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Interception of Comets and Asteroids on Collision Course with Earth

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ABSTRACT

I derive expressions for the weight and range of applicability of interceptors capable of deflecting a comet or asteroid on collision course with Earth. The expressions use a fairly general relationship between the energy deposited and the mass of material blown off the astral assailant. To assess the probability that the astral assailant will fracture, I also calculate the fraction of the astral assailant's mass that will be blown off. The interaction is calculated for both kinetic-energy deflection and nuclear-explosive deflection. In the nuclear-explosive case, I calculate the interceptor mass and cratering effect for detonations above the surface and below the surface as well as directly on the surface of the astral assailant. Because the wide range of densities and material properties that the astral assailant may possess, the principal value of this work is to show the relationships among the salient parameters of the problem. However, using typical values for the various physical properties, I make the following observations. (1) Kinetic-energy deflection is effective for ocean diversion of astral assailants smaller than about 70 m, if the interceptor is launched when the astral assailant is further than $\frac{1}{30}$ AU. At shorter range, interceptors become impractically massive and the probability of fracture increases rapidly. Furthermore, ocean impact is probably unacceptable for larger astral assailants. An interceptor with an order-of-magnitude larger mass is required to cause the astral assailant to miss the planet rather than *splash-down* in an ocean. The more massive interceptor introduces a larger probability of fracturing the astral assailant. Higher specific impulse interceptors are more effective at increasing deflection and reducing fracture probability, mainly because they divert the astral assailant at a greater distance. Objects less than 10 m are better pulverized by interception at short range with special mass arrays. (2) Nuclear-explosive deflection is imperative for astral assailants greater than about 100 m detected closer than $\frac{1}{30}$ AU because of interceptor size. Nuclear-surface-burst deflection offers a three-to-four order of magnitude reduction in interceptor mass. The advantage of nuclear-explosive deflection decreases slightly with specific impulse and decreases dramatically with astral assailant velocity. Fragmentation is a problem for nuclear explosive intercepts launched closer than about $\frac{1}{3}$ AU. (3) Nuclear penetrators offer no advantage for deflection, but are better for pulverization. (4) Nuclear stand-off deflection greatly reduces fragmentation probability, but with a substantial increase in interceptor mass.

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1. Introduction

The problem of preventing a collision with a comet or asteroid can be considered two domains: (1) actions to be taken if the collision can be predicted several orbital periods in advance, and can be averted be imparting a small change in velocity at perihelion and (2) actions to be taken when the colliding object is less than an astronomical unit (AU) away, collision is imminent, and deflection or disruption must be accomplished as the object closes on Earth. I call the first domain of actions, "*interdiction*" and the second domain of actions "*interception.*"

If all of the Earth-threatening asteroids were known, the orbits could be calculated and the process of deflection could be carried out in a leisurely manner. But 99% have not yet been discovered.[1] Furthermore, there are an enormous number of unknown comets for which a thorough search is completely impractical.

Asteroids in the 100-m size range are exceedingly difficult to detect unless they are very close. Comets are more conspicuous owing to their coma, but they will be moving a lot faster and can be in retrograde orbits or out of the plane of the ecliptic. In either case, it seems likely we will have little time to respond to a potential collision. It therefore appears that interception or deflection at relatively close range is one of the most important issues.

In 1984, Hyde[2] suggested using nuclear explosives to counter the comets or asteroids, which I collectively call *astral assailants* at the risk of creating a pathetic fallacy. In 1990, Wood, Hyde, and Ishikawa[3] showed that defense against small astral assailants could be accomplished with non-nuclear interceptors, largely using the kinetic energy of the astral assailant itself. In this paper, I explore the possibility of using kinetic-energy deflection as well as nuclear explosives. Nuclear explosives can be employed in three different modes depending on their location at detonation: (1) buried below the assailant's surface by penetrating vehicle; (2) detonated at the assailant's surface; or (3) detonated some distance above the surface

Figure 1 shows the interception scenario. The asteroid or comet is headed toward Earth at a velocity v. The interceptor traveling at velocity V is about to engage the astral assailant. The astral assailant has a mass M_a, and the interceptor, because it has long since exhausted its fuel, it has its final mass M_f. We cannot hope to deflect the astral assailant like a billiard ball because $M_a \gg M_f$. So the interceptor must supply energy to ***blow-off*** a portion of the astral assailant's surface, that blow-off material being very massive compared to the interceptor, $M_a \gtrsim M_e \gg M_f$. One might think that a conventional high explosive would suffice, but the energy it would supply would be relatively insignificant. Standard high explosive releases 10^3 calories $= 4.184 \times 10^{10}$ ergs per gram. An asteroid moving at 25 km $\cdot$ sec^{-1} has a specific energy of 3.125×10^{12} ergs per gram — about 75 times the specific energy of high explosive. If the interceptor is moving at the same speed in the opposite direction ($V = v = 25$ km $\cdot$ sec^{-1}), the interceptor would impact with a specific energy 300 times that of high explosive. There is a whole lot of kinetic energy available; a chemical energy release would be in the noise. However, even this tremendous kinetic energy would be completely swamped by a nuclear explosive. The yield-to-weight ratio of nuclear explosives is generally measured in kilotons per kilogram, that is, tons per gram. A typical specific energy is a million times that of chemical high explosive, or about four orders of magnitude higher that the kinetic energy of the interceptor collision.

2. Kinetic-Energy Deflection

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

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

where M_i and M_f are the initial and final mass of the interceptor and I_{sp} is the specific impulse of the rocket fuel. In general, 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

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

where $\Re_l$ is the range when the interceptor is launched and v is the speed at which the astral assailant is closing on the Earth. So the range at which the astral assailant is intercepted will be given by

$$\Re_i = \Re_l \left(1 - \frac{v}{v + V}\right), \tag{3}$$

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

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

where I have neglected the effect of the Earth's gravitational field. To obtain the transverse velocity component, we would use the kinetic energy of the interceptor to blast a crater on the side of the astral assailant. The momentum of the ejecta would be balanced by the transverse momentum imparted to the astral assailant. From Glasstone's empirical fits[4], 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 a myriad of other parameters. Clearly the *crater constant* α and the *crater exponent* β will be vary depending on whether we are considering an astral assailant composed of nickel-iron, stony-nickel-iron, stone, chondrite, or dirty snow. For almost every situation, however, we find $\beta \simeq 0.9$.

The kinetic energy available when the interceptor collides with the astral assailant is

$$E = \frac{1}{2} M_f (V + v)^2. \tag{6}$$

Only a fraction of the interceptor's kinetic energy is converted to kinetic energy of the ejected or "blow-off" material. Let this fraction be equal to $\frac{1}{2}\delta^2$, or

$$\delta = \sqrt{2\frac{\text{ejecta kinetic energy}}{\text{interceptor kinetic energy}}}. \tag{7}$$

The reason for this strange definition is that it greatly simplifies the algebra. I will call the parameter δ the *energy fraction*. Then the transverse velocity imparted to the astral assailant is

$$v_{\perp} = \delta\frac{\sqrt{M_e E}}{M_a} = \frac{\delta}{M_a}\sqrt{\frac{M_e M_f (V+v)^2}{2}} = \frac{\alpha\delta}{M_a}\left(\frac{M_f(V+v)^2}{2}\right)^{\frac{\beta+1}{2}}, \tag{8}$$

where M_a is the mass of the comet or asteroid. We can combine Eqs. (4), (5), and (8) to obtain

$$\epsilon = \alpha\delta\Re_l\frac{V(V+v)^\beta}{M_a v}\left(\frac{M_f}{2}\right)^{\frac{\beta+1}{2}}. \tag{9}$$

Equation (9) reveals the importance of the intercept velocity V, which is proportional to specific impulse I_{sp}. If $V \ll v$, the deflection is proportional to V, and if $V \gg v$, the deflection is proportional to $V^{\beta+1} \sim V^2$.

2.1. Optimum Mass Ratio for Kinetic Energy Deflection

The energy on impact is proportional to the final mass of the interceptor and the square of its relative velocity as given in Eq. (6). The smaller its final mass, the higher its relative velocity, so there is some optimum mass ratio that produces the greatest deflection for a given initial mass. This would be the optimal interceptor design, the most bang for the buck.

Substituting Eq. (1) into Eq. (9), setting

$$\frac{d\epsilon}{d(M_i/M_f)} = 0, \tag{10}$$

and solving, we find the mass ratio that produces the largest value of ϵ,

$$\frac{M_i}{M_f} = e^Q, \tag{11}$$

where

$$Q = 1 - \frac{v}{2gI_{sp}} + \sqrt{1 + \frac{1-\beta}{1+\beta}\frac{v}{gI_{sp}} + \left(\frac{v}{2gI_{sp}}\right)^2}. \tag{12}$$

We note that this optimal mass ratio depends only on the velocity of the astral assailant relative to earth v and the interceptor's specific impulse I_{sp}. The value of β is a constant of the astral assailant's soil composition and is very close to 0.9, and $g \simeq 980\ \mathrm{cm \cdot sec^{-2}}$ is a constant of Planet Earth. In the limit of very high specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = e^2. \tag{13}$$

The maximum displacement of the impact location on Earth is then given by

$$\varepsilon = \frac{\alpha \delta v^{\beta} \Re_l}{M_a} \left(\frac{M_i e^{-Q}}{2} \right)^{\frac{\beta+1}{2}} \frac{g I_{sp} Q}{v} \left(1 + \frac{g I_{sp} Q}{v} \right)^{\beta}. \tag{14}$$

Figure 2. plots the dimensionless parameter $\varepsilon M_a / \alpha \delta v^{\beta} \Re_l M_i^{\frac{1}{2}(\beta+1)}$ versus the dimensionless parameter $g I_{sp}/v$ for β =0.8, 0.9, and 1.0. It shows the increasing advantage to higher specific impulse derived from Eq. (14).

