NEAR EARTH ASTEROID ORBIT PERTURBATION AND FRAGMENTATION

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ABSTRACT

Collisions by near earth asteroids or the nuclei of comets pose varying levels of threat to man. A relatively small object, ~100 m diameter, which might be found on an impact trajectory with a populated region of the Earth, could potentially be diverted from an Earth impacting trajectory by mass driver rocket systems. For larger bodies, such systems would appear to be beyond current technology. For any size object, nuclear explosions appear to be more efficient, using either the prompt blow-off from neutron radiation, the impulse from ejecta of a near-surface explosion for deflection, or as a fragmenting charge. Practical deflection of bodies with diameters of 0.1, 1, and 10 km require interception, years to decades prior to earth encounter, with explosions a few Ktons, Mtons, or Gtons, respectively, of equivalent TNT energy to achieve orbital velocity changes or destruction to a level where fragments are dispersed to harmless spatial densities.

3/18/92

1. INTRODUCTION

Several hundred asteroids and comet nucleii with diameters $> 10^2$ m, in Earth crossing orbits, have been discovered. Upon extrapolating this known population of near Earth objects (NEO's) to those not yet discovered, it is estimated that $\sim 2 \times 10^3$ objects ≥ 1 km in diameter are present in a transient population [1]. New comets are brought into the swarm of NEO's by gravitational perturbation from their orbits in the Kuiper belt and/or Oort cloud [2]. In the case of asteroids, the source of NEO's is largely from the main asteroid belt. Some objects currently classed as near-earth asteroids may be devolatilized comets. Earth- or near-Earth crossing objects are removed from the population either via collision with a planet or by gravitational perturbation which causes them to be ejected into hyperbolic orbits.

We consider NEO's in three size ranges, 0.1, 1, and 10 km in diameter. Their flux per year are respectively, 10^{-3}, 10^{-5}, and 10^{-8} (Table 1). Objects significantly smaller than this pose very little threat, because they do not penetrate the atmosphere intact. For example, meteoroids ~ 10 m in diameter enter the atmosphere at least once per decade, but no such object has caused fatalities in all recorded history. Shoemaker [1,3]; and Weissman [2] have modeled the flux of objects impacting the Earth.

Impact of objects as small as 100 m diameter would cause severe local damage comparable to the 1908 Tunguska explosion ~ 12 Mton equivalent energy. Impacts by 100 m objects are expected about once in 10^3 years.

A collision with a 1 km object is expected to cause global climatic effects which could lead to worldwide casualties from disruption in food supply and societal infrastructures, etc. A 1 km-sized impactor strikes the Earth about once in 10^{5-6} years.

Larger impacts, involving ~ 10 km objects (e.g. the 65 Ma Cretaceous Tertiary (K/T) bolide), occur about once in 10^8 years and are expected to lead to the total extinction of some species. Although similar impacts undoubtedly occurred previously in Earth history, the K/T event is the most drastic change in speciation of living organisms recorded

in the evolutionary record. More than half of all the organisms that existed at that time became extinct. These included terrestrial, marine, micro- and macro-organisms, and the well-known group of dinosaurs. The impact of such a large bolide on the Earth is believed to give rise to a large number of global, physical, and chemical effects which are strongly dilatorious to life, however, these effects are not yet thoroughly understood.

In the present paper we examine the orbit perturbation requirements to deflect objects from the Earth, which upon astronomical orbit determination are found to have earth impacting trajectories. We then examine several physical means for both deflecting and explosively fragmenting such objects. Short duration responses, which might be appropriate for new comets, have recently been described by Solem [4,5]. This study addresses the physical means of encountering NEO's with spacecraft-bearing energetic devices many years, or even decades, before projected earth impact.

2. NEAR EARTH ASTEROID ORBIT DEFLECTION CONSIDERATIONS

Two possible approaches to orbit deflection are perturbation perpendicular to orbital motion and perturbation along the trajectory of motion, e.g. either speeding up or slowing down the orbital velocity relative to the Sun.

