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“DAMAGE FROM THE IMPACTS OF SMALL ASTEROIDS”

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ABSTRACT

The fragmentation of a small asteroid in the atmosphere greatly increases its aerodynamic drag and rate of energy dissipation. The differential atmospheric pressure across it disperses its fragments at a velocity that increases with atmospheric density and impact velocity and decreases with asteroid density. Extending our previous work, we use a spherical atmosphere and a fitted curve to its density profile to find the damage done by an asteroid entering the atmosphere at various zenith angles. At zenith angle 0 degrees and a typical impact velocity of $\dot{V} = 17.5$ km/s, the atmosphere absorbs more than half the kinetic energy of stony meteoroids with diameters, $D_M < 230$ meters and iron meteoroids with $D_M < 50$ meters. At zenith angle 45 degrees the corresponding figures are 360 meters and 70 meters while at 60 degrees they are 500 meters and 100 meters. Comets with $V = 50$ km/s have critical diameters $D_M < 1900$ and 3000 meters for 45 and 60 degrees respectively using typical values of ablation, but they are much smaller if ablation is reduced. Most of this energy dissipation occurs in a fraction of a scale height, so large meteors appear to “explode” or “flare” at the end of their visible paths. This atmospheric dissipation of energy protects Earth from direct impact damage (e.g., craters), but the blast wave from it can cause considerable damage. In previous work we estimated the blast damage by scaling from data on nuclear explosions in the atmosphere during the 1940s, 1950s and early 1960s. This underestimated the blast from asteroid impacts because nuclear fireballs radiate away a larger fraction of their energy than do meteors, so less of their energy goes into the blast wave. We have redone the calculations to allow for this effect. We have found the area of destruction around the impact point in which the over pressure in the blast wave exceeds $4 \text{ pounds/inch}^2 = 2.8 \times 10^5 \text{ dynes/cm}^2$, which is enough to knock over trees and destroy buildings. We find that for chondritic asteroids entering at zenith angle 45 degrees and an impact velocity of 17.5 km/s that it increases rapidly from zero for those less than 50 meters in diameter (13.5 megatons) to about 2000 square

km for those 76 meters in diameter (31 megatons). If we assume that a stony asteroid 100 meters in diameter hits on land about every 1000 years, we find that a 50 meter diameter one (causing some blast damage) hits land every 125 years while a Tunguska size impactor occurs about every 400 years. If iron asteroids are about 3.5% of the frequency of stony ones of the same size, they constitute most of the impactors that produce areas of blast of less than 300 square km. About every 100 years an impactor should blast an area of 300 km² or more somewhere on the land area of Earth. The optical flux from asteroids 60 meters or more in diameter is enough to ignite pine forests. However, the blast from an impacting asteroid goes beyond the radius within which the fire starts. It tends to blow out the fire, so it is likely that the impact will char the forest (as at Tunguska), but it will not produce a sustained fire. Because of the atmosphere, asteroids less than about 200 m in diameter are not effective in producing craters and earthquakes. They are also not effective in producing water waves and tsunami in ocean impacts. Tsunami is probably the most devastating type of damage for asteroids that are between 200 meters and 1 km in diameter.

1. INTRODUCTION

In a previous paper (Hills and Goda 1993), the authors studied the fragmentation of small asteroids in the atmosphere to determine how much damage they do as function of their mass and composition. This model was limited to a plane parallel atmosphere into which the impactors enter from the zenith. The atmospheric density as a function of height was assumed exponential with a constant scale height. In the current paper we improve the model by using a spherical atmosphere in which its density as a function of height is found by fitting a curve to the Standard Atmospheric Model. These refinements allow us to consider objects that enter at large zenith angles and to improve the results for impactors that suffer large energy dissipation high in the atmosphere. The work at this conference suggests that the Tunguska impactor entered the atmosphere at a large zenith angle. We made other improvements that will be mentioned in the text, and we introduced several new tests of the sensitivity of the results to various assumed parameters.

2. THE FRAGMENTATION MODEL

Fragmentation enormously increases the atmospheric drag on a meteoroid, so it dissipates much more of its energy in the atmosphere. It greatly increases the minimum size of objects that are large enough to retain most of their kinetic energy until ground impact.