A great deal of physical insight can be obtained just by studying the axis labels of the dimensionless plot. From the ordinate, we see that for the same value of $g I_{sp}/v$, which is more or less fixed by interceptor design, the asteroid deflection ε is

- Proportional to the range of the astral assailant at launch ($\Re_l$).
- Inversely proportional to the mass of the astral assailant (M_a).
- Nearly proportional to the velocity of the astral assailant relative to Earth ($v^{\beta} \simeq v^{0.9}$).
- Nearly proportional to the initial mass of the interceptor ($M_i^{\frac{1}{2}(\beta+1)} \simeq M_i^{0.95}$).
- Proportional to the crater constant (α).
- Proportional to the square root of the fraction of interceptor kinetic energy converted to blow-off kinetic energy ($\frac{1}{2}\delta^2$).

Equation (14) can be rearranged to give the required initial mass of the interceptor,

$$M_i = 2e^{Q} \left[\frac{M_a v \varepsilon}{\alpha \delta \Re_l g I_{sp} Q} \left(\frac{1}{v + g I_{sp} Q} \right)^{\beta} \right]^{\frac{2}{\beta+1}}. \tag{15}$$

To appreciate the magnitude of the problem, it is now necessary to put in a few numbers. The best chemical fuels might have a specific impulse as high as 500 sec, which I will use to make the point. The density of potential astral assailants varies greatly, from less than 1 $\mathrm{gm \cdot cm^{-3}}$ for a snow-ball comet to a little over 1 $\mathrm{gm \cdot cm^{-3}}$ for a dirty-ice comet to about 3 $\mathrm{gm \cdot cm^{-3}}$ for a chondrite to about 8 $\mathrm{gm \cdot cm^{-3}}$ for a nickel-iron asteroid. An agreeable average is 3.4 $\mathrm{gm \cdot cm^{-3}}$. The velocity of the astral assailant relative to Earth could range from 5 $\mathrm{km \cdot sec^{-1}}$ for an asteroid in nearly coincident orbit with Earth to 70 $\mathrm{km \cdot sec^{-1}}$ for a long-period comet in retrograde orbit near the plane of the ecliptic. I will take 25 $\mathrm{km \cdot sec^{-1}}$ for this example.

Because the material properties of asteroids and comets vary so widely, an estimate of the crater constant and crater exponent is somewhat arbitrary. Here I will make an estimate for impact cratering of medium hard rock. Glasstone uses $\beta \simeq 0.9$ and $\alpha \simeq 8.4 \times$

$10^{-4}\ \mathrm{gm}^{\frac{1}{3}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \sec^{\beta}$ for an explosive buried at the optimal depth for maximum ejection of dry soil. For a surface burst, Glasstone takes $\alpha \simeq 1.6 \times 10^{-4}\ \mathrm{gm}^{\frac{1}{3}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \sec^{\beta}$. The correct value of α for the impact crater is somewhere between a surface burst and an optimally buried explosion. For the purpose of the estimating the crater size for kinetic energy deflection, I will take $\alpha \simeq 2 \times 10^{-4}\ \mathrm{gm}^{\frac{1}{3}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \sec^{\beta}$. Kreyenhagen and Schuster[5] have noted that impacts in the 20 $\mathrm{km} \cdot \sec^{-1}$ range couple 50-80% of their energy to the ground, while surface bursts couple only 1-10%. I will assume about 60% coupling and about half that goes to the blow-off. Thus about 30% of the interceptor's kinetic energy is converted to kinetic energy of the blow-off, corresponding to $\delta \simeq 0.775$.

Figure 3 shows the initial mass of the interceptor required to deflect the astral assailant by 1 Mm, as a function of the astral assailants diameter and its range when the astral assailant is launched. The one-megameter deflection is typical of the course change required to divert an astral assailant from impact in a populated area to a nearby ocean. To interpret Fig. 2 for a ten-megameter deflection, which would be conservative for missing the planet entirely ($R_{\odot} = 6.378$ Mm), we need to multiply the masses by about a factor of ten*. Figure 3 makes a clear statement about the applicability of kinetic-energy deflection. Kinetic-energy deflection is practical only for astral assailants considerably less than 100 m in diameter. To handle a 100-m astral assailant would require a 1000 ton interceptor even if launched when the astral assailant was still $\frac{1}{10}$ AU away. The mass would go to 10,000 tons if the astral assailant were deflected to miss the planet entirely rather than diverted to an ocean. Thus dealing with 100-m assailants requires another technology. For practical purposes, the kinetic-energy interceptor is limited to the 3- to 30-m assailant, which would require an interceptor mass of 1 to 100 tons.

2.2. Kinetic-Energy Fragmentation and Pulverization

Equation (15) gives the initial mass of an optimally designed interceptor for deflecting an astral assailant by blowing-off its surface. It was derived under the assumption that the amount of mass blown off is small compared to the assailant's mass. If the ejected mass is too large, the crater will have dimensions a significant fraction of the assailant's dimension, and it is more likely that the assailant will break up. If the fragments are too large and are scattered at random, they may still be able to penetrate the Earth's atmosphere and do damage. A two-meter fragment of a nickel-iron asteroid has about the same average ρr as the atmosphere measured vertically from sea level, and thus will penetrate the atmosphere loosing only about half its energy. A ten-meter chondrite, however, will probably break-up owing to the dynamic stress of traversing the atmosphere. Shock from the energy of its explosion may still do damage. In order to ensure that no damage is done, it will be necessary to pulverize the astral assailant, that is, break it into very small pieces that are sure to dissipate all of their energy in the atmosphere.

To get a handle on the problem of whether the astral assailant will be deflected, fragmented, or pulverized, we need an estimate of what fraction of the assailant will be blown off in

* From Eq.(15), $M_i \propto \epsilon^{\frac{2}{\beta+1}}$, so a factor of 10 in ϵ corresponds to a factor of 11.3 in M_i.

the collision. By combining Eqs (1), (5), (11), and (15), we find that the fraction of the assailant blown-off is given by

$$f = \frac{M_e}{M_i} = \frac{\alpha^2}{M_a}\left(\frac{M_i}{2e^Q}\right)^{\beta}(gI_{sp}Q + v)^{2\beta}$$
$$= M_a^{\frac{\beta-1}{\beta+1}}\left\{\alpha\left[\frac{\varepsilon v}{\Re_l \delta}\left(1+\frac{v}{gI_{sp}Q}\right)\right]^{\beta}\right\}^{\frac{2}{1+\beta}}, \tag{16}$$

where Q is again given by Eq.(12). Some qualitative features of the blow-off fraction are immediately apparent.

- f is nearly independent of astral assailant mass ($M_a^{\frac{\beta-1}{\beta+1}} \simeq M_a^{-0.0526}$).
- f is nearly proportional to the crater constant ($\alpha^{\frac{2}{1+\beta}} \simeq \alpha^{1.05}$) .
- f is nearly inversely proportional to the energy coupling ($\delta^{\frac{2\beta}{1+\beta}} \simeq \delta^{0.947}$).
- f is decreases asymptotically with specific impulse.

Using the parameters above, Fig. 4 shows the blow-off fraction for ocean diversion as a function of astral assailant diameter for three different ranges to the astral assailant at interceptor launch. If more than 10% is blown-off, the astral assailant will probably break-up. What we learn from Fig. 4 is that if we cannot launch the interceptor at about $\frac{1}{30}$ AU or better, we cannot deflect the astral assailant without fractuing it. Under those circumstances it is better to try to pulverize it with an array of masses, probably resembling spears for maximum penetration.

Equation (16) suggests a way to beat the fracture problem. The blow-off fraction can be reduced by increasing the specific impulse. Figure 5 shows the blow-off fraction as a function of specific impulse for a 100-m astral assailant with the sortie launched at a range of $\frac{1}{100}$ AU. With a specific impulse of 500, over 14% of the astral assailant mass is blown-off, whereas at a specific impulse of 5000, less than 4% is blown-off.

