty$, equation (1) is below this by a factor of only 1.41.)

ABSORPTION OF ENERGY FROM NEUTRONS

An accurate computation of the deposition of energy from neutrons in the surface material of an asteroid would follow the neutrons and any particles produced in their interactions with atomic nuclei, as the neutrons and the other particles interact with the nuclei. This would involve the use of complete cross-section data[14] for the interactions and the distribution of scattering angles,[15] all of which are functions of neutron energy. (Apparently something like this has been done before to a certain extent, with partial results presented.[16]) This computation would take into account the distribution of neutron energies, which is different for different kinds of bombs, and the fact that the energy of a particular neutron decreases each time it is scattered. In order to accurately determine the resulting impulse given to the asteroid, the computation also would include computations such as those of Holsapple described in the previous section, but using the actual distribution of deposited energy as a function of depth, instead of using the assumption of uniform deposition of energy along a straight line.

Something simpler was done here. Although a Monte Carlo simulation was done, following the neutrons through multiple scatterings until each neutron either is absorbed, escapes from the material, or is left with negligible energy, four approximations to the above complete computation were made.

First, a single value of total cross section was used for the interaction of neutrons with nuclei, instead of making it a function of energy. The values do not change enormously over the range of energies of interest here, and a reasonable average for SiO_2 over these energies produced the following value for the amount of material traversed in one mean free path:

$$m_A \;=\; 150\text{ kg/m}^2 \;=\; 15\text{ g/cm}^2 \qquad (2)$$

which will be used in the next section. (Therefore, in solid quartz the mean free path would be $(15\text{ g/cm}^2)/(2.65\text{ g/cm}^3)$ = 5.7 cm, for example.) The specific energy is inversely proportional to m_A. Since in a typical deflection attempt the situation probably would be chosen so that the specific energies would be near the value that maximizes the impulse produced, the resulting impulse usually is not highly sensitive to the exact value of m_A.

Second, a single simple approximation for the angular distribution of scattering angles was used for all energies and for both silicon and oxygen. This approximation assumes that the probability per steradian is proportional to $\exp(0.5\cos\psi)$, where ψ is the scattering angle. (Using other reasonable approximations typically changed the results by only a few percent.)

Third, it was assumed that, on any given free path, at the end of the free path each neutron has a 0.05 probability of being absorbed and releasing all its energy instantaneously, and a 0.95 probability of being elastically scattered. The actual situation is much more complicated, but these values were chosen to represent roughly on average what happens to most of the energy. (Changing the 0.05 value to 0, 0.1, or 0.2 caused the total effective absorbed energy at vertical incidence as computed below to change by –14%, +9%, or +21%, respectively.)

Fourth, the results from the Monte Carlo simulations, which gave the complete distribution of energy over depth for each of several incident angles from the vertical, were used to estimate an equivalent uniform distribution that, when used in Holsapple's computations, would produce the actual amount of momentum. For this purpose, it was assumed that the specific energy at the surface for vertical incidence is 100 MJ/kg and that the radius of the object is 5 times the altitude. (These are fairly typical values. These assumptions are only for the purpose of estimating the equivalent uniform distribution, and the final results are not highly sensitive to them. The computation of momentum using (1) will be done below in (5) using the actual values.) The contribution to momentum at each depth was computed using (1) and was integrated over all depths. (This is only an approximation, since (1) assumes a uniform distribution.) Dividing the total momentum by the momentum per unit depth at the surface produced the equivalent maximum depth, and multiplying this by the energy per unit depth at the surface produced the equivalent energy.

Finally, the results of these computations were approximated by the following simple empirical functions:

$$\varepsilon(\alpha) = 0.06 + 0.62 \cos\alpha \tag{3}$$

$$\delta(\alpha) = 3.1 - 1.0\,\alpha^2 \tag{4}$$

where α is the incident angle from the vertical (in radians), ε represents the effective portion of the neutron energy, and δ represents a correction factor to obtain the equivalent maximum depth of absorption from the mean free path times $\cos\alpha$. (The absolute accuracies of the fits for ε and δ compared to the actual computed values, which themselves are only approximations for the reasons stated above, are about 0.01 and 0.05, respectively.)