In this paper we use the atmospheric fragmentation model of Hills and Goda (1993), which is similar to one developed independently by Chyba, et. al. (1993). It quantitatively reproduces many of the observed properties of fragmenting large meteoroids. The model (sometimes called the pancake model) gives the increase in the radius of an asteroid after it begins fragmenting in the atmosphere. The standard equations of meteor motion and ablation in the atmosphere were integrated using a 4th-order Runge- Kutta integrator with the meteor radius being given by the pancake model when fragmentation is occurring. The method is discussed in more detail in Hills and Goda (1993). We assume that the meteoroid

enters the atmosphere at a height $h = 100$ km above the Earth, where we specify the initial velocity V_o and zenith angle θ . The integrations were done using the spherical atmospheric model.

2. NUMERICAL RESULTS

2.1. VELOCITY AND KINETIC ENERGY REDUCTION

Fig. 1 and 2 show the velocity of representative impactors as a function of height in the atmosphere. Here we have considered stony meteoroids, nickel-iron meteoroids, and comets with the initial impact velocities at the top of the atmosphere of $V_o = 17.5$ km/s for stones and irons and 50 km/s for comets. This is approximately the average impact velocity for each type of object. The effect of changing the velocities can be seen in Hills and Goda (1993) for the limiting case of zero zenith angle. The impactor has a diameter of 60 meters, which may be comparable to that of the Tunguska impactor. We have considered impactors entering the atmosphere at zenith angles $\theta = 0, 45, 60, 80$, and 81 degrees, where at $\theta = 81$ degrees they would return to space if it were not for the atmosphere. Here we have assumed material strengths of $S = 1 \times 10^8$ dynes/cm² for weak stones (which are likely to be representative of a majority of chondritic meteoroids), 5×10^8 dynes/cm² for hard stones, 2×10^9 dynes/cm² for irons, and 1×10^7 dynes/cm³ for comets. We assume that the impactors undergo continuous fracturing and spreading of their debris as long as the ram pressure exceeds S . We assume densities of $\rho_M = 3$ g/cm³ for stones, 8 g/cm³ for irons, and 1 g/cm³ for comets. Fig. 1 assumes a standard ablation parameter of $\sigma = 1.0 \times 10^{-12}$ cgs (Bronshten 1983) while Fig. 2 assumes the limiting case of no ablation ($\sigma = 0$). Lyne (this conference) has used astronomical procedures to study ablation as a function of the thermal history of the object in the atmosphere. He finds that ablation calculated in the standard fashion in meteoritics is too high especially for comets. We can be confident that the true results must lie between those of Fig. 1 and 2.

With or without ablation, all the objects except the irons in Fig. 1 and 2 lose most of their kinetic energy in the atmosphere. For those objects losing their kinetic energy in the atmosphere, most of the energy loss occurs in fraction of a scale height, which is about 7 km. Generally the larger the zenith angle, the more atmosphere the object goes through and the higher up it loses its energy. The no-ablation cases lose their energy lower in the atmosphere. This is particularly true of the model comets used in these figures, which with the usual ablation totally burn up in the atmosphere. The termination of the plots for them at a finite height is due to their total ablation.

Irons lose much less energy in the atmosphere because they break up much lower in the atmosphere due to their greater internal strength, so their dissipative cross sections are much smaller when they reach sea level. The rather anomalous appearance of the iron curve for zenith angle 81 degrees in Fig. 1 and 2 is due to the asteroid passing through enough low-density atmosphere for it to slow enough that it never fragments. It hits the ground at a relatively large velocity. At zenith angle 80 degrees, the asteroid breaks up relatively high in the atmosphere, which causes a rapid dissipation with most of its energy being lost in the atmosphere.

Fig. 3 shows the energy deposited in the atmosphere as a function of height [(megatons of TNT)/km] for the impactors shown in Fig. 1. We see from the figure that if most of the energy is deposited in the atmosphere, the bulk of the deposition occurs in a fraction of a scale height, which explains why large stony meteoroids including Tunguska appear to “explode” or flare towards the end of their path. The rapid decrease in velocity and the correspondingly large increase in the rate of energy deposition in a narrow range of atmospheric height results from the increasing drag area of the meteoroid due to fragmentation and to the exponential increase in atmospheric density. The very narrow range of heights of energy dissipation at large zenith angles is due to the object moving nearly parallel to the surface.