3. Nuclear Explosive Deflection

Much more deflection can be obtained if a nuclear explosive is used the provide the cratering energy. In this scenario, most of the weigh after the rocket fuel is expended would be the nuclear explosive, which produces a yield of

$$E = \varphi M_f, . \tag{17}$$

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 astral assailant is

$$v_\perp = \frac{\delta}{M_a}\sqrt{\varphi M_f M_e} = \frac{\alpha\delta}{M_a}(\varphi M_f)^{\frac{\beta+1}{2}} . \tag{18}$$

We can combine Eqs. (4), (5), and (18) to obtain

$$\epsilon = \frac{\alpha\delta R_l}{M_a v}\frac{V(\varphi M_f)^{\frac{\beta+1}{2}}}{V+v}. \tag{19}$$

3.1. Optimum Mass Ratio for Nuclear Explosive Deflection

Substituting Eq. (1) into Eq. (19) and solving Eq. (10), we find the logarithm of the mass ratio that produces the largest value of ϵ,

$$Q = -\frac{v}{2gI_{sp}} + \frac{1}{2}\sqrt{\frac{8v}{(1+\beta)gI_{sp}} + \left(\frac{v}{gI_{sp}}\right)^2}. \tag{20}$$

In the limit of very high specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = 1. \tag{21}$$

In the limit of very low specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = \exp\left(\frac{2}{1+\beta}\right). \tag{22}$$

The maximum displacement of the impact location on Earth is then given by

$$\varepsilon = \frac{\alpha\delta\Re_l}{M_a v}\frac{gI_{sp}Q(\varphi M_i e^{-Q})^{\frac{\beta+1}{2}}}{gI_{sp}Q + v}. \tag{23}$$

For a surface burst, Glasstone uses $\beta = 0.9$, but takes $\alpha \simeq 1.6\times10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$. He describes the medium as dry soil. Medium strength rock would be more consistent with $\alpha \simeq 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$, and, in the 20-kt range, would roughly agree with Cooper[6]. If about 5% of the nuclear explosive energy goes into kinetic energy of the blow-off, then $\delta = 1/\sqrt{10} \simeq 3.16$.

Equation (23) can be rearranged to give the required initial mass of the interceptor,

$$M_i = \frac{e^Q}{\varphi}\left[\frac{M_a v\varepsilon}{\alpha\delta\Re_l}\left(1 + \frac{v}{gI_{sp}Q}\right)\right]^{\frac{2}{\beta+1}}, \tag{24}$$

where now Q is given by Eq. (20).

It is generally known that nuclear warheads can be a few kilotons per kilogram if they weigh more than about a hundred kilograms. For the purpose of these estimates, I will take the conservative of $\varphi = 1$ kiloton $\cdot$ kilogram^{-1}. Figure 6. is analogous to Fig. 3, using the values of α and δ given above.

A good way to compare kinetic-energy deflection with nuclear-explosive deflection is to look at the ratio of the initial masses of the interceptors. If we divide Eq. (24) by Eq. (15), we see that all variables drop out except specific impulse (I_{sp}), the astral assailant's velocity (v), the energy fraction (δ), and the cratering constant (α). For a comparison of the techniques, we would keep the same values of I_{sp} and v. We define the ratio

$$R_m = \frac{M_i \text{ given by Eq. (24)}}{M_i \text{ given by Eq. (15)}}. \tag{25}$$

The the appropriate dimensionless ratio for the comparison is

$$R_m \frac{\alpha_n \delta_n}{\alpha_k \delta_k}, \tag{26}$$

where the subscripts n refer to the parameters for nuclear-explosive deflection and the subscripts k refer to the parameters for kinetic-energy deflection. This is the actual ratio of initial interceptor weights for kinetic-energy versus nuclear-explosive deflection. Figure 7a shows this ratio as a function of astral-assailant velocity (v) for specific impulse $I_{sp} = 500$ sec. Figure 7b shows the same ratio as a function of specific impulse (I_{sp}) for assailant velocity $v = 25\ \text{km} \cdot \text{sec}^{-1}$. Figure 7c shows the same ratio as a function of both specific impulse and astral-assailant velocity. For the numerical examples we have chosen, we have

$$\frac{\alpha_n \delta_n}{\alpha_k \delta_k} = \frac{10^{-4} \times 0.316}{2 \times 10^{-4} \times 0.775} = 0.204. \tag{27}$$

So for my particular selection of parameters, we can read the mass ratios in Figs. 7a, 7b, and 7c by multiplying the number on the vertical axis by 0.204.

From Figs. 7a, 7b, and 7c, we learn the following qualitative features.

- The interceptor weight is about three orders of magnitude less for nuclear-explosive deflection than for kinetic-energy deflection.
- The advantage of nuclear-explosive deflection decreases significantly with astral assailant velocity.
- The advantage of nuclear-explosive deflection decreases slightly with specific impulse.

3.2. Nuclear-Explosive Fragmentation and Pulverization

By combining Eqs (1), (5), (11), and (24), we find that the fraction of the astral assailant blown-off is given by

$$\begin{aligned} f = \frac{M_e}{M_i} &= \frac{\alpha^2}{M_a}\left(\frac{\varphi M_i}{e^Q}\right)^{\beta} \\ &= M_a^{\frac{\beta-1}{\beta+1}}\left\{\alpha\left[\frac{\varepsilon v}{\Re_l \delta}\left(1+\frac{v}{g I_{sp} Q}\right)\right]^{\beta}\right\}^{\frac{2}{1+\beta}}, \end{aligned} \tag{28}$$

where Q is given by Eq. (20). Somewhat remarkably, Eq. (28) is independent of φ and has the same form as Eq. (16). The only differences are: (1) the different form of Q, (2) the value of the energy fraction δ, and (3) the value of the cratering constant α.

Figure 8 shows the blow-off fraction for planetary miss (10 Mm) as a function of astral assailant diameter for two different ranges to the astral assailant at interceptor launch. If the interceptor is launched at a range much closer than $\frac{1}{3}$ AU, the astral assailant will be fragmented rather than deflected.

3.3. Penetrators

The biggest crater is not produced by a surface burst, but by an explosive buried some distance below the surface. Clearly if it is buried too deeply, it will produce no crater at all. The optimum depth for cratering is a function of all the usual parameters describing material properties, but most importantly, gravity, which, to a large extent, can be ignored for comets and asteroids. For dry soil on the surface of the Earth, Glasstone gives the optimum depth as 150 $E^{0.3}$ feet and he would obtain the crater constant and exponent as $\beta \simeq 0.9$ and $\alpha \simeq 8.4 \times 10^{-4}\ \mathrm{gm}^{\frac{1}{3}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \mathrm{sec}^{\beta}$ for use in Eq. (5). For the moment, let us say that the value of α is increased an order of magnitude.

Looking at Eq. (24), we might expect the initial mass to decrease an order of magnitude, but in order to penetrate to the optimal depth the explosive has to be fitted with a weighty billet: a cylinder of metal (probably tungsten) that will erode during penetration of the astral assailant's soil. In general, this will increase the weight by about an order of magnitude, or decrease the yield-to-weight φ by about an order of magnitude. Thus in Eq. (24), the decrease in initial interceptor mass M_i owing to the increase in the cratering constant α is just about compensated by the decrease in yield-to-weight φ.

However, the blow-off fraction given in Eq. (28) becomes an order of magnitude larger, because it does not depend on yield-to-weight φ. The conclusion is that a penetrator has no value enhancing deflection, but may be of great value if we choose to pulverize the astral assailant.

3.3. Stand-off Deflection

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 assailant's surface. This will spread the impulse over a larger area and lessen the shear stress to which the assailant 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.

The problem of calculating the momentum transferred from a stand-off detonation is sufficiently complicated that it is difficult to address analytically. Computer simulations seem the most effective approach. However some general statements can be made. At an optimal height of burst, about 2 to 8% of the explosive's energy is coupled to the astral assailant's surface, again depending on the assailant's actual composition and the neutron spectrum and total neutron energy output of the explosive. This corresponds to an energy fraction δ of 0.2 to 0.4. Most of the energy is deposited in the first 10 cm of the soil. The cratering constants can still be used as in Eq. (5), but for this surface blow-off, $\beta \simeq 1$ and α ranging from 10^{-6} to 2×10^{-6} $\text{cm}^{-1} \cdot \text{sec}$. If we select an astral assailant for which $\delta = 0.3$ and $\alpha = 1.5 \times 10^{-6}$ $\text{cm}^{-1} \cdot \text{sec}$, we find from Eq. (24) that the blow-off fraction will be about a factor of 35 times smaller than the surface burst. The blow-off fraction given in Fig. (8) would be in the range of 1% for $\Re_l = \frac{1}{10}$ AU and in the range of $\frac{1}{3}$% for $\Re_l = \frac{1}{3}$ AU. Similarly, from Eq. (28) we find that the initial mass of the interceptor would have to be about 40 times as large. So in Fig. (6) the mass would be multiplied by 40, i.e. ranging from about 28 tons to about 28 kilotons. The latter would not be very practical.