What has been accomplished above is to come up with the simple, approximate expressions (3) and (4) that can be used as needed, instead of having to do a Monte Carlo simulation at each incident angle for every combination of warhead, distance, and object. Most of the loss in effectiveness of the energy from neutrons indicated by (3) is due to neutrons escaping from the material, which is not affected by the fourth approximation above. (The Monte Carlo simulation indicates that 32% of the incident energy escapes when α = 0 and 63% when α = 90°. The corresponding values from (3) are 32% and 94%, which include both the escaped energy and that which is ineffective in producing momentum, mostly because the specific energy becomes too low.) The total momentum is greatly affected by the depth from (4) only at very low or very high energy levels. Near the optimum situation it doesn't have a large effect. For these reasons, the results may be fairly accurate in typical situations, in spite of all of the approximations that were made

SCALING OF SIZE, DISTANCE, ENERGY, AND MOMENTUM

If the same ratios hold between the square of asteroid diameter, the square of explosion distance, and the energy of the explosion, then the same energy density exists on corresponding points on the asteroid, so that the deflection momentum also scales as the square of the diameter. In order to investigate how these ratios change relative to each other, computations were done using the information presented in the previous two sections.

By using $p_m(E_m)$, m_A, $\varepsilon(\alpha)$, and $\delta(\alpha)$ from equations (1), (2), (3), and (4), for a source of energy E radiating isotropically at a height h above the surface of a spherical asteroid with radius R, the total momentum p produced can be obtained as follows:

$$p = \int_0^{\theta_{\max}} 2\pi R^2 \sin\theta \cos\theta \cos\alpha\, \delta(\alpha)\, m_A\, p_m(E_m)\, d\theta \tag{5}$$

where

$$r^2 = R^2 + (R+h)^2 - 2R(R+h)\cos\theta$$

$$\sin\phi = \frac{R\sin\theta}{r}$$

$$\alpha = \theta + \phi$$

$$\cos\theta_{\max} = \frac{R}{R+h}$$

$$E_m = \frac{E\,\varepsilon(\alpha)}{4\pi r^2 m_A \delta(\alpha)}$$

These quantities are illustrated in Figure 1, which is adapted from Ahrens and Harris.[3]. Notice that, if p_m

were proportional to E_m, m_A and $\delta(\alpha)$ would cancel out. (At small values, p_m increases faster than does E_m; at large values, slower.) Also, if there were no scattering, $\varepsilon(\alpha)$ and $\delta(\alpha)$ would be constant, so the only effect of α would be the $\cos\alpha$ factor. (Only it would affect the depth and only the inverse-square law would affect the energy density.)

Equation (5) was evaluated by means of numerical integration in order to generate Figure 2. By using it, the energy needed from neutrons at a given height above a spherical asteroid of a given diameter in order to produce a desired momentum can be determined. In practice, the height usually would be chosen so as to maximize the momentum produced by a given energy. Maxima of (5) were found numerically in order to generate Figure 3, which shows how the optimum height of an explosion above the surface of an asteroid varies with the energy and diameter, and what the resulting maximum net deflection momentum is. However, in some cases the optimum height may be impractically small (especially with small objects), so that it would be too difficult to aim a vehicle at it and to detonate the bomb at the correct time. (Perhaps 20 m or so is the smallest reasonable value.) In such a case, Figure 2 shows what can be achieved.

In the limiting case where $E \to \infty$, the optimum height in Figure 3 approaches 29.5% of the diameter. If the correction functions ε and δ for departures from uniform straight-line absorption were not used, it would approach 25.1% instead. This differs from the value of 20.7% in the Appendix of Ahrens and Harris, because there they considered only the portion of the surface illuminated and not the differing angles of incidence over that portion as they did in their main text. Furthermore, because the efficiency drops off at low specific energy, the optimum distance decreases for small explosions.