An increment of velocity, Δv applied transversely to a circularly orbiting particle induces an eccentricity or inclination which results in an oscillation about the original orbiting point of amplitude.

$$\delta \sim \frac{\Delta v}{v_0} a \tag{1}$$

where v_0 is the orbit velocity (30 km/s for the Earth) and a is the semimajor axis. Thus to perturb a particle by $\delta \sim 1 R_\oplus$. The Δv required is

$$\Delta v \sim \frac{v_0 R_\oplus}{a} \approx 1 \text{ m/s} \tag{2}$$

To perturb a body on a time t short compared to the orbit period, a simple linear estimate

3/18/92

suffices:

$$\delta = \Delta vt \qquad (3)$$

To perturb a body 1 $R_\oplus$ in time, t, requires

$$\Delta v \sim \frac{R_\oplus}{t} \sim \frac{75 \text{ m/s}}{t, \text{ days}} \qquad (4)$$

Note that the linear estimate reduces to the orbital oscillation after ~ 1 radian of orbital motion.

In contrast, an increment of velocity Δv applied parallel to the orbit motion changes the orbital semimajor axis, but more importantly, changes the orbit period which results in a secular drift of the perturbed body from its original path. For an initially circular orbit, the mean drift velocity, $\Delta v'$ is in the opposite sense and larger than Δv:

$$\Delta v' = -3\Delta v \qquad (5)$$

An even larger amplification occurs if the impulse is applied at the perihelion of an eccentric orbit. For an eccentricity of 0.5, $\Delta v' \approx -5\Delta v$. Thus, over a time long compared to the orbit period, an increment Δv applied parallel to v produces a deflection of

$$\delta \sim 3\Delta vt \qquad (6)$$

Hence, for 1 $R_\oplus$ deflection

$$\Delta v \sim \frac{R_\oplus}{3t} \sim \frac{0.07 \text{ m/s}}{t, \text{ years}} \qquad (7)$$

Thus, with a lead time of the order of a decade, a velocity increment as small as ~0.01 m/sec could suffice to divert an asteroid from a collision course with the Earth.

3. IMPLEMENTATION OF ORBITAL DIVERSION

Several scenarios are considered, including deflection via rocket mass driver systems, as well as nuclear explosive radiation and blow-off, and ejecta impulse from cratering explosions.

A. CHEMICAL ROCKETS.

Typical chemical rockets can deliver exhaust velocities of 2 to 3 km/s. We assume that mass drivers might achieve similar performance. By simple action/reaction, we can write:

$$\Delta m v = m \, \Delta v \qquad (8)$$

where Δm is the mass of material ejected, v, is the "exhaust" velocity of Δm (~3 km/s), m is the asteroid mass, and Δv the required change in velocity of m. Thus

$$\Delta m = \frac{m \Delta v}{v} \ \sim 3 \times 10^4 R^3 \Delta v \text{ tons}, \qquad (9)$$

where R is in km and Δv is in m/sec. It is quickly apparent that this requires a very large amount of propellant for rapid-response, e.g. to deflect an asteroid 1 month before encounter requires $\Delta v \sim 2.5$ m/s. For an asteroid 100m in radius, this requires 7500 tons of propellant. Since propellant requirements are large, even for long-term orbit perturbation, we do not consider this technique further.

B. MASS DRIVERS

As a long-term response, one might imagine employing a mass driver system which is in operation for many years. A lead time of three decades, prior to earth encounter would, from Eq. 7, require a $\Delta v \sim 0.2$ cm/s. The fuel requirement to move a 1 km diameter asteroid becomes $\Delta m \sim 6000$ tons. It might be technically feasible to deliver a reaction engine (mass driver or some such rocket engine) to an asteroid to perform the needed Δv. However, even for very small asteroids and for very long lead times, the mass delivery requirements appear to be very large. This approach appears to involve many launches with the largest rockets now available on Earth. Although we believe such a system could be built, it will become clear from what follows that nuclear energy offers a much less expensive solution.