4. Comments, Summary, and Tentative Conclusions

Since Alvarez[7] announced evidence for asteroid impact as the putative cause of the cretaceous-tertiary extinction, there has been a heightened awareness that our fair planet is and always has been in a state of merciless cosmic bombardment. Not all this cannonade has been deleterious, for example, the event Alvarez suggests may have cleared the way for the rise of homo sapiens. But being a selfish sub-species, we would rather hold on to our domination of the Earth, and deny a chance to any more well adapted creature for as long as we can. Less facetious is the possibility of a strike from an interplanetary body with radius on the order of 100 m. If an asteroid, such an astral assailant would likely have a relative velocity of about 25 $\text{km} \cdot \text{sec}^{-1}$, which would give it a kinetic energy of about 1000 megatons. In a populated area, the damage would be catastrophic. If it were a comet, the relative velocity would be more like 50 $\text{km} \cdot \text{sec}^{-1}$ and the energy would quadruple. The Tunguska Event[8] (1908) offers sobering evidence that such potentially catastrophic collisions are not so infrequent that they can be ignored. That impact was about 10 megatons and could be expected every few hundred years. Recent estimates[9] indicate that a 20-kiloton (Hiroshima-size) event should occur every year. This would be conspicuous, apparently much of the energy is dissipated in penetrating the atmosphere. That such cataclysms are not generally recorded in the archives of natural disaster seems somewhat of a mystery. Perhaps it can be attributed to the fact that until the 20th century, very little of the Earth's surface was populated.[10] Nevertheless, the risk of being killed as a result of asteroid impact is somewhat greater than the risk of being killed in an airplane crash.[11]

The problem naturally divides into two parts: (1) detection of these relatively small astral assailants; and (2) smashing or deflecting them should they be on an endangering course. In this paper, I have addressed the latter issue. The relationships I have derived should guide thinking on how to counter such astral assailants. Their main value is to show the functional relationship among the parameters. This paper is not intended to be an exhaustive study, and much research will be required to evaluate the constants in the equations I have derived. But the following observations are compelling and unavoidable.

- Kinetic-energy deflection is effective for ocean diversion for astral assailants smaller than about 70 m, if the interceptor is launched when the astral assailant is further than $\frac{1}{30}$ AU

  - At shorter range, interceptors become impractically massive and the probability of fracture increases rapidly
  - Ocean impact is probably unacceptable for larger astral assailants, and an order-of-magnitude larger interceptor is required for missing the planet with concomitant increase in fracture probability
  - Higher specific impulse interceptors are more effective at increasing deflection and reducing fracture probability, mainly because they divert the astral assailant at a greater distance.
  - Objects less than 10 m are better pulverized at short range.

- Nuclear-explosive deflection is imperative for astral assailants greater than about 100 m detected closer than $\frac{1}{30}$ AU because of the enormous mass of the interceptor required for kinetic-energy diversion.
- Nuclear-surface-burst deflection offers a three-to-four order of magnitude reduction in interceptor mass.
  - Advantage decreases slightly with specific impulse
  - Advantage decreases dramatically with astral assailant velocity
  - Fragmentation is a problem for intercepts closer than about $\frac{1}{30}$ AU.
- Nuclear penetrators offer no advantage for deflection, but better for pulverization.
- Nuclear stand-off deflection greatly reduces fragmentation probability, but involves a substantial increase in interceptor mass

5. References

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Figure Captions

Figure 1. *Interception Scenario.* The asteroid or comet is headed toward Earth at a velocity v. The interceptor traveling at velocity V is about to engage the astral assailant. The assailant has a mass M_a, and the interceptor, because it has long since exhausted its fuel, it has its final mass M_f. The interceptor must supply energy to *blow-off* a portion of the assailant's surface, that blow-off material being very massive compared to the interceptor, $M_a \gg M_e \gg M_f$.

Figure 2. *Dimensionless Plot of Kinetic-Energy Deflection.* Shows the dimensionless parameter $\varepsilon M_a/\alpha\delta v^\beta \Re_l M_i^{\frac{1}{2}(\beta+1)}$ versus the dimensionless parameter gI_{sp}/v for β =0.8, 0.9, and 1.0.

Figure 3. *Initial Masses of Optimally Designed Interceptors Using Kinetic-Energy Deflection.* Initial mass of the interceptor required to deflect the astral assailant by 1 Mm, as a function of the assailant's diameter and its range when the assailant is launched. $\rho = 3.4\ \mathrm{gm\cdot cm^{-3}}$, $v = 25\ \mathrm{km\cdot sec^{-1}}$, $\alpha = 2\times10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$ and $\delta \simeq 0.775$. The one-megameter deflection is typical of the course change required to divert an astral assailant from impact in a populated area to a nearby ocean. To interpret a ten-megameter deflection, which would be conservative for missing the planet entirely ($R_\odot = 6.378$ Mm), multiply the masses by about a factor of ten ($M_i \propto \varepsilon^{\frac{2}{\beta+1}}$, so a factor of 10 in ε corresponds to a factor of 11.3 in M_i.).

Figure 4. *Blow-off Fraction for Ocean Diversion (1 Mm) using Kinetic-Energy Deflection.* $\rho = 3.4\ \mathrm{gm\cdot cm^{-3}}$, $v = 25\ \mathrm{km\cdot sec^{-1}}$, $\alpha = 2\times10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$ and $\delta \simeq 0.775$. If more than 10% is blown-off, the astral assailant will probably break-up.

Figure 5. *Asymptotic Decrease of Blow-off Fraction with Specific Impulse.* The blow-off fraction as a function of specific impulse for a 100-m astral assailant with the sortie launched at a range of $\frac{1}{100}$ AU. With a specific impulse of 500, over 14% of the astral assailant mass is blown-off, whereas at a specific impulse of 5000, less than 4% is blown-off.

Figure 6. *Initial Masses of Optimally Designed Interceptors Using Nuclear-Explosive Deflection.* Ocean deflection of 1 Mm is sought. $\rho = 3.4\ \mathrm{gm\cdot cm^{-3}}$, $v = 25\ \mathrm{km\cdot sec^{-1}}$, $\alpha = 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$ and $\delta \simeq 0.316$.

Figure 7. *Ratio of Kinetic-Energy Interceptor Mass to Nuclear-Explosive Interceptor Mass.* (a) As a a function of assailant velocity (v) for specific impulse $I_{sp} = 500$ sec. (b) As a function of specific impulse (I_{sp}) for assailant velocity $v = 25\ \mathrm{km\cdot sec^{-1}}$. (c) As a function of both specific impulse and assailant velocity. For the present numerical examples we have chosen, $\alpha_n\delta_n/\alpha_k\delta_k = 0.204$. So figures can be read by multiplying the number on the vertical axis by 0.204.

Figure 8. *Blow-off Fraction for Collision Avoidance (10 Mm) using Nuclear-Explosive Deflection.* If the interceptor is launched at a range much closer than $\frac{1}{3}$ AU, the astral assailant will be fragmented rather than deflected.

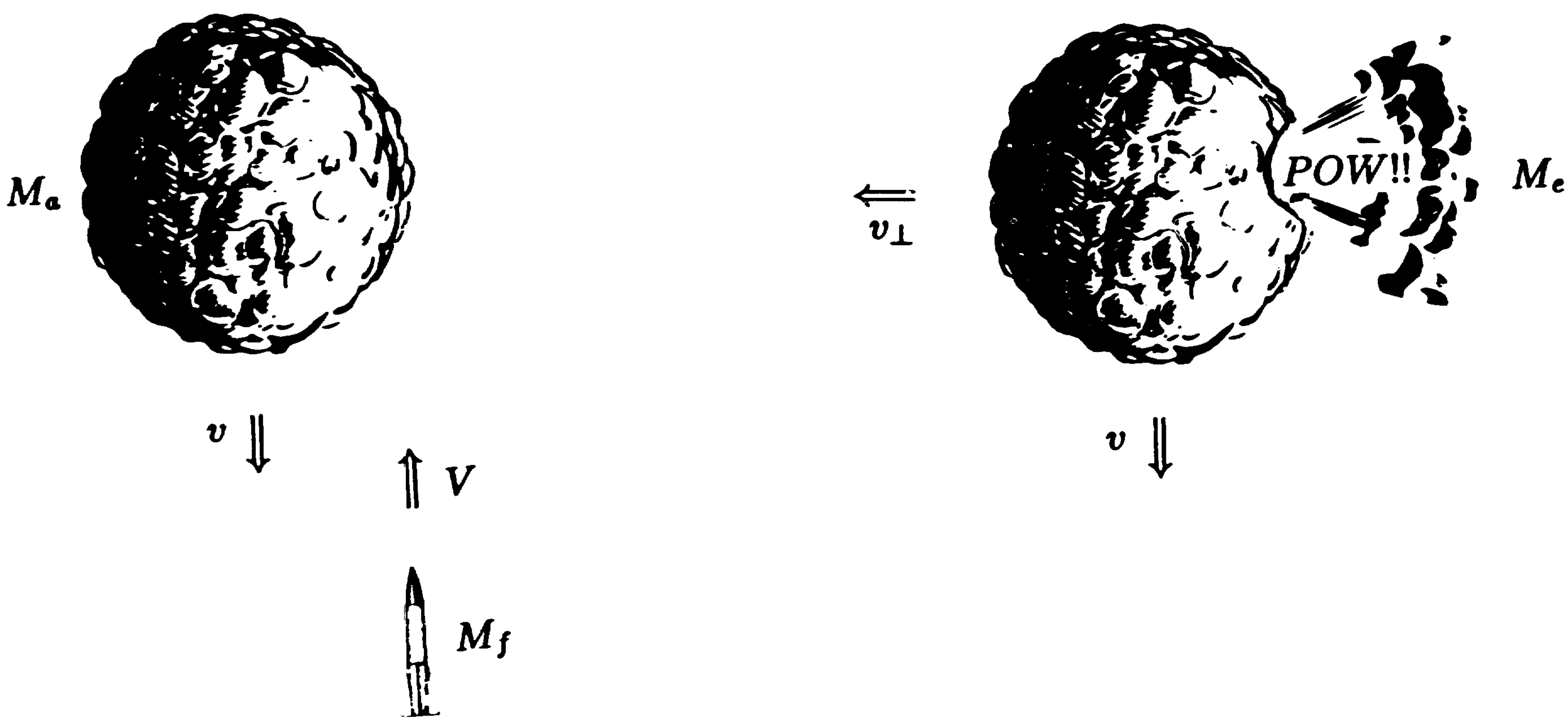


Figure 1.