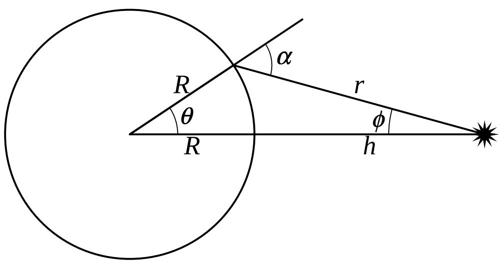

Figure 1. Geometry of irradiation of a sphere by a nuclear explosion.

Figures 2 and 3 do not include the loss of energy because of thermal radiation from the asteroid. However, this is apt to be important only if $E/h^2 > \sim 10^{14}$ J/m^2, when the energy is from neutrons. (If reradiation of energy were considered, the optimum height would increase above 29.5% of the diameter at very high energy, depending on the nature of the material.)

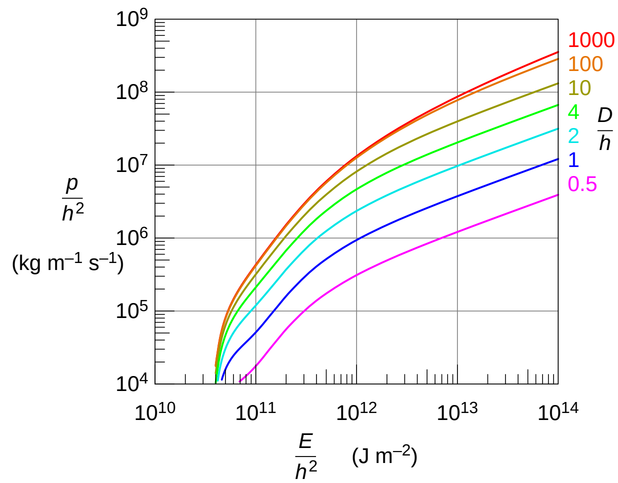

Figure 2. Momentum given to a spherical stony asteroid with 50% porosity, as a function of radiated neutron energy for a few asteroid diameters, all normalized relative to the height of the neutron source above the surface.

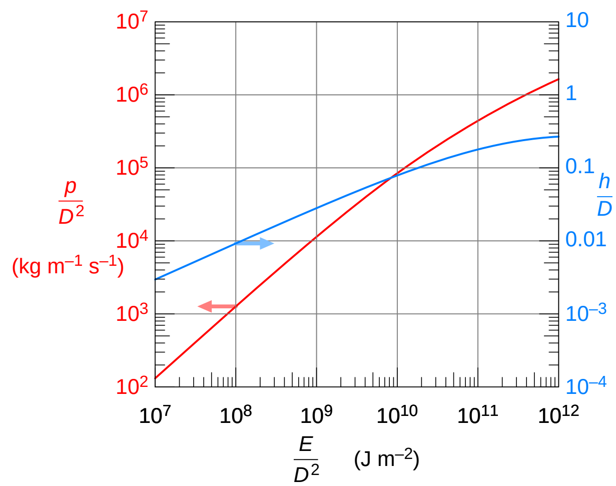

Figure 3. Maximum momentum (left scale) given to a spherical stony asteroid with 50% porosity, and the height of a neutron source above the surface (right scale) at which the maximum occurs, as a function of radiated neutron energy, all normalized relative to the diameter of the asteroid.

DEFLECTION VS. DISPERSION

The gravitational binding energy of a sphere of uniform density is $\frac{3}{5} Gm^2/R$. This is equal to the kinetic energy that the object would have with a velocity equal to $\sqrt{3/5}$ of its escape velocity. However, when an object is accelerated by a very brief impulse (such as that from a nuclear explosion), energy is transferred into the object by a shock wave that has many times the resulting kinetic energy of the object (if it remains intact), because of compliance. This extra energy can be disposed of in several ways, including fracturing the object, dispersing it by overcoming its gravity, spalling material from its opposite surface, heating it by means of internal damping of the wave, and (to a small extent) producing rotational kinetic energy if the force was applied off-center. For the purposes of deflection, the only one of these that usually is desirable is damping.

The internal damping of the wave is aided by inhomogeneities, especially voids. Therefore, a rubble pile may be more effective in this damping than would a solid object, so that large-scale dispersal could be less likely for a rubble pile in a borderline case (assuming that the pressure wave would fracture the object if it was not already rubble).