3/18/92

C. NUCLEAR EXPLOSION RADIATION

By detonating a nuclear explosive which emits a large portion of its yield via neutrons, a large area of the asteroid/comet surface can be irradiated. Subsequent blow-off of surface material in excess of escape velocity can provide the necessary impulse for orbital deflection. As demonstrated in Fig. 1, by detonating a charge at a normalized altitude $h/R = 0.42$, where h and R are defined in Fig. 1, a maximum dose of $f_{max} = 0.27$ times the total radiative yield is delivered to 0.296 times the unit area of an assumed spherical asteroid. For a mean neutron cross-section of 10^{-24} cm^{-2}, an assumed asteroid density of 2 g/cm^3 and mean atomic weight of 25, a characteristic neutron penetration depth of ~20 cm is inferred. This results in an irradiated asteroid volume corresponding to a 20 cm deep surface shell which encompasses 0.296 of the surface area. Thus, a 50 m radius object will have a shell volume of 7.4×10^9 cm^3 or a mass of 1.5×10^{10} g. Assuming that a nuclear charge is always detonated at the optimum height $h/R = 0.42$, the asteroid subtends a solid angle of 0.145 of the 4π radians. We further assume that some 0.3 of the explosive yield is delivered as neutron or other radiation and that this radiation is completely converted to internal energy, ΔE, per unit mass. The resulting increase in pressure, ΔP, at constant volume in this shell will be given by

$$\Delta P = \gamma \rho \, \Delta E \qquad (10)$$

where γ is the thermodynamic Gruneisen ratio. We assume γ to be unity, and ρ is the asteroid/comet density which we assume is 2 g/cm^3. This irradiation occurs on a short time scale compared to the sonic travel-time through the shell. For the blow-off to be effective, the surface material must be launched to greater than asteroid escape velocity. For a 1 kton charge and a 50 m radius asteroid, the shell material contains an energy density $\Delta E = 1.2 \times 10^8$ ergs/g. From Eq. 10, this energy density will raise the shell thermodynamic pressure to 0.22 kbar. Since a stress pulse is delivered to the asteroid, the shell must blow-off the asteroid to conserve momentum. By assuming a compressional wave velocity, C_p, of 2 km/sec, we find

3/18/92

$$\Delta v_r = \Delta P / \rho C_p \qquad (11)$$

in the asteroid material, the resulting outward particle velocity of the shell material is 5.8 m/sec. Considering only the component of velocity along the direction between the explosive and the asteroidal center yields a reduced velocity of 4.1 m/sec. For the 50 m radius asteroid, this velocity is much greater than the escape velocity of 16.7 cm/sec. To achieve escape velocity of 16.7, 167.3, and 1.67×10^3 cm/sec, for 0.1, 1, and 10 km diameter asteroids, requires minimum charges of 0.04, 41, and 41×10^3 Kton to be detonated. By conservation of momentum, the rebounding surface material translates into an asteroidal rebound velocity of 0.73 cm/sec/Kton for charges greater than the minimum given above. For 1 and 10 km objects, the comparable rebound velocities are 0.73×10^{-3} and 0.73×10^{-6} cm/sec/Kton. Thus we conclude that to achieve deflection velocities on the order of 1 cm/sec requires detonation of 1.4 Kton, 1.4 Mton, and 1.4 Gton nuclear explosives, for asteroids of diameter 100 m, 1 km, and 10 km, respectively.