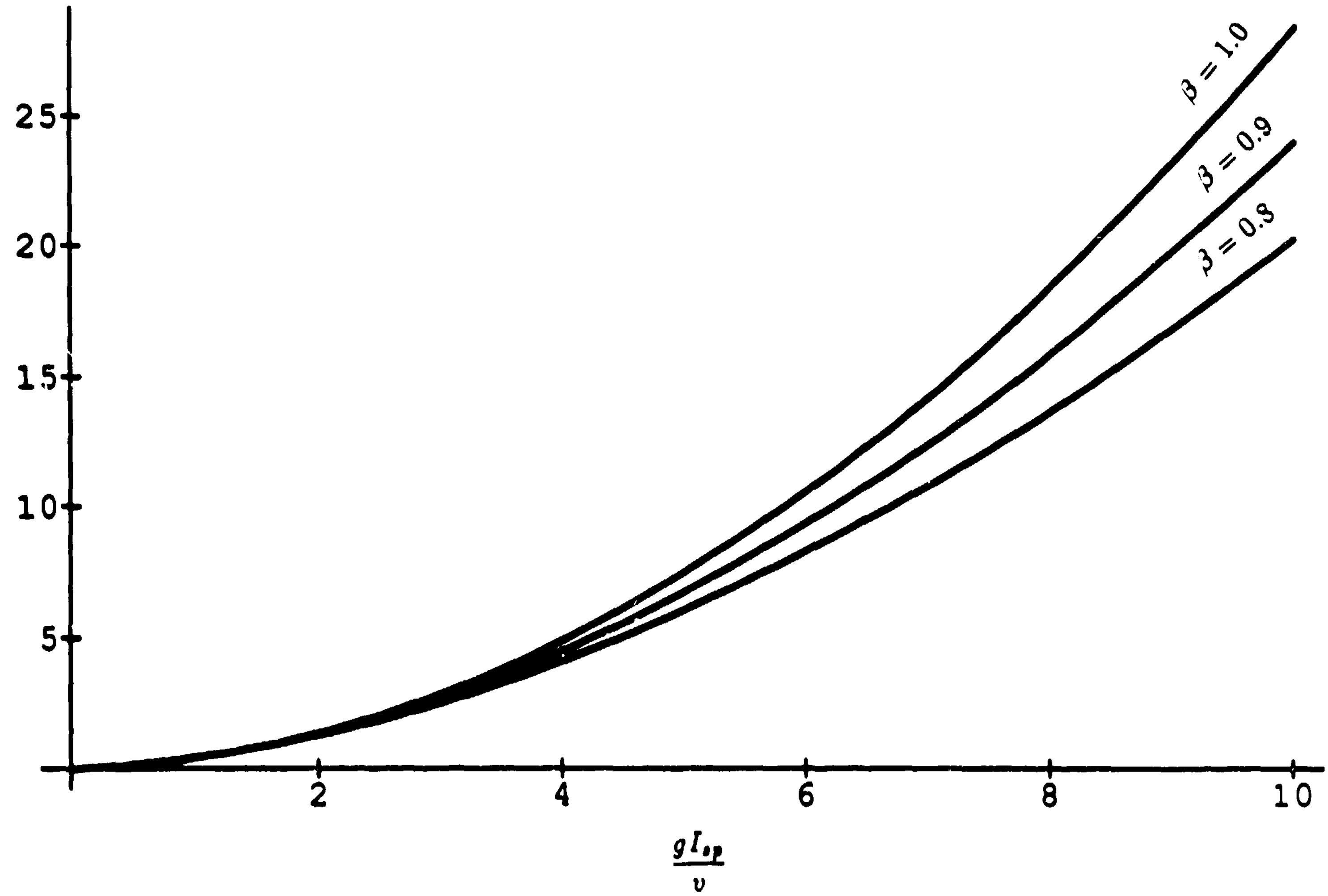
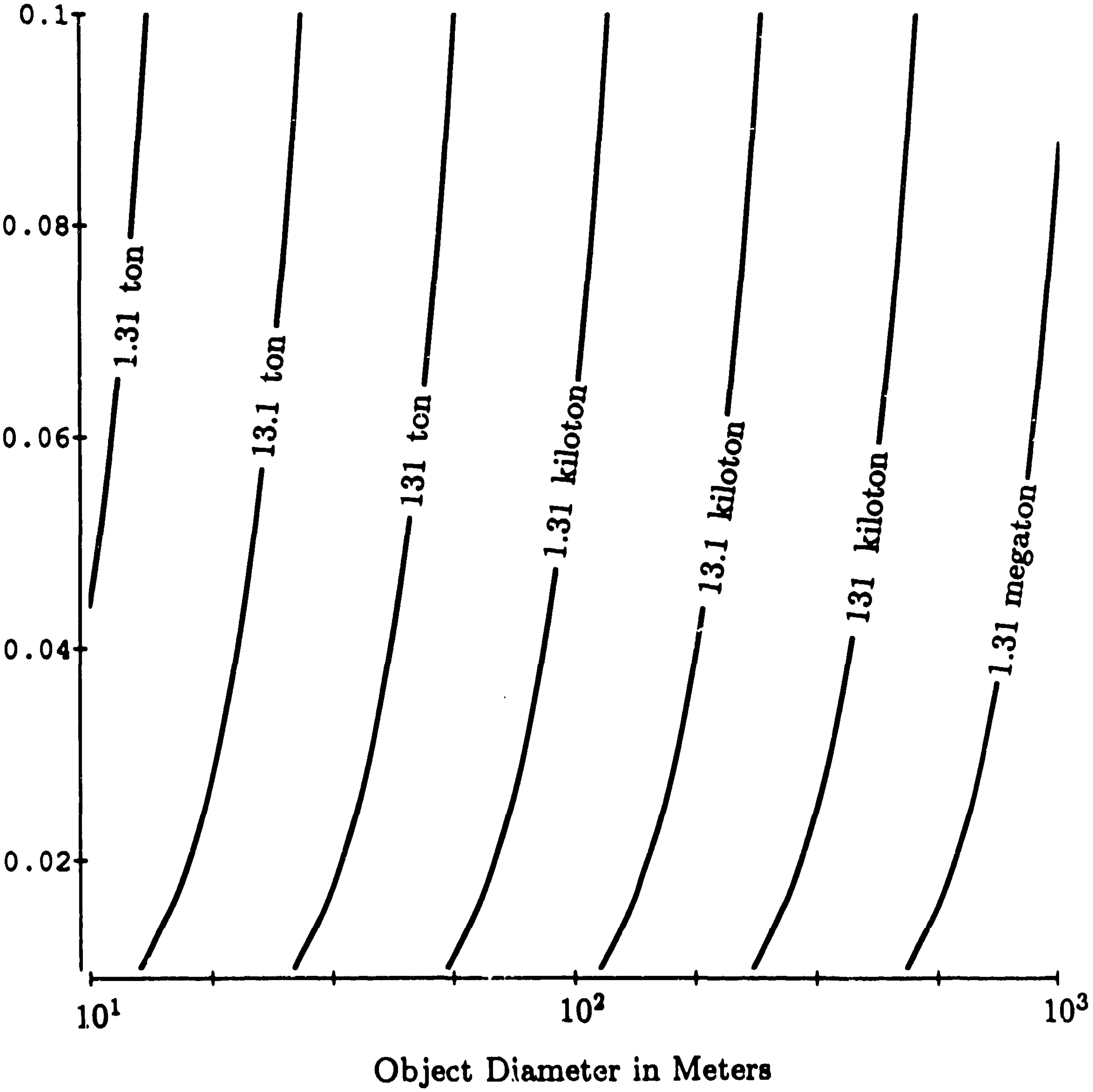