The peaks in the energy deposition curves of Fig. 3 occur near the height, h_{half} , by which half the kinetic energy has been dissipated. Fig. 4 shows h_{half} as a function of

impactor radius for various types of impactors and their zenith angles. The straight-line sections on the left side of the iron meteoroid plot are produced by small objects that never fragment. They slowed sufficiently in the upper atmosphere that they do not feel enough aerodynamic pressure to fragment. Fragmentation greatly increases the atmospheric drag, so h_{half} is higher in the atmosphere than it would be without fragmentation. Soft stones ($S = 10^8$ dynes/cm²), which are the most common variety, are able to impact the ground with more than half of their impact energy if their radii exceed about 100 meters at small zenith angles. This increases to 200 meters for an angle of 45° and 300 meters for an angle of 60°. Without fragmentation, stones with radii of 10 meters would hit the ground with more than half their kinetic energy (Hills and Goda 1993).

The peculiar spike in Fig. 4 for large comets in grazing collisions is due to their returning to space after a very close approach to the surface of Earth (without hitting it). They have a larger cross section for atmospheric drag after the closest approach than before it, so they tend to lose their energy higher in the atmosphere (in the return to space). The smaller comets lose enough energy to return to space.

While the atmosphere protects the ground from impact damage from moderate size asteroids, the blastwave produced by the energy dissipated in the air can cause considerable damage at ground level, as it did at Tunguska. Larger objects can cause direct impact damage with the ground. We consider this damage in the next section.

2.2 DAMAGE DONE BY THE IMPACT

Knowledge of the damage done by impactors is needed for both estimating the effect of future asteroid-comet collisions and for finding signatures of impactors that may be identified in the geological record of Earth.

2.2.1 THE ATMOSPHERIC BLASTWAVE

Even if all the meteoroid energy is dissipated in the atmosphere, the impact can cause considerable ground damage due to the atmospheric blast wave; e.g., the Tunguska

impactor of 1908 devastated an area of 2000 km² without producing an impact crater (Sekanina 1983).

We saw in Fig. 2 and 3 that most atmospheric energy dissipation occurs in a narrow range around h_{half} , the half-energy height. This allows us to approximate the energy release as a point explosion at h_{half} . There is much experimental data from the 1940's, 1950's, and early 1960's on the effects of nuclear explosives fired at various heights and yields. Johndale Solem (Theoretical Division, LANL) finds from this data that the outer radius r_4 at the ground below the point of detonation at height h where the over pressure due to the atmospheric airburst exceeds 4 p.s.i = 2.8×10^5 dynes/cm², which is enough to knock down trees and economically destroy most buildings, can be approximated by the fitting formula

$$r_4 = ah - bh^2E^{-1/3} + cE^{1/3} \quad (1)$$

where $a = 2.09$, $b = 156 \text{ erg}^{1/3}/\text{cm}$ and $c = 0.0146 \text{ cm/erg}^{1/3}$. For r_4 and h in km and E in Mgttons (Megatons of TNT = 4.2×10^{22} ergs), $a = 2.09$, $b = 0.449$, and $c = 5.08$. (Similar results, in less convenient form, may be found in Glasstone and Dolan (1977, Chapter 3)). (Determining r_4 directly from theory is difficult because it depends on an interplay between the shock propagating directly from the point of energy release and that reflected from the ground, the Mach effect.)

This empirical formula is believed to be highly accurate for heights less than 65 km and yields less than 1 gigaton = 1000 megatons = 4.2×10^{25} ergs. For yields larger than this value, the curvature of the Earth is important. Energies above a gigaton are large enough to blow off most of atmosphere along the line of site, so a yield above a gigaton would simply blow off the atmosphere at a higher velocity, but it would do no more damage to the rest of the atmosphere than would a lower yield event. Stony meteorites with a typical velocity of 20 km/s exceed this energy if their radii exceed 120 m.