D. NUCLEAR EXPLOSIVE EJECTA PERTURBATION

Another approach to the use of nuclear explosives employs the use of a surface charge to induce cratering on the asteroid. The thrown-off ejecta effectively induces a velocity change in the asteroid and the ejecta is highly dispersed and is not expected to be a hazard when it is encountered by the Earth. This method suffers the disadvantage in that the asteroid may be inadvertently broken into large fragments which may represent a hazard to the Earth. We assume that only gravity limits ejecta production, and basically, the asteroid is weak. For the case of an asteroid where cratering processes are limited by the asteroid yield strength is qualitatively discussed below. The mass of ejecta cratered per unit mass of explosive, when cratering is limited by gravity, is given by Schmidt et al.[6]

$$\pi_v = \pi_2^{-0.46} (0.25 - 0.7 \, d/a)^{-1} [0.55 + 1.1 \, \pi_2^{0.153} (d/a) (2.5 - 0.7 \, (d/a))^{1/3}] \qquad (12)$$

Eq. 12 was obtained on the basis of small-scale laboratory centrifuge experiments under high gravity and large-scale nuclear explosive tests. Equation 12 also describes a limited number of small scale experiments conducted by Johnson et al. [7] at reduced gravity and

3/18/92

reduced atmospheric pressures. Here π_v is the mass of material ejected from the crater per unit mass of explosive. It is assumed that nuclear explosives can be assigned an equivalent TNT (high explosive) mass based on their yield. Here d and "a" are explosive depth and equivalent explosive mass radius. Also, π_2 is defined as the gravity scaling parameter

$$\pi_2 = (m/\delta)^{1/3}\, g/Q \tag{13}$$

where m is the equivalent charge mass and δ is charge density. For simplicity, we again assume that charge density and asteroid density are equal at a value of $2\,Mg/m^3$. Q is the energy per unit mass of TNT which is $4 \times 10^6\,J/kg$ and g is asteroid surface gravity. Since the only ejecta which will alter the orbit of an asteroid must be thrown off the object at a velocity exceeding the escape velocity, we use the generalized equations of Housen et al. [8] to calculate the mass of ejecta, m_e launched at speeds greater than escape velocity

$$m_e/(\rho\, R_c^3) = 0.32\, [2R/R_c]^{-0.61} \tag{14}$$

where R_c is the final crater radius. The mass of ejecta escaping the asteroid and the resulting asteroid velocity perturbation versus surface explosive charge are shown in Fig. 2. To relate R_c to m_e, we assume a conical-shaped crater with a depth to diameter ratio of 5. Like the case of nuclear radiative perturbations treated above ~1, 10^3 and 10^6 Kton of explosive energy, detonated at the asteroid surface, is required to perturb 0.1, 1, and 10 km diameter asteroidal or cometary object's orbital velocity by ~1 cm/sec.

The energetics of perturbing a strong asteroid are more difficult to quantify. In this case, although the mass of ejecta thrown-off is considerably reduced from the gravity-controlled case, we expect the mean velocities to be greater . Future physical and numerical experiments are required to investigate this case quantitatively.

5. FRAGMENTATION AND DISPERSAL

Small scale fragmentation experiments on solid rocks demonstrate that the bulk of the fragments have velocities of ~10 m/s. However, the "core" or largest fragment has been demonstrated to have a differential velocity of no more than ~1 m/s (e.g. Nakamura

3/18/92

and Fujiwara [9]). From equation 4, if the body is fragmented ~75 days before earth encounter then most of the $\geq$ 10 m fragment will still impact the Earth. For a small object (0.1 to 1 km) dispersal of the bulk of the fragments into the Earth's atmosphere may be sufficient, as long as no fragments $\geq$10 m are allowed. For a really large object (> 1 km) fragmentation would need to be conducted one or more orbits before intersection with the Earth to assure that most fragments miss the Earth. In general, the debris cloud would spread along the orbit according to Eq. 7 and in the transverse direction according to Eq. 2. For a characteristic velocity of ejecta of 10 m/s, the debris cloud would be ~10$R_\oplus$ in radius (with some oscillation about the orbit) and grow in length by ~200 $R_\oplus$ per orbit period. Thus, if the asteroid were destroyed one orbit before encounter, the Earth might encounter as little as 0.1% of the debris. But more conservatively, if many large fragments with $\Delta v \leq$ 1 m/s remained, as much as 10% of that mass might be intercepted. Thus fragmentation is likely to be a safe choice only for long lead-time response (decades) or for relatively small bodies where the fragments may still hit the Earth.