But what would happen if the object is dispersed? The center of mass of the fragments would have its velocity changed by the same amount as would that of an intact object, because of conservation of momentum. Therefore, if the deflection is enough to cause the intact object to miss Earth, so would most of the fragments. If the fragments fly apart with speeds considerably greater than the needed deflection velocity, the vast majority of the fragments would miss, so that the damage would be significantly decreased as compared to doing nothing. This last situation would occur under any of three conditions.

The first of these desirable conditions occurs when the desired deflection velocity is much less than the escape velocity of the object. Because of their random distribution, most fragments move either slower than the escape velocity, so that they fall back, or considerably faster than the escape velocity, so that they have an appreciable speed after escaping. Therefore, the average speed after escaping is at least comparable to the escape velocity, so that, if the deflection velocity is much less than the escape velocity, it is also much less than the speed of the fragments.

The second desirable condition occurs when there is naturally so much excess energy left over that the speed of dispersal is high. Note that the two extremes are desirable but the middle condition is not. We want the object either not to disperse, or to disperse widely.

The third desirable condition occurs by deliberately simulating the second. If the impulse needed to cause an intact object to miss Earth would cause the object to disperse just barely, and if it is practical to increase the impulse to a few times that amount, a large majority of the fragments could be practically guaranteed to miss Earth.

If the fragments from a random dispersal fly apart with speeds generally considerably less than the deflection velocity, few of them will be able to reach Earth; if the dispersal speeds are high, the fragments will be scattered so much that few will hit, as stated above. It follows that there is a worst case in between these extremes that maximizes the number of impacts. (Actually, the truly worst case would occur if just a cylinder of material were pushed through the object and out the other side or if just spalling from the other side occurred, leaving the rest of the object undisturbed. However, random inhomogeneities within the object probably would scatter the impulse, to produce a roughly isotropic distribution.)

For a given ratio of average deflection to the size of Earth, the maximum expected portion of impacts depends on the shape of the dispersion distribution. Of all isotropic distributions that do not increase with radial distance, the uniform distribution over a sphere is nearly the worst, but a Gaussian (normal) distribution probably is closer to what would occur with a well-dispersed object. If the dispersal occurs on the final approach to Earth, the distribution would remain nearly isotropic in three dimensions. However, if the object is dispersed more than one revolution in advance, the fragments would spread out along the orbit to produce a distribution that would approach being one-dimensional in extreme cases. (Actually, it would be approximately ellipsoidal, but one axis of the ellipsoid could be much longer than the other two.)

As the cloud of debris approaches Earth, the important thing is its two-dimensional distribution in the plane perpendicular to the relative approach velocity before Earth's gravity deflects it. Earth's effective radius as projected into this plane is enlarged by the factor $\sqrt{1 + (v_{esc}/v_\infty)^2}$, where v_{esc} is Earth's escape velocity and v_∞ is the approach velocity (far from Earth but close relative to the Sun). Since an isotropic three-dimensional Gaussian function can be factored into separate Gaussian functions for each dimension, in effect a two-dimensional Gaussian function is used in the three-dimensional case, but this simplification does not work for the uniform distribution over a sphere.

The worst case in each of the special cases of both one-dimensional and three-dimensional and both uniform and Gaussian distributions was computed by integrating over the area of the circle represented by the projected outline of Earth. The maximum of the integral was found over all possible sizes of the distribution. The results are illustrated in Figure 4 by means of random fragments plotted according to each distribution for one special case of the amount of deflection relative to the projected size of Earth, and they are shown in Figure 5 as function of the amount of deflection. (Actual cases usually would be somewhere between the cases for one and three dimensions.) A large number of small fragments is shown in Figure 4 for the three-dimensional cases in order to allow the nature of the distributions to be seen. In reality the fragments might be larger but less numerous.