In estimating the magnitude of the blastwave from the asteroid, Hills and Goda (1993) equated the kinetic energy of the asteroid to the yield used in Equation (1). However, as

it has been emphasized to us since this publication, nuclear explosions are very effective radiators in the visual and infrared compared to meteors, so only about half the energy goes into the blastwave. We will assume that the yield in Equation (1) is twice the kinetic energy of the asteroid. The kinetic energy of the asteroid is given by

$$E = \frac{1}{2} M V_o^2 = 75 \text{ Mgtons} \left(\frac{\rho_M}{3 \text{ gm/cm}^3} \right) \left(\frac{R}{50 \text{ meters}} \right)^3 \left(\frac{V_o}{20 \text{ km/s}} \right)^2. \quad (2)$$

Fig. 5 and 6 show the radius of destruction derived from Equation (1) as a function of impactor radius for various compositions and zenith angles. They are computed at an impact velocity of 17.5 km/s for stony and iron asteroids and 50 km/s for comets. For h in Equation (1) we used h_{half} . We used $h = 0$ if less than half the kinetic energy was lost before ground impact. Fig. 5 shows the results with conventional ablation while Fig. 6 shows what would happen if there were no ablation.

We see from Fig. 5 that the blast waves from soft stony meteorites, which constitute most of the meteoroids, only cause ground damage if their radii exceed about 22 meters at zero zenith angle. At zenith angle 60° , the minimum radius is about 28 meters. The corresponding energies for these two bodies is 5 megatons and 10 megatons. Smaller stony asteroids breakup too high in the atmosphere to produce any blast damage at 4 p.s.i. overpressure. Fig. 6 shows that the corresponding figures for no ablation are about 20 and 26 meters, so there is a relatively weak dependence on ablation for stones. The radius of destruction increases rapidly with increasing asteroid radius. Fig. 5 shows that it reaches an area of 2000 sq km at a radius of 35 m at zenith angle 0 and about 40 m at 60° . Without ablation, the corresponding radii would only be about 5% less. This would be the required radius of the Tunguska impactor if its knocking down the forest required an overpressure pressure of 4 p.s.i. The corresponding kinetic energies for models with conventional ablation at zenith angles 0 and 60° would be about 20 and 26 megatons, respectively. If the 4 p.s.i. overpressure was only reached over 1000 km sq. at Tunguska, the radius of the impactor would drop to 30 meters at zenith angle 0 and to about 35 meters

at 60° . The corresponding impact energies would be 13 and 20 megatons. The lower figure is close to the energies estimated by Shoemaker (this conference) from microbarographic measurements.

We see from Fig. 5 and 6 that much smaller irons do the damage done by larger stones. This is largely due to the greater strength of iron, which causes them to fragment much lower in the atmosphere. It also results from the irons being denser, so they have more energy for a given radius. The lack of a crater indicates that Tunguska was not an iron meteorite.

Comets require much larger impactors to produce a given amount of blast damage. They are also much more sensitive to ablation. With ablation, comets do not cause blast damage (at 4 p.s.i.) unless their radii are at least 32 meters at zenith angle zero and at least 40 meters at 60° . The corresponding minimum impact energies (at the top of the atmosphere) are 41 and 80 megatons respectively. To devastate an area of 1000 sq km at 4 p.s.i. overpressure requires minimum radii at these two zenith angles of about 38 and 42 meters or initial impact energies of 69 and 93 megatons. If the comets suffered no ablation, Fig. 6 shows that the absolute minimum radius of a comet required to produce the damage at Tunguska (1000 sq km at 4 p.s.i) would be about 30 and 35 meters for zenith angles 0 and 60° . The corresponding energies would be 34 megatons and 54 megatons, which are much larger than the energies given by the microbarograph records. There is also some question whether comets this small could hold together gravitationally against the pressure produced by the solar heating of their volatiles at Earth.

The lack of a crater combined with the microbarograph data suggests that the Tunguska impactor was a stony asteroid that entered the atmosphere at a moderate zenith angle.