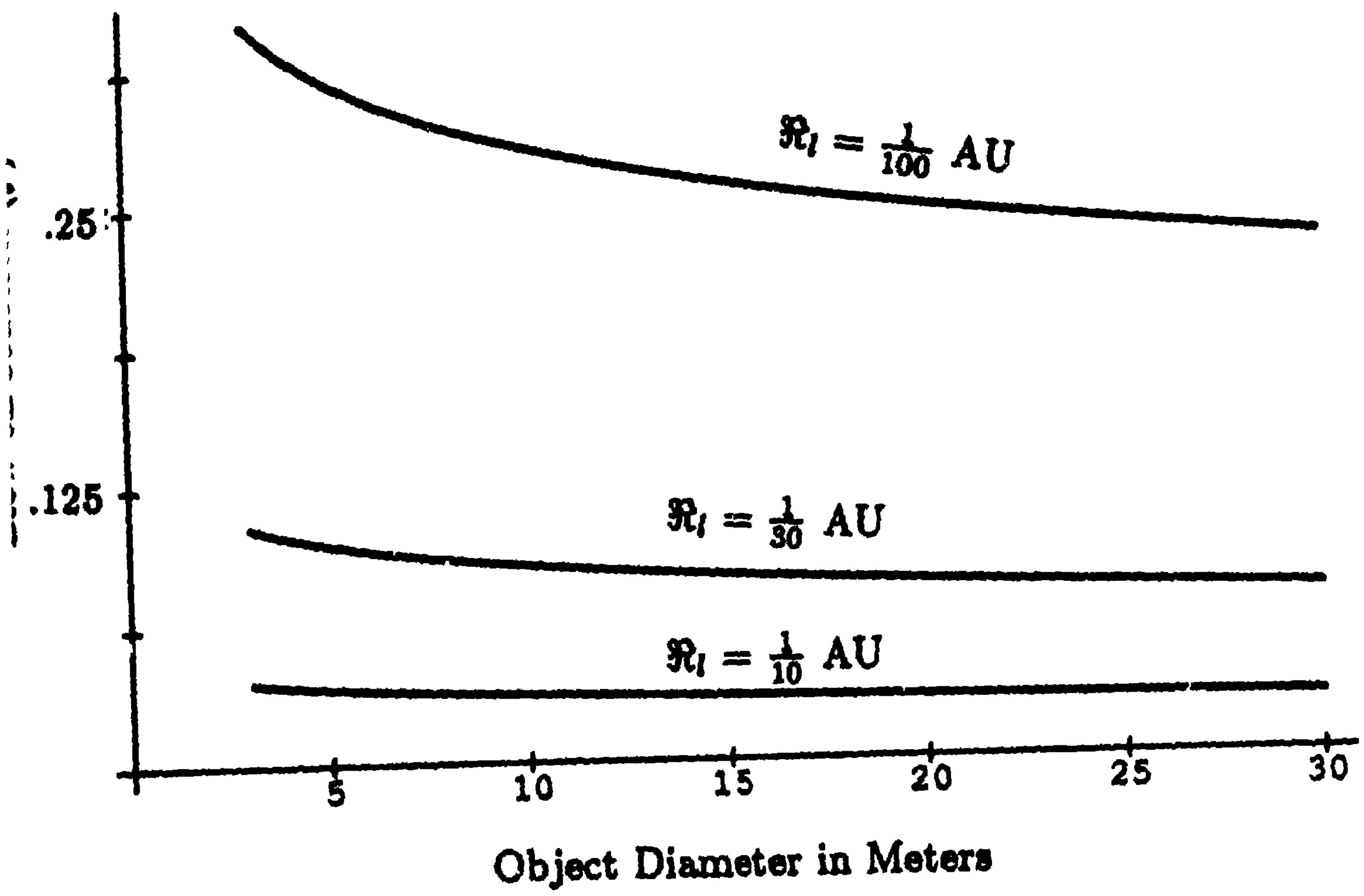
Figure 2.



$\alpha = 2 \times 10^{-4}$

$\delta = 0.775$ (30% energy to blow-off)

Figure 3



.25
.125
$\Re_l = \frac{1}{100}$ AU
$\Re_l = \frac{1}{30}$ AU
$\Re_l = \frac{1}{10}$ AU
5
10
15
20
25
30
Object Diameter in Meters

Figure 4.

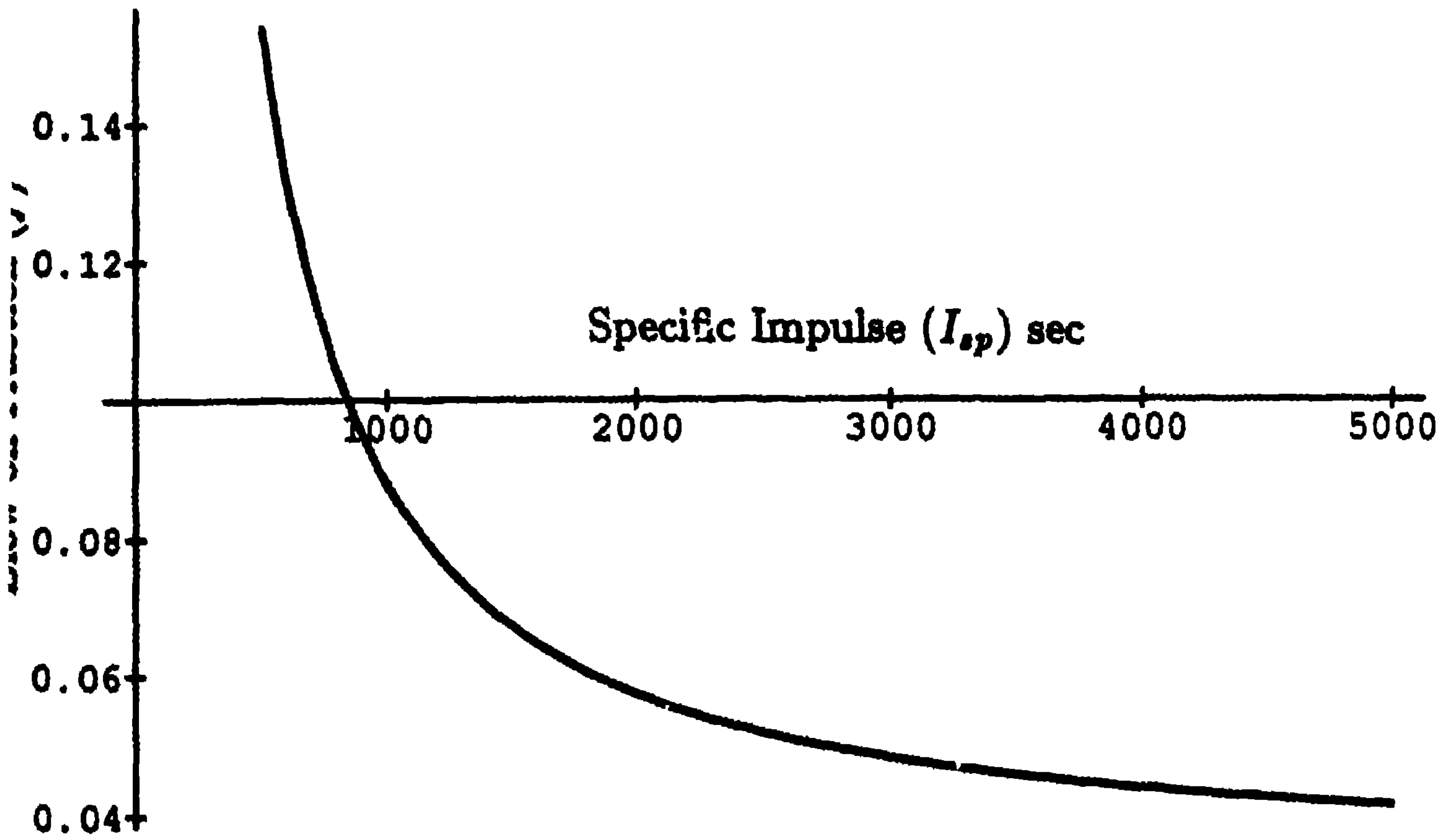
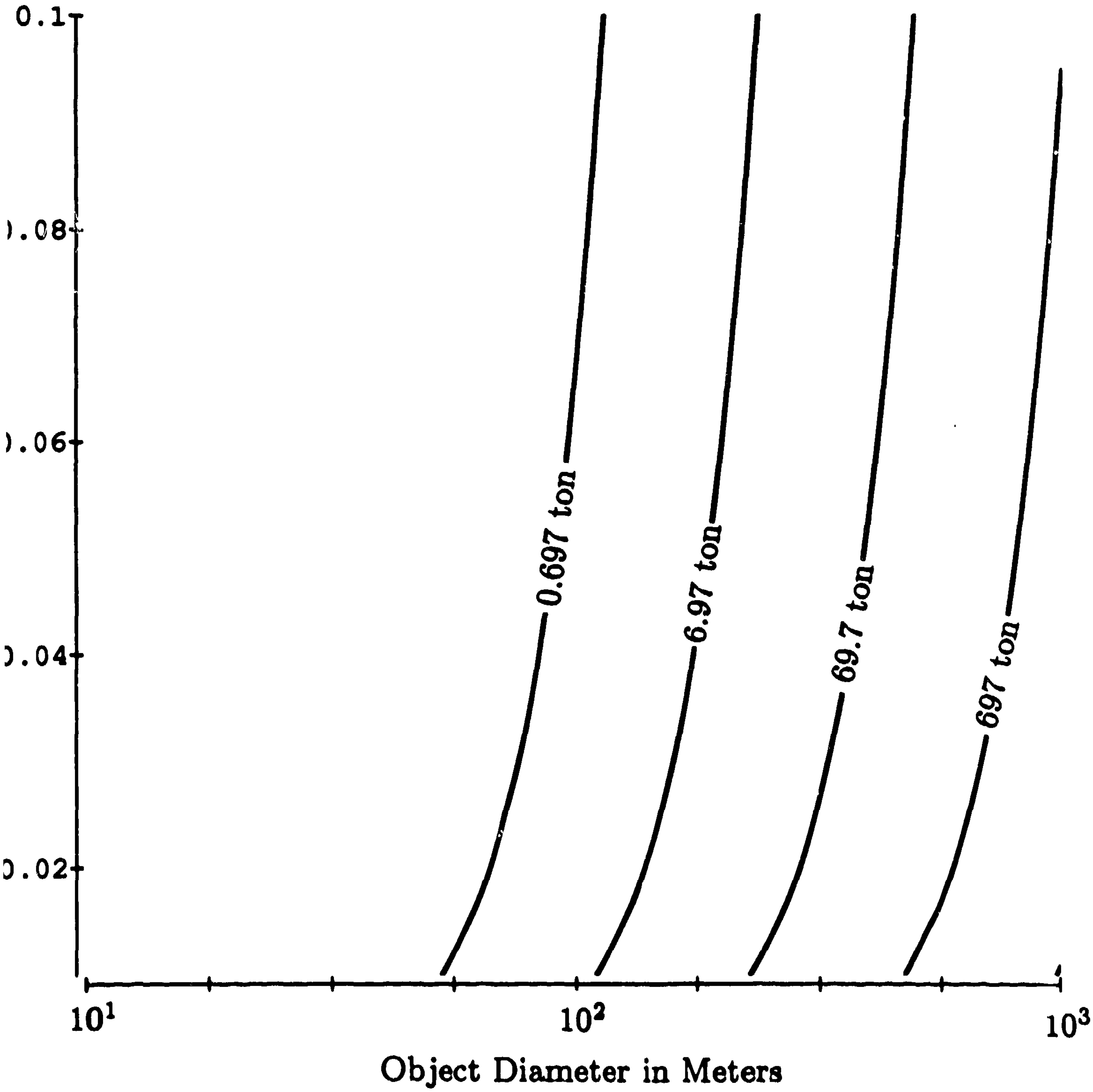

