Deep Impact: The Physics of Asteroid/Earth Collisions

Donald Metz and *Arthur Stinner*

About 65 million years ago, a great change took place: more than half of the world's reptiles vanished along with more than half of all species of plants, and land and marine animals, including the dinosaurs. Mammals somehow survived and became the dominant large animal. One of these species lived long enough eventually to investigate the fossil record of its distant origins and ask the question: *Who or what committed the mass murder?*

From about 1970 on, researchers around the world, in diverse disciplines including particle physics, paleontology, geology, chemistry, and astronomy, collaborated in trying to answer these questions. To explain the mystery, the physics Nobel laureate Luis Alvarez, and his geologist son Walter, proposed an *asteroid impact hypothesis* in the late 1970s.

The Asteroid Impact Hypothesis

This hypothesis holds that a giant asteroid of about 10-km cross section plunged into the Earth's atmosphere at more than 10 km/s. The enormous energy involved in such a collision caused a chain of disasters: storms, tsunamis, cold and darkness, acid rain, and global fires. The evidence and arguments to back up this theory make a great scientific detective story, and the theory is an excellent example of how scientists might model such an event.

A significant problem with studying and hypothesizing about asteroid impacts is the relative lack of opportunity to study the details of such an impact. One exception to this is an explosion that occurred in Siberia more than 90 years ago.

The Tunguska Event: Modeling an Asteroid Impact

On June 30, 1908, at 7:14 a.m., a mysterious explosion was seen in the remote skies over Siberia, at latitude 60°55' N and longitude 101°57' E. The most famous eyewitness account of this event is the one given by S.B. Semenov, who was sitting on the porch of the trading station in the village Vanavara, about

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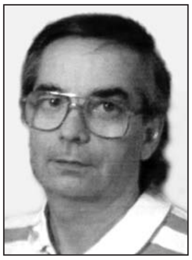

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65 km from the impact area, when he saw what was certainly the most brilliant flash of light ever seen in historical time:

> *My shirt almost burned off my back. I saw a fireball that covered an enormous part of the sky. I only had a moment to note the size of it. Afterward it became dark, and at the same time I felt an explosion that threw me about twenty feet from the porch. I lost consciousness, and when I came to, I heard a noise that shook the whole house and nearly moved it off its foundation. The glass and the framing of the house shattered.*[1]

There are a great many other reports by witnesses of the event. Nearly 700 km to the southwest, the Trans-Siberian Express was wildly jolted, and thousands of kilometers away, in Germany, the United States, and Java, seismic detectors recorded the event so that later it was possible to determine not only the approximate location of the "explosion" but the exact time of its occurrence.

The first scientist to make the journey to Tunguska was Leonid Kulik, who traveled by horseback in 1927 to the epicenter of the burst itself. As he approached the site, he stared in astonishment at the devastation stretching to the horizon before him. While he was convinced that a meteorite collision was the cause of the destruction, he did not find any evidence for an asteroid impact.

For 30 years the investigation of the Tunguska mystery remained exclusively in the Russian scientific domain. By the end of the Cold War, in 1989, outside researchers were allowed to visit and study the Tunguska site. The Italian physicist Menotti Galli argued that if the asteroid had showered any particles into the forest upon impact, they would have been trapped in the resin of the trees and might still be intact. In analyzing tree samples, Galli used a scanning electron microscope with an attached energy dispersive x-ray spectrometer. He found significant evidence, in the layer that included the year 1908, that indicated unusually high levels of certain elements, especially copper, gold, and nickel. Could these particles in which a high level of these elements occur have an extraterrestrial origin?

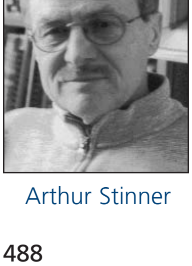
Meanwhile other American researchers were making computer simulations of the Tunguska event. One of the models that attracted attention was the one tested by planetary scientist Chris Chyba and his collaborators.[2] They developed a model that describes the dynamics and structure of comets and asteroids of various types (carbonaceous, iron, stone) as they move through the atmosphere at hypersonic speeds (15–35 km/s).