The energy necessary to disrupt an asteroid has been discussed at great length in attempts to understand the collisional evolution of asteroids and planetary satellites. It is well known that small rocky bodies (~10 cm) can be disrupted by specific energies of ~10^7 ergs/gm. The major uncertainty is in scaling to asteroidal dimensions (e.g. Housen and Holsapple [10]). However, it should be kept in mind that the main reason the specific energy decreases with increasing size is due to the definition of the threshold of "catastrophic disruption" - that is that the largest fragment is about one-half the initial body mass. We are dealing with a somewhat different problem. We require the specific energy to break the body into pieces all smaller than say 10 m, regardless of initial size. We believe the energy requirement is nearly constant energy density. Housen and Holsapple propose a model which predicts an energy density of just under 10^7 ergs/gm to disrupt a 10 m object. According to the above argument, we should assume the same energy density for a larger body to be broken into fragments $\leq$ 10 m in size.

3/18/92

Because of the large energy requirements to fracture a well consolidated asteroid, we assume that only nuclear explosives are practical for massive fragmentation. In order to relate the energy density as a function of radius for a completely coupled (buried) nuclear charge, we employ the empirical relations of shock-induced particle velocity, v, versus energy scaled radius ($r/kT^{1/3}$) of Cooper [11]. For hard (mainly igneous) terrestrial rocks of Cooper finds

$$\ell n_{10} \, v(m/s) = 5.233 - 2 \, \ell n_{10} \, (r/kT^{1/3}) \tag{15}$$

where the r, radius is hydrodynamically scaled by the one-third power of explosive yield ($kT^{1/3}$). Similarly, for soft rocks, Cooper finds

$$\ell n_{10} \, v(m/s) = 4.590 - 2 \, \ell n_{10} \, (r/kT^{1/3}) \tag{16}$$

Since the shock wave energy per unit mass is equal to v^2, the quantity

$$E_{frac} = v^2(r, kT^{1/3}) \tag{17}$$

where v^2 can be specified via Eq. (15) or (16) and $E_{frac} = 10^3$ J/kg = 10^7 ergs/g. Upon substituting Eq. (16) into Eq. (17) for 1 kT, we find r = 35 m. Thus, a 1 kT explosive is expected to fragment a 35 m radius sphere of rock, if the explosive is placed well within the asteroid. Also, a 1 megaton charge of explosive will fragment 350 m radii of rock and 1 Gton of explosive will fragment 3.5 km of rock. In contrast, for hard rock (Eq. 15), which describes less attenuative rock, gives the radius of fracture of 74 m for 1 Kton explosion.

The above discussion is based on the premise that the charge is buried to sufficient depth so as to obtain optimum fragmentation. There is good reason for desiring some nuclear charge burial, as surface exploded nuclear charges couple only a small fraction of their energy to rock (0.2 to 1.8%) for radiative and hydrodynamic coupling [6], whereas the large fraction of the energy of a deeply buried charge is coupled into rock.

As can be seen from Table 1, charge burial of 3.5 (TNT) charge radii approximately doubles the volume of crater ejecta. Figure 3 shows that the charge depth for different d/a values and yield required to completely excavate asteroids of 100, 1,000,

and 10,000 m diameter. The yield values required for an excavating charge are less by a factor of ~3 than those calculated for fragmentation. These charges are in the 1-3 kton range for 100 m asteroid, 8-29 Mton for a 1 km asteroid and 7 to 29 Gton for a 10 km diameter asteroid. The effect of gravity on the radius of excavated volumes is seen to be substantial. Fig. 3 shows that the radius of excavated volumes between craters on the Earth and asteroidal objects differ by a factor of 4 to 3 going from 0.1 to 10 km diameter objects. Dispersal seems to require about the same energy as deflection, and also is benefitted by charge burial. Hence, asteroid deflection rather than destruction, via fragmentation, appears the favorable choice.