0.14
0.12
0.08
0.06
0.04
Specific Impulse (I_{sp}) sec
1000
2000
3000
4000
5000

Figure 5.



$\alpha = 10^{-4}$

$\delta = 0.316$ (5% energy to blow-off)

Figure 6.

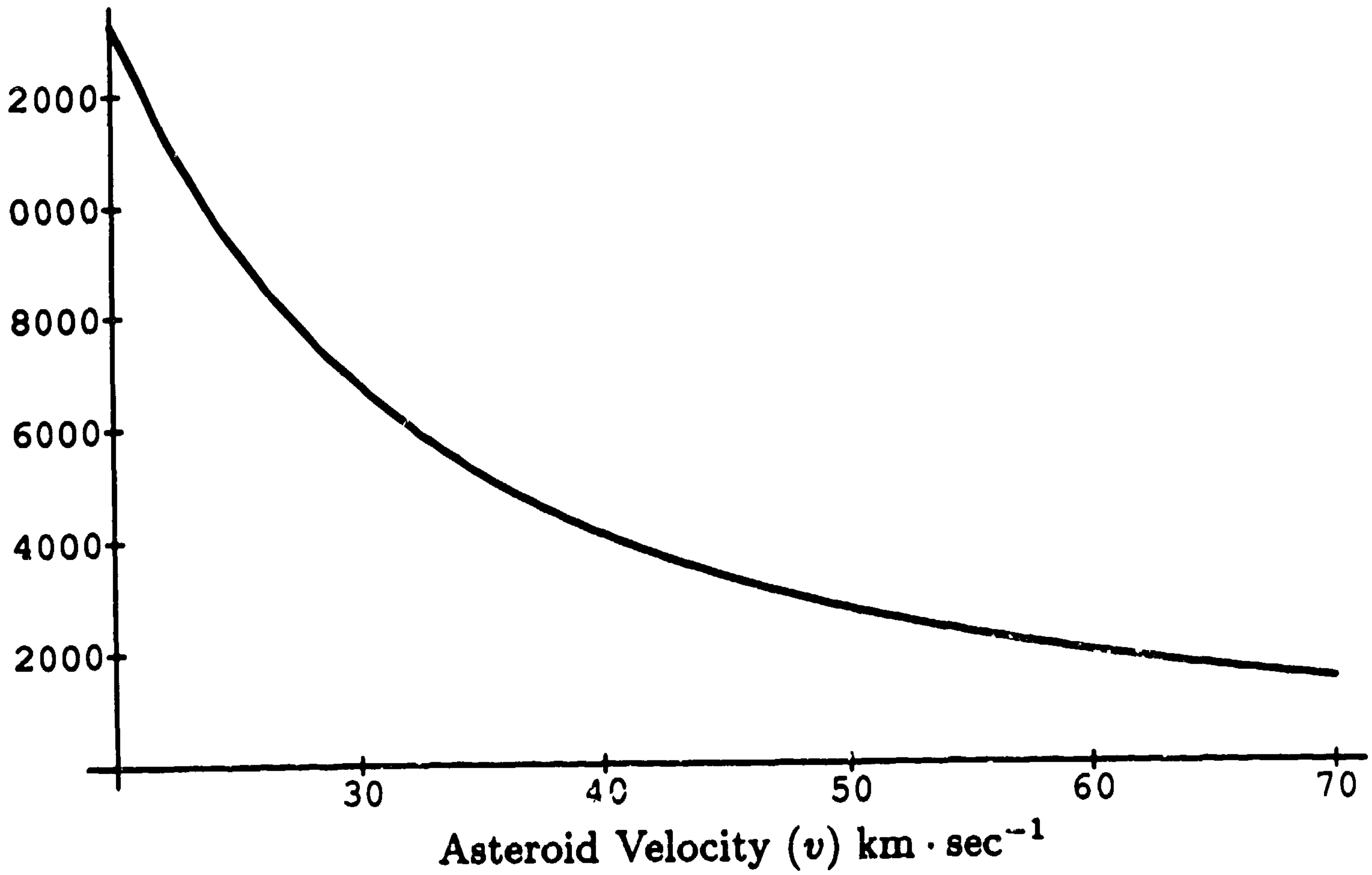
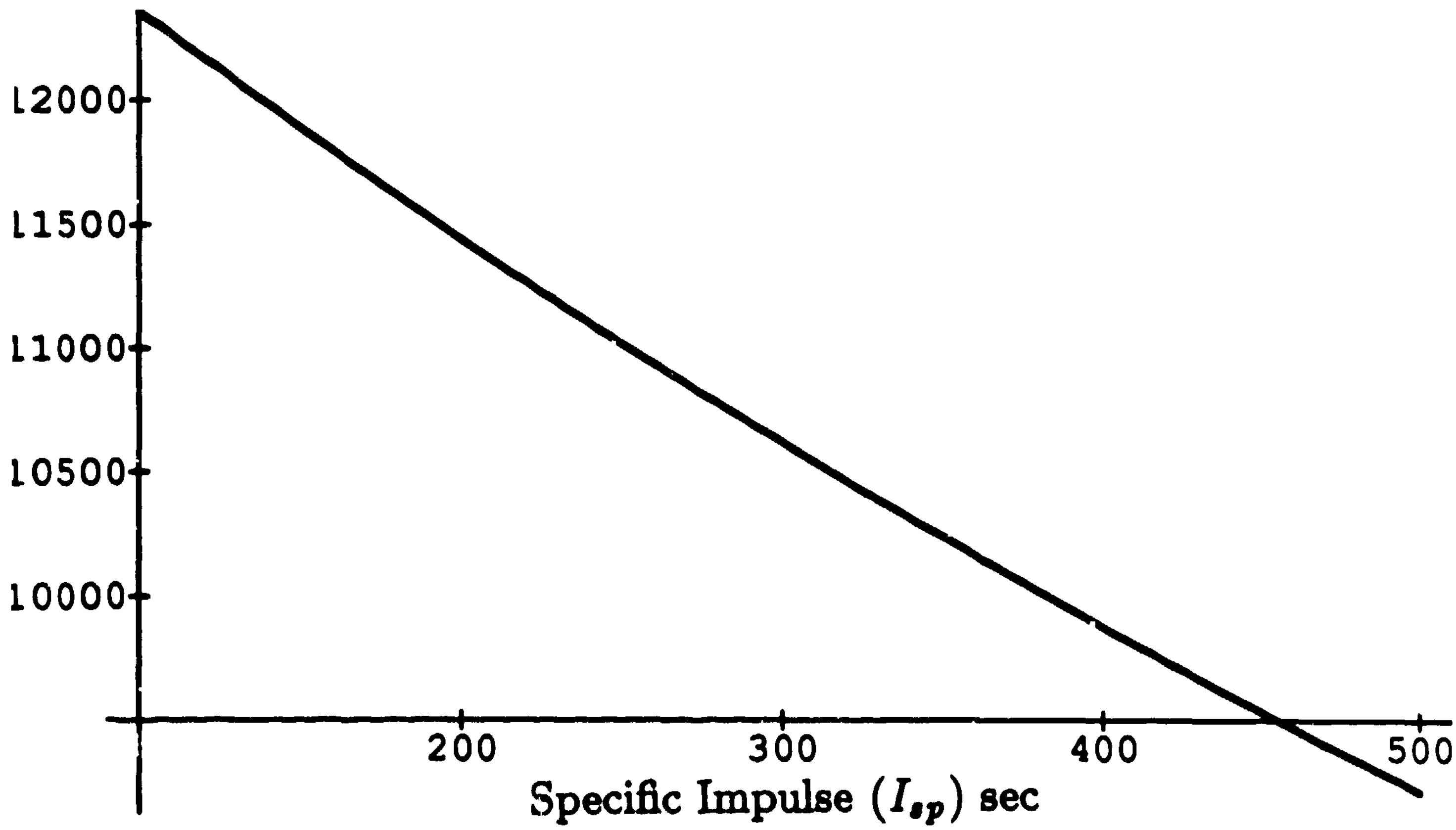
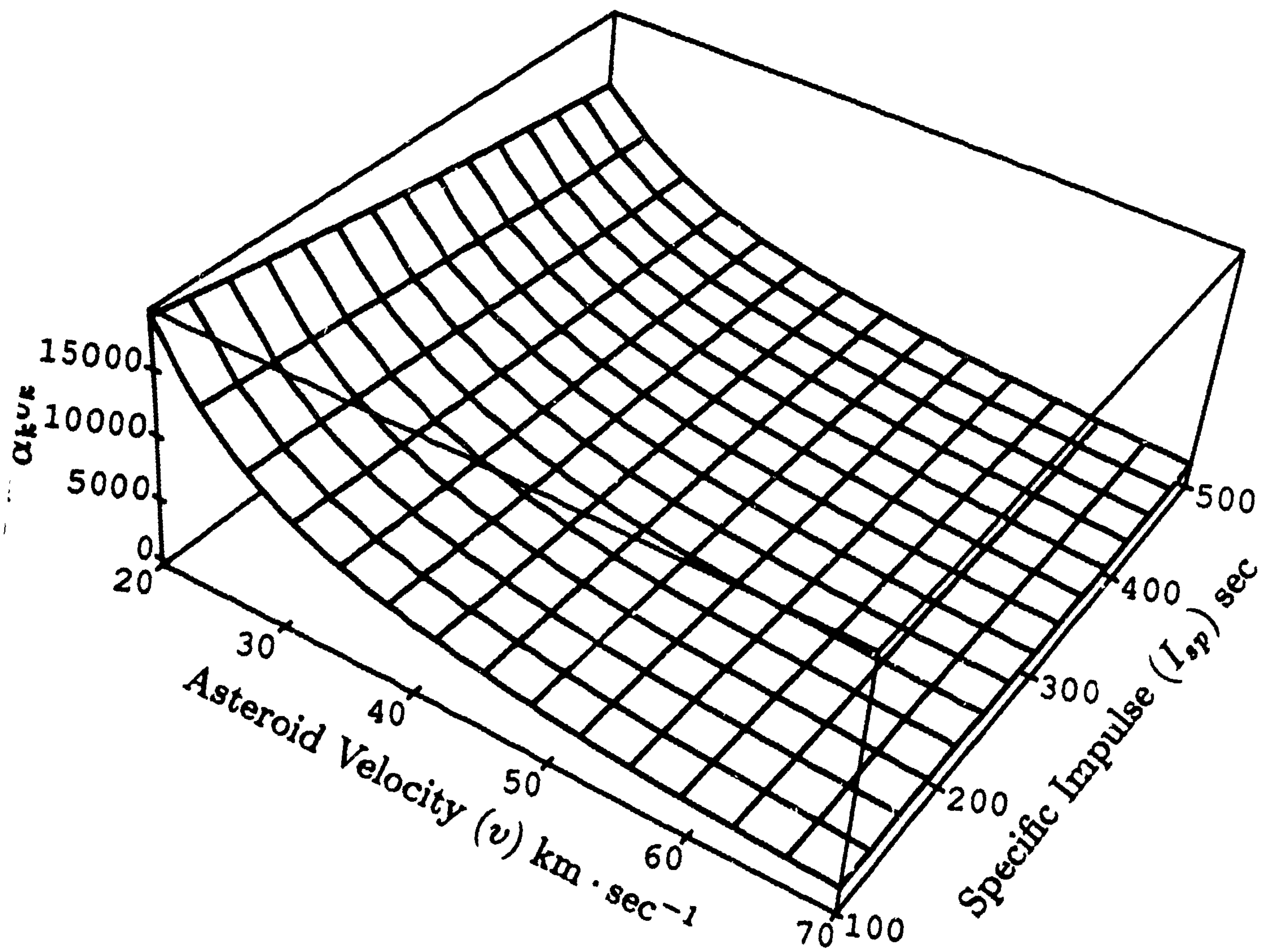