Analytical expressions were derived for the general case of the one-dimensional uniform distribution and for the limiting case of large distances for the other distributions. These are as follows, where s is the distance in Earth radii and η is the maximum portion expected to hit:

$$\eta = \frac{1}{\sqrt{3s^2+1}} \quad \text{for 1D uniform}$$

$$\eta = \sqrt{\frac{2}{\pi e}} \cdot \frac{1}{s} \quad \text{for 1D Gaussian, } s >> 1$$

$$\eta = \frac{1}{\sqrt{3}\,s^2} \quad \text{for 3D uniform, } s >> 1$$

$$\eta = \frac{1}{es^2} \quad \text{for 3D Gaussian, } s >> 1$$

These allow accurate extrapolation from Figure 5 for $s > 10$.

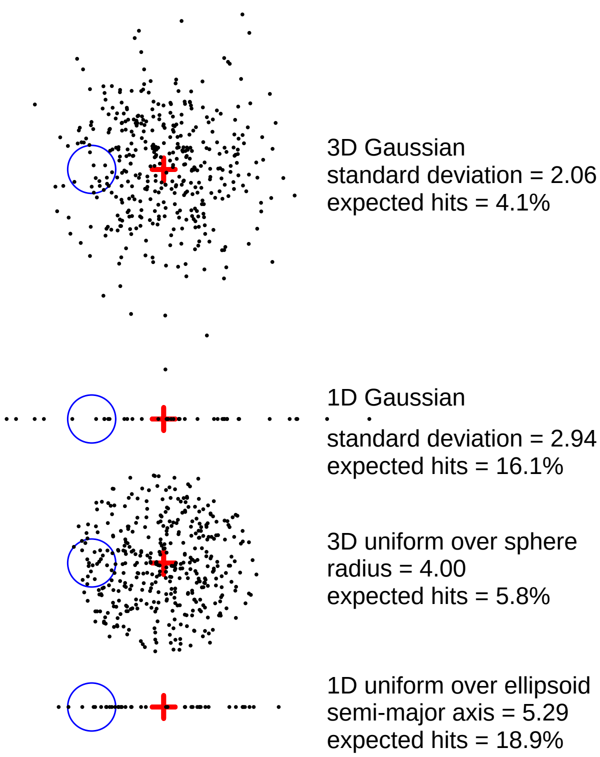

Figure 4. Examples of fragments randomly dispersed according to four different distributions, for the case in which the center of the distribution (shown by a red cross) is 3 Earth radii from the center of Earth (whose outline is shown by a blue circle), all projected into a plane perpendicular to the relative approach trajectory. In each example the size of the distribution is chosen so as to maximize the expected number of impacts, in order to represent a worst-case scenario.

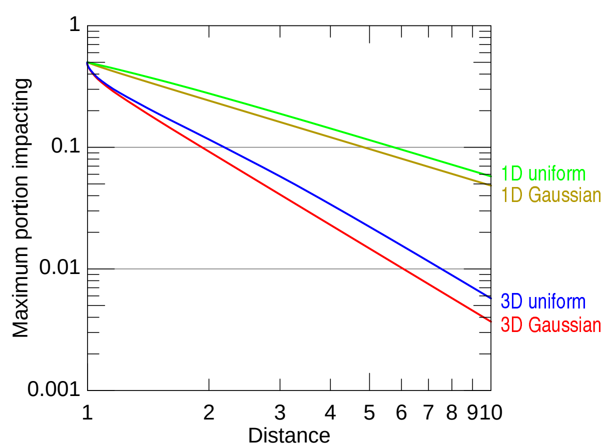

Figure 5. Worst cases for the expected portion of fragments hitting Earth, as a function of the distance of the center of the distribution from the center of Earth relative to Earth´s radius. Four different types of distribution are shown: uniform over an ellipsoid that is essentially one–dimensional compared to the size of Earth, one–dimensional Gaussian, uniform over a sphere in three dimensions, and isotropic three–dimensional Gaussian. In each case the size of the distribution is chosen so as to maximize the expected number of impacts.

There is one case in which dispersal of an object could be desirable, even if most of the fragments hit Earth. For a sufficiently small object (probably less than 100 m), the fragments would be so small and so few that they would be destroyed harmlessly in the atmosphere (unless they were iron).