We can use the data in this section to determine the relative frequency of impact damage from stony and iron asteroids. We shall assume that a stony impactor 100 meters in diameter hits land (rather than ocean) on Earth about every 1000 years, the number of

small impactors of radius r or larger scales at r^{-3} , and that the frequency of iron impactors of a given size is about 3.5% of that of stones (Shoemaker, this conference). We can pick a given asteroid radius and then find the radius of the damaged area from Fig. 5 and 6. We can then use the above relation to find how often such impacts occur. We can then combine this data to find how frequently asteroids produce blast damage of a given area somewhere on the land mass of Earth. The results are given in Fig. 7a for normal ablation and Fig. 7b for no ablation. The calculations assume an impact velocity of 17.5 km/s and a zenith angle of 45° , which is the average zenith angle for impactors. They show the number of impacts per year in which the radius of blast damage at 4 p.s.i. exceeds a given value. This is done separately for stones and irons as well as the total. Comparing Fig. 7a to Fig. 7b, we see that the results depend only weakly on ablation.

From the figure, we see that regions subject to 4 p.s.i. overpressure that have radii less than 10 km (or areas less than 300 km²) are primarily produced by iron impactors while stones are responsible for most of the larger areas of destruction. Blast areas of 300 km² or larger occur about every 200 years. Damaged areas with radii of 3 km or larger should occur about every 35 years somewhere on the land area of Earth. Most of these regions are damaged by iron impactors.

2.2.2 GROUND IMPACT DAMAGE

If an asteroid is large enough, the atmosphere is not able to dissipate all of its kinetic energy, so it can produce ground impact damage: craters, tsunamis, and earthquakes. Fig. 8 shows the fraction of the initial kinetic energy of the impactor that goes into ground impact. These results allow for ablation. We see from the figure that for soft stones ground-impact damage is not important unless the radius of the object exceeds 80 meters at zero zenith angle and about 150 meters at 60° . Near-grazing encounters at zenith angles 80° and 81° allow most of the energy to be dissipated in the atmosphere for objects up to 1 km in radius. For irons, ground impact damage is not important unless the radius exceeds about

10 meters while for comets the minimum radius is about 500 meters. If there were no ablation, comets with radii as small as 100 meters would cause ground damage.

We can use the data from Fig. 8 to find the crater size, earthquake magnitude, and tsunami heights caused by objects as a function of their radii and zenith angles. We will show the results for the case of tsunami, but the other types of damage can easily be found from Fig. 8 using the relationships given in Hills and Goda (1993).

2.2.2.1 TSUNAMI

It has been recognized since Hills and Goda (1993) that tsunami are probably the most serious consequence of impacting asteroids smaller than the super killers such as the Cretaceous-Tertiary impactor. Just as on land, most of the kinetic energy of a large asteroid that impacts the ocean goes into the formation of a crater. The crater fills in and then rebounds to produce a series of gravity waves that propagate radially away from the impact. These waves do not dampen significantly until they run into shallows where they increase in height to form tsunami (Mader 1988). The average tsunami runup is an order of magnitude higher than the deepwater wave that formed it. Deepwater waves are inherently two-dimensional, so geometric dilution causes their height to drop with the inverse distance from the impact point. Tsunami can be a serious problem far from the impact point (cf, Hills, Nemtchinov, Popov, and Tetrev 1994).

We can use ground impact energies given in Fig. 8 to determine the height of the deepwater waves using the equations given in Hills and Goda (1993). The results are given in Fig. 9. The figure shows the height of the deepwater wave at 1000 km from the impact point. This is before any runup at a continental shelf. The figure shows the wave height as a function of composition type and zenith angle. We note that for soft stones, there is no significant tsunami wave generation unless the radius of the asteroid is about 100 meters for zenith angles less than 60° . At zenith angle 80° the critical radius approaches 800 meters. We note that the height of the wave quickly goes up with increasing asteroid

radius. Stony asteroids 200 meters in radius entering at zenith angles under 60° would produce waves over 10 meters high at 1000 km from the impact point. When these waves run ashore, their average heights exceed 100 meters.

2.2.2.2 OTHER DAMAGE

In this paper we have not discussed the formation of earthquakes and craters in land impacts, which can be scaled from the tsunami deepwater wave heights given in Fig. 9 by using the relations in Hills and Goda (1993). We also have not discussed global effects due to massive impactors: formation of a new high-entropy atmospheric layer around the Earth and the distribution of a dense dust layer around the Earth. These effects only apply to very massive impactors that are not much affected by the atmosphere, so their effect should not be much different from that discussed in Hills and Goda (1993).