CONCLUSIONS

We have examined the velocity criteria for perturbation of the orbits of earth-crossing objects (asteroids and comets) so as to cause objects which have trajectories which intersect the Earth to be deflected. For objects discovered only as they approach on a collision course, the velocity perturbations required are tens to hundreds of m/sec (according to e.g. 4). However, the required perturbation impulse would disrupt the body.

We also note that perturbation of an object perpendicular to its orbit is more effective by applying a change in velocity, (Δv) along its original orbit and thereby inducing a change in orbital period, and hence the radius of the orbital axes. Upon applying an impulse at perihelion, gives rise to a Δv, which, in turn, provides a larger deflection δ, after time, t, of the order of 3Δvt, than can be achieved for perpendicular deflection. The rocket fuel requirements for short term deflection of even 100 m radius asteroids from the Earth are very large, e.g. for a one month response time requires 7500 tons of chemical propellant to change the Earth crossing point by one Earth radius. Mass drivers require ~10^3 to 10^4 tons of propellant to deflect from Earth impact a 1 km asteroid over an interval of 30 years prior to encounter. Nuclear explosive irradiation may be used to blow-off a 20 cm shell encompassing (~0.3) times the asteroid surface area by exploding

a charge at an optimum height of $h/R = 0.42$. Minimum charges of 0.4, 41, and 41×10^3 Kton of explosive are required to cause this shell to blow-off with a velocity greater than the local escape velocity. Asteroid perturbation velocities of 0.73, 0.73×10^{-3} and 0.73×10^{-6} cm/sec/kT, are required to deliver a velocity change of ~1 cm/sec to 0.1, 1, and 10 km diameter, $2g/cm^3$ asteroids or comets. Surface charges of ~1, 10^3, and 10^6 Kton may be used to eject crater material to greater than local escape velocity, and hence, perturb 0.1, 1, and 10 km diameter asteroids by a velocity increment of ~1 cm/sec. Burial of nuclear charges to induce fragmentation and dispersal requires in-situ drilling which is difficult for a low gravity object or technically challenging if dynamic penetration methods are to be employed. Cratering charges required to fragment 0.1, 1, and 10 km diameter asteroids require energies of 1 to 3 Kton, 8 to 29 Mtons and 7 to 29 Gtons, respectively, depending upon burial depth.

FIGURE CAPTIONS

Figure 1. f, the fractional explosive yield absorbed by asteroid versus normalized altitude of explosion, h/R, assuming the asteroid is a sphere of radius, R, and the explosion occurs at a point. f is the product of the fraction of the solid angle of the asteroid irradiated by the explosive times the fraction of the explosive yield intercepted by this irradiated area. The maximum value of f, is 0.27, and occurs when the area of the asteroid irradiated is 0.296 of the total asteroid area. When f is f_{max}, the optimum velocity impulse is transmitted to the asteroid with the minimum blow-off velocity, and hence, minimum shock pressure delivered to the asteroid.

Figure 2. Mass ejecta accelerated to greater than escape velocity (left) for cratering explosive charges on surface and 0.1, 1, and 10 km diameter asteroid as a function of explosive yield. Plotted on right is the resultant asteroid velocity change resulting from momentum conservation.

Figure 3. Radius of excavated sphere of asteroidal material for 0.1, 1, and 10 km asteroids, versus, normalized charge depth. Effect of nominal yield explosive for each size asteroid indicated. The effect of gravity is demonstrated by the curve labeled "Earth" which gives the excavated crater volume assuming terrestrial rather than asteroidal gravity.