2000
0000
8000
6000
4000
2000
30
40
50
60
70
Asteroid Velocity (v) km · sec^{-1}

Figure 7a.



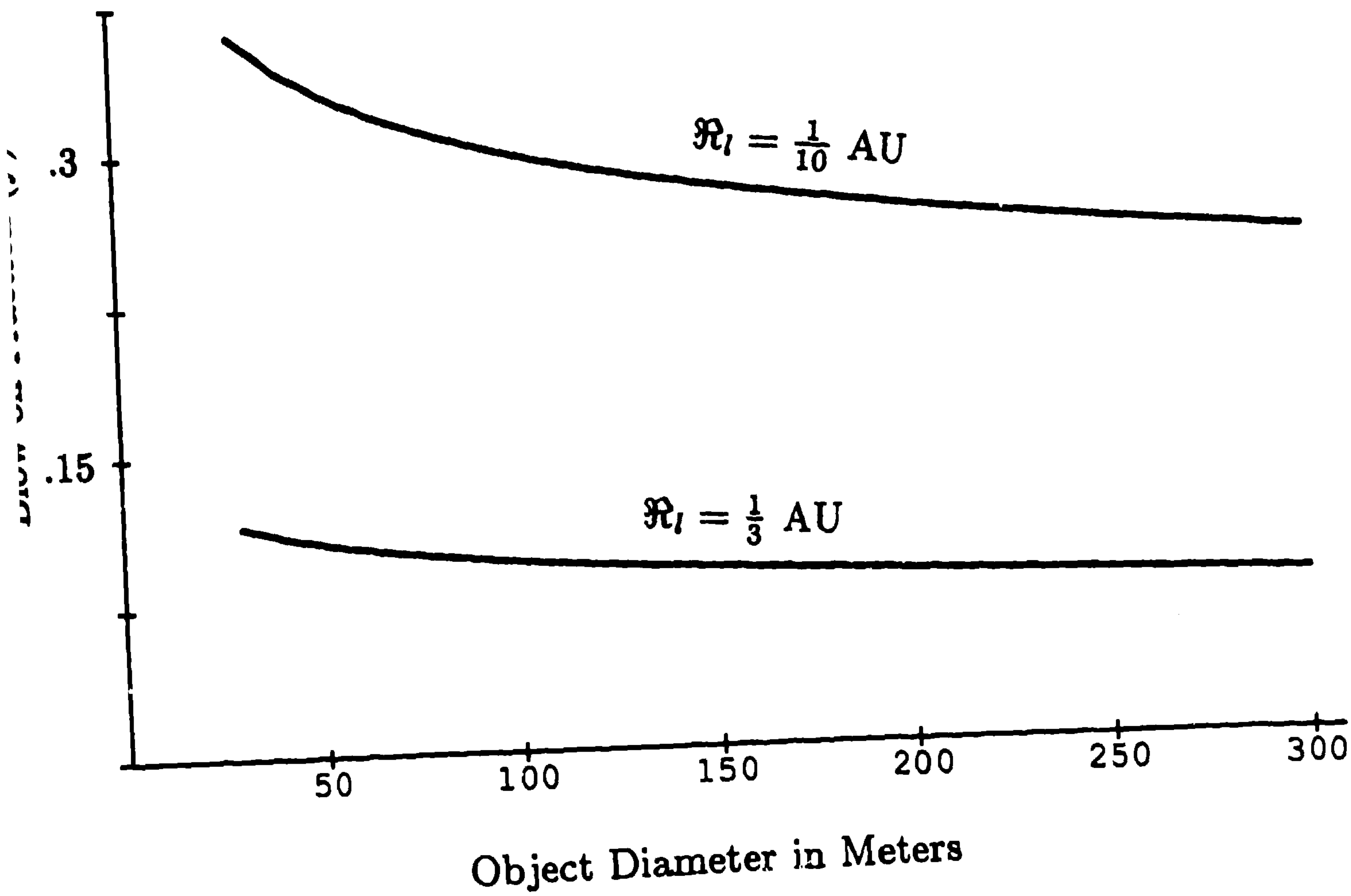
12000
11500
11000
10500
10000
200
300
400
500
Specific Impulse (I_{sp}) sec

Figure 7b.



15000
10000
5000
0
20
30
40
50
60
70
Asteroid Velocity (v) km · sec⁻¹
100
200
300
400
500
Specific Impulse (I_{sp}) sec

Figure 7c.



.3
.15
$\Re_l = \frac{1}{10}$ AU
$\Re_l = \frac{1}{3}$ AU
50
100
150
200
250
300
Object Diameter in Meters

Figure 8.