SAMPLE SCENARIOS

General Discussion

Examples are given here to illustrate some of the above points. These are based on the Defined Threat (DEFT) scenarios recommended for use in this conference.[17] These scenarios include information on the orbits and their uncertainties. However, the given uncertainties in velocity are rather large, because of the short time span initially available for observing the object, resulting in large position uncertainties at the time of impact. These uncertainties would be significantly reduced as more data is collected. The purpose of this paper is to examine the effects of nuclear explosions on the objects and not to examine methods of observation and orbit determination. Therefore, it is assumed here that the component of uncertainty orthogonal to the relative approach trajectory (before being deflected by Earth's gravity) is less than 10,000 km by the time a vehicle is launched, or at least by the time it intercepts the object. The required deflection below is such as to cause the approach trajectory to miss by 10,000 km the projection of Earth (with a radius of 6500 km, allowing about 130 km for the atmosphere) as enlarged because of the focusing effect of Earth's gravity. Note that the approach trajectory in each case is not aimed at Earth's center. This fact can either increase or decrease the needed deflection, depending on the direction of approach to the object, which limits the direction in which it is practical to deflect it.

As an approximation, each object is assumed to be spherical, and the geometric mean of the given three dimensions is used as the diameter. The given nominal mass is used for each object. To be safe, actually the upper limit of mass should be used, but it is assumed here that a precursor flyby mission could refine the mass if needed. The results described above, which were derived for stony objects (specifically silicon dioxide), are used for all objects here, even though Aramis is carbonaceous. The transfer of energy by means of neutrons is assumed, except where otherwise indicated.

Each warhead in these examples would require a spacecraft to guide it to the proper point, similar to what will be used on the Deep Impact project.[18] A mass allowance of about 1000 kg (depending somewhat on the mass of the warhead), including propellant for minor course corrections, is included for this below. (It is assumed that there are no other midcourse maneuvers or spacecraft Δv at rendezvous.) A standard existing launch vehicle[19] would send the spacecraft and its warhead on an intercept trajectory, with a velocity after escape from Earth v_∞ (also known as $\sqrt{C_3}$) as specified below.

Keplerian orbits were assumed, considering only the Sun's gravity, except that corrections for Earth's gravity were computed by using hyperbolic trajectories relative to Earth for the approach of objects. Launch dates and intercept dates were chosen so as to be reasonably efficient and to allow sufficient time for preparation before launch, but thorough searches to find optimum dates were not done. For the chosen dates, optimum directions of deflection were assumed, subject to the ability to position the spacecraft based on its direction of approach.

The hypothetical DEFT examples concerning asteroids follow. (The comet Porthos is not considered here.)

Aramis

Aramis is an asteroid with diameter = 1200 m and mass = 1.15×10^{12} kg, discovered in February 2006 and predicted to hit Earth on May 13, 2033.

A launch on May 1, 2014 with v_∞ = 2.64 km/s could cause an interception on Dec. 17, 2015, at which time an asteroid deflection velocity (ΔV) of 0.0035 m/s would be needed. This is much less than the asteroid's escape velocity of 0.51 m/s, so dispersal is unlikely; if dispersal does occur, it will be so wide as to be relatively harmless. (Probably far less than 1% of the fragments would hit Earth.) The needed impulse (change in momentum) is 4.0×10^9 N s (equivalent to kg m s^{-1}). According to Figure 3, the optimum height for a single explosion when relying on neutrons is 16 m, which might be impractical. If 20 m is used instead, the neutron energy needed is 3.3×10^{14} J, as can be seen from Figure 2. One warhead B would suffice. In fact, at a height of 29 m it would produce just barely enough momentum. At the greater distance, there would be less risk of dispersion by reducing the force and spreading it over a larger area, but, since that risk is small in this case anyway, having the extra margin of safety in producing enough momentum probably is more important.

Alternatively, warhead A at 20 m would produce a momentum of 2.5×10^8 N s, so that 16 launches would be needed.

However, with such a small ΔV needed and such a small yield of neutrons from warhead A or B, it might be better to rely on X rays instead of neutrons in this case, since the former would be efficient if the explosion is moved much farther away in order to lower the energy density. Probably one warhead B at a height around 500 m would be more than enough, although precise calculations for X rays have not been done for this paper. (At this large distance the risk of dispersal would be further reduced, by spreading the force over an even larger area.)