Table 2 reference

12

Table 2. Minimum diameter bolides which can penetrate the Earth's atmosphere (after Melosh[12]).

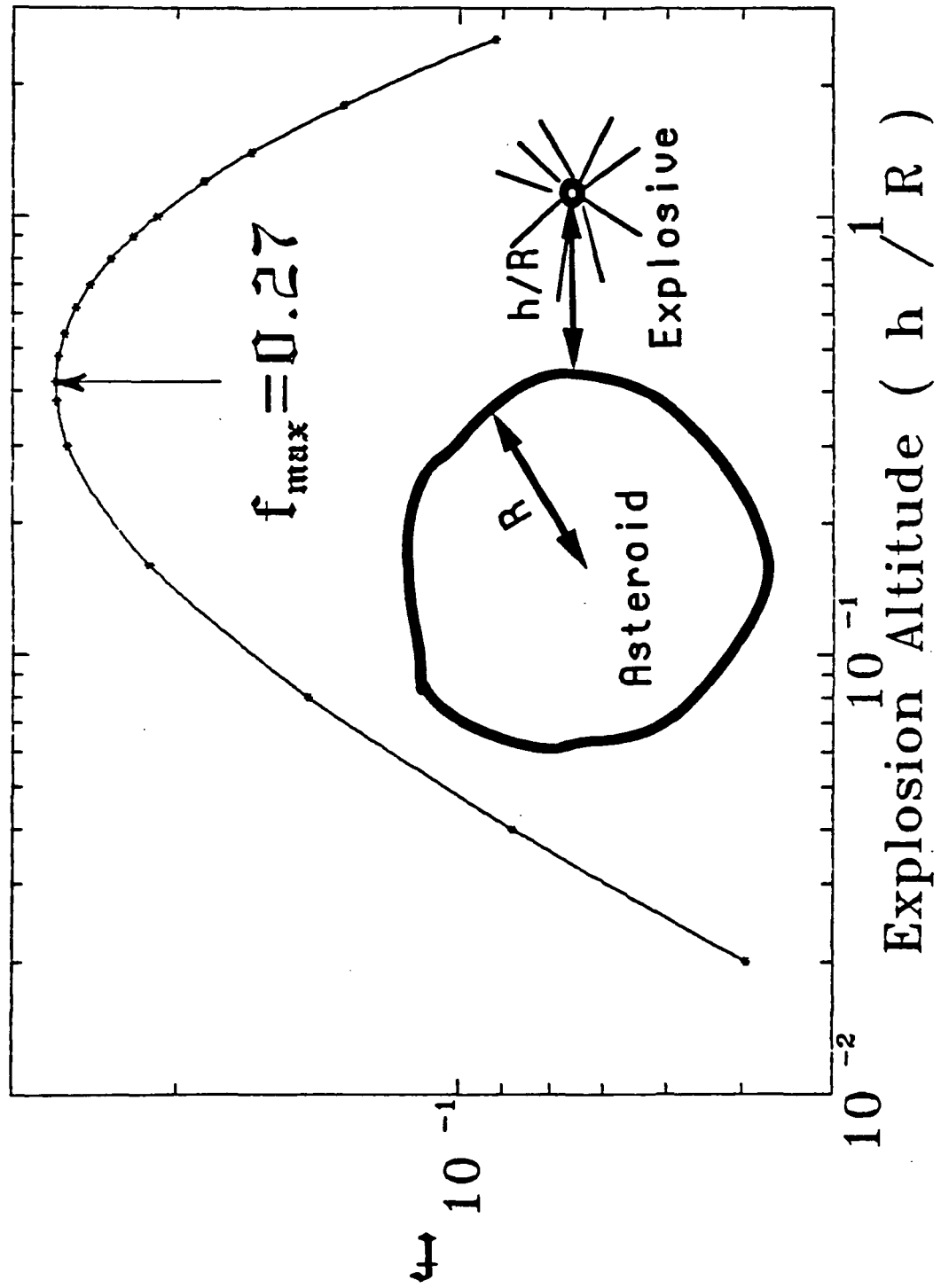| Material	ice	stoney	iron
Diameter (m)	15	6	2