One effect that is not addressed in the current paper and one that does depend on the zenith angle is the burning down of forests by the luminosity of the meteor. This was discussed in Hills and Goda (1993) for the case where the impactor comes in at zero zenith angle. It was found that impactors more than 60 meters in diameter (such as Tunguska) are luminous enough to start forest fires. However, the shockwave travels well beyond the area in which the fires start, so it blows out the fire. If the asteroid comes in at a large zenith angle, the results may be significantly different. The transverse velocity will result in the meteor spending less time over a given area, but this may be commensated by the energy being dissipated higher in the atmosphere. This results in less of it reaching the ground as a shock wave, so there is less likelihood of the fires being blown out as they apparently were at Tunguska. There is also some evidence that larger meteors are more efficient at producing radiation than smaller ones, which would make asteroids more effective at starting fires than implied by the results given in Hills and Goda (1993).

3. CONCLUSIONS

We have found that the atmosphere is ineffective in preventing impact damage to the ground at zenith angles less than 60° when the radius of a stony asteroid exceeds 100 meters and that of a comet exceeds 500 meters. For iron meteorites the critical radius is about 30 meters at a moderate impact velocity. While the dissipation of energy in the atmosphere protects the ground from impact damage (craters, earthquakes, and tsunamis), it can enhance the damage done by the airburst. Near grazing collisions can cause stony asteroids as large as 2 km in diameter to lose most of their energy in the atmosphere.

We would like to thank Johndale Solem for supplying us with Equation (1). MPG would like to thank the Theoretical Astrophysics Group at Los Alamos for a graduate research assistantship.

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FIGURE CAPTIONS

Fig. 1 The decrease in the velocity of an impactor as a function of height in the atmosphere. This is given for an impact velocity of 17.5 km/s at the top of the atmosphere for various values of zenith angle. The stony meteoroids have material strengths of $S = 1 \times 10^8$ dynes/cm² (soft) and 5×10^8 dynes/cm² (hard) and densities of 3 grams/cm³. The nickel-iron meteoroids have $S = 2 \times 10^9$ dynes/cm³ and densities of 8 g/cm³. The comets have $S = 1 \times 10^7$ dynes/cm³ and densities of 1.0 g/cm³. All the impactors have radii $R = 30$ meters. The ablation parameter $\sigma = 1 \times 10^{-12}$ cgs.

Fig. 2 The same as Fig. 1 except there is no ablation ($\sigma = 0$).

Fig. 3 The energy deposited in the atmosphere as a function of height (megatons/km) by the impactors given in Fig. 1.

Fig. 4 The height in the atmosphere by which half the impact energy has been dissipated. This is computed as a function of impactor radius for various zenith angles for an impact velocity $V_o = 17.5$ km/s. The composition types and ablation parameters are the same as in Fig. 1.

Fig. 5 The radius of destruction around the impact point due to the atmospheric blast wave. This is defined to be where the overpressure is at least 4 p.s.i $= 2.8 \times 10^5$ dynes/cm², which is enough to knock down trees and economically destroy buildings. This is computed as a function of zenith angles for various compositions. Here we have assumed conventional ablation with $\sigma = 1 \times 10^{-12}$ cgs.

Fig. 6 The same as Fig. 5 except that ablation has been turned off.

Fig. 7a,b The frequency at which impactors produce airblast damage as a function of the amount of area destroyed where 7a allows for ablation and 7b does not. The results

are given separately for stones, irons, and for the sum of the two. It is assumed that the frequency of irons is 3.5% the frequency of stones of the same radius. We see that most of the small areas of blast damage are due to iron impactors.

Fig. 8 The fraction of the initial kinetic energy that goes into the ground impact. This is given as a function of zenith angle for principal asteroid types. The results allow for ablation.

Fig. 9 The full height of a tsunami wave at 1000 km from the impact point as a function of asteroid radius and zenith angle for the four principal material types. When this wave runs ashore, it is about an order of magnitude higher than the values given in this figure. The results allow for ablation.

FIGURE 1

Aug 2 09:33:15 1996

FIGURE 2

Aug 2 10:48:11 1996

FIGURE 3

Aug 2 09:38:06 1996

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9