With v_∞ = 2.64 km/s, the total payload of about 2000 kg for each warhead A could be launched by any of several vehicles, such as the Atlas IIIB or the Delta III, for example. For warhead B, the payload of about 5000 kg would require a larger rocket, but the Atlas V Heavy and the Delta IV Heavy each have more than enough capability.

Athos

Athos is an asteroid with diameter = 183 m and mass = 1.1×10^{10} kg, discovered on Feb. 22, 2005 and predicted to hit Earth on Feb. 29, 2016.

A launch on March 1, 2012 with v_∞ = 1.65 km/s could cause an interception on Nov. 22, 2013, at which time the deflection ΔV = 0.13 m/s would be needed. Since this is comparable to the escape velocity of 0.13 m/s, a dangerous dispersal is possible if only this much deflection velocity is used. However, warhead B detonated at a height of 20 m would produce an impulse of 3.0×10^9 N s and a ΔV of 0.27 m/s, which is 2.1 times the needed deflection. Figure 5 then shows that probably less than 25% of the fragments would come within 10,000 km of Earth (so that less than 4% would be expected to hit).

The fraction of hits could be reduced further by a warhead that would produce a greater impulse. An Atlas V Heavy or Delta IV Heavy could launch a 10-MtTNT warhead C (whose mass is 5900 kg) and its associated spacecraft on the trajectory used here. At the optimum height of 35 m, this would produce an impulse of 1.7×10^{10} N s and a ΔV of 1.5 m/s, which is 12 times the needed deflection. The fraction of hits probably would be well under 1%.

Alternatively, multiple launches detonated at larger distances could be used in an attempt to avoid dispersal, both by making each impulse smaller and by spreading it over a larger surface area (although this approach could be dangerous). For example, with warhead B at a height of 55 m, each impulse would be 8.2×10^8 N s, which would produce 0.075 m/s, so that 2 launches would be needed in that case.

As the height passes 100 m, the effectiveness of neutrons from warhead B on porous material falls off rapidly, but X rays become more important. At a height of 1000 m, about 5 doses of X rays from Warhead B, each producing somewhere around 0.03 m/s, probably would suffice. Moving it even further away to reduce each ΔV to 0.01 m/s would reduce the risk of dispersal even more, since this is only 1/13 of the escape velocity.

Athos has a satellite, deWinter, with a diameter of 70 m and an orbital velocity around Athos of 0.038 m/s. Since this is somewhat greater than the 0.01 m/s ΔV that each warhead would produce in the last example above, the satellite would be dragged along by the gravity of Athos, if the 13 detonations were judiciously timed and Athos did not disperse. However, if one of the above approaches with ΔV = 0.27 m/s or 1.5 m/s were used, the satellite would be left behind. It could be dealt with separately, and its small mass makes easy to deflect. In fact, deflection by kinetic energy from an impacting spacecraft might be sufficient, in which case a nuclear bomb would not be needed for it.

D'Artagnan

D'Artagnan is an asteroid with diameter = 120 m and mass = 2.7×10^9 kg, discovered on Feb. 22, 2004 and predicted to hit Earth on Sept. 14, 2009.

A launch on Oct. 1, 2007 with v_∞ = 1.04 km/s could cause an interception on Oct. 25, 2008, at which time the deflection ΔV = 0.31 m/s would be needed. This is considerably greater than the escape velocity of 0.077 m/s, so the object probably would be dispersed. Warhead B at an altitude of 20 m would produce an impulse of 2.4×10^9 and a ΔV of 0.89 m/s. Therefore, the object would be fairly widely dispersed in this case, but even if a considerable number of the fragments hit Earth, they may be small enough to be harmless.

CONCLUSION

If an Earth-threatening asteroid is discovered in the near future, it is likely to be roughly in the size range of the above examples. (Approximately 80% of the near-Earth asteroids discovered in 2003 are between 40 m and 1100 m in diameter.) Therefore, the examples show that deflection of typical asteroids by means of standoff nuclear explosions is practical.

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