REFERENCES

1.   Shoemaker, E. M., Wolfe, R. F. & Shoemaker, C. S. in *Global Catastrophes in Earth History* (eds. Sharpton, V. L. & Ward, P. D.) 155-170 (Geol. Soc. Amer. Sp. Paper, 1990).

2.   Weissman, P. R. in *Global Catastrophes in Earth History* (eds. Sharpton, V. L. & Ward, P. D.) 171-180 (Geol. Soc. Amer. Sp. Paper, 1990).

3.   Shoemaker, E. M. *Annual Rev. Earth Planet. Sci.* **11**, 461-494 (1983).

4.   Solem, J. C. Interception of comets and asteroids on collision course with Earth, LA-UR-231, Los Alamos National Laboratory (1992).

5.   Solem, J. C. Nuclear explosive propelled interceptor for deflecting comets and asteroids on a potentially catastrophic collision course with Earth, LA-UR-91-3765, Los Alamos National Laboratory (1991).

6.   Schmidt, R. M., Holsapple, K. A. & Housen, K. R. Gravity effects in cratering, DNA-TR-86-182, Boeing, Seattle, WA 98124 (1986).

7.   Johnson, S. W., Smith, J. A., Franklin, E. G., Moracki, L. K. & Teal, D. J. *J. Geophys. Res.* **74**, 4838-4850 (1969).

8.   Housen, K. R., Schmidt, R. M. & Holsapple, K. A. *J. Geophys. Res.* **88**, 2485-2499 (1983).

9.   Nakamura, T. & Fujiwara. *Icarus* **92**, 132-146 (1991).

10.   Housen, K. R. & Holsapple, K. A. *Icarus* **84**, 220-253 (1990).

11.   Cooper, H. F., Jr. in *Impact and Explosion Cratering* (eds. Roddy, D. J., Pepin, R. O. & Merrill, R. B.) 11-44 (Pergamon Press, 1977).

12.   Melosh, H. J. *Impact Cratering, A Geologic Process* 1-245 (Oxford University Press, New York, 1989).

Table 1. Near Earth Asteroid Destruction

Asteroid diameter (m)	Surface gravity g m/sec^2	Earth flux impacts/year	Asteroid mass (g)	Centrally placed explosive energy required to deliver 10^{3}J/kg (Mton)	Depth of burial, d, such that depth is equal to equivalent charge diameter (m)	Excavating charge such that excavated volume equals that of asteroid, at burial depth, d (Mton)
100	0.0003	10^{-3}	1x10^{12}	0.003	10	0.001
1000	0.003	10^{-5}	1 x 10^{15}	30	200	8
10,000	0.03	10^{-8}	1 x 10^{18}	3 x 10^4	4,000	7,000

$f_{max} = 0.27$

Explosive

h/R

R

Asteroid

10^{-2}

10^{-1}

10^0

10^{-1}

f

Explosion Altitude (h / R)

Asteroid Velocity Change(cm/sec)

ORBIT PERTURBATION
VIA EXPLOSIVE EJECTA

10 km

MASS

VELOCITY

1 km

VELOCITY

MASS

100 m

VELOCITY

MASS

Explosive Charge (kT)

Mass Ejecta (gm)

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CHARGE PLACEMENT

Charge Depth / Radius − (d / a)

Radius Excavated Volume (m)

10 km Asteroid
Earth
a = 2 km
6.7 GT

1 km
Earth
a = 100 m
8.4 MT

100 m
Earth
a = 5 m
1 kT

3   TJA92015SFD