Modeling the Tunguska Event

Astronomers like Chyba and his associates at the Space Science Division of NASA recognized that the solution of the long-standing puzzle of the Tunguska collision lay in developing a realistic model of the atmospheric entry of small bodies. The puzzle, of course, was connected with the sudden tremendous explosion at a height of about 8 km that was seen, heard, and felt from hundreds of kilometers away.

We are now in the position to study a simple model based on Chyba's hypothesis for the collision between meteorites and the Earth. Our concern is this: "What if" an asteroid or comet fell to the Earth? Will it burn up, will it explode, or will it pass through the atmosphere to create a huge explosion, a crater lake, or even worse, an extinction event?

First, like the old physics comedian, we assume that the object is a *cube* and has a uniform composition. In reality, of course, asteroids are irregular, often shaped like a potato or a peanut, and can often rotate



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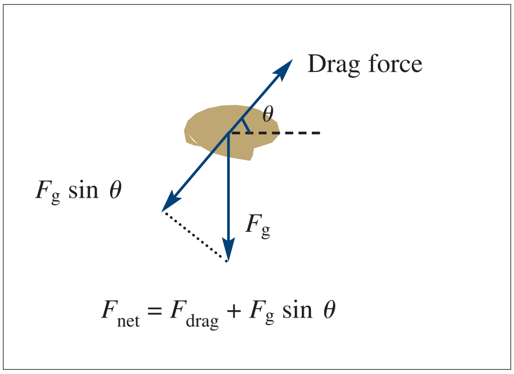


Fig. 1. Asteroid enters the Earth's atmosphere.

wildly. However, the assumption that the asteroid is a cube turns out to be quite adequate for what scientists call a "first order" approximation before they develop a better model. Later, we will show how to modify this option to approach a "more realistic" model.

As the asteroid enters the Earth's atmosphere, it experiences a drag force opposite to its motion. Therefore, the net force acting on the object is $F_{net} = F_{drag} + F_g \sin\theta$, where θ is the angle measured to the horizontal (see Fig. 1). A drag force is proportional to the density of air (d) times the square of the velocity (v) times the area of exposure (A) in the direction of the motion, or:

$$F_D \propto dv^2A.$$

Introducing a proportionality constant k, we can write $F_D = -kdv^2A$. The constant is represented by

$$k = ½\, C_D,$$

where C_D is the drag coefficient, so that

$$F_D = -½\, dv^2AC_D. \tag{1}$$

We may now write the equation of motion,

$$ma = F_D - F_g \sin\theta. \tag{2}$$

However, as the asteroid falls through the atmosphere, a tremendous pressure builds up on its leading edge and the asteroid ablates by absorbing thermal energy emitted by the hot gases on the leading edge. Following Chyba's analysis, we may write the mass loss rate as

$$\frac{\Delta m}{\Delta t} = \frac{-(C_h dAv^3)}{2Q}, \tag{3}$$

where A is the area of the leading surface, C_h is the heat transfer coefficient, and Q is the heat ablation constant for the asteroid's composition.

For a given set of initial conditions, Eqs. (2) and (3) may be solved numerically using a spreadsheet program. The initial conditions are all well-known constants for an asteroid of given composition. The great advantage of using a spreadsheet is that it is easy to change some of these initial conditions. The primary components of the model would be the composition (and therefore the density and mass), and the shape and velocity of the asteroid. The spreadsheet program immediately recalculates all dependent values, allowing us to examine many different types of asteroids in a very short period of time.

There are three possible scenarios for the asteroid as it passes through the atmosphere. First, if the asteroid burns up, the mass will be reduced to zero. Second, if the interior pressure of the asteroid exceeds the yield strength of the asteroid, it explodes in the air if there is enough time for the shockwave to break up the meteorite. Initially, there is a great pressure buildup on the leading edge, and the meteorite spreads out quickly like a pancake as the pressure wave moves through it. The leading edge of the meteorite experiences a pressure of F_{drag}/area; that is, using Eq. (1), pressure $= -½\, dv^2C_D$. The pressure at the rear and sides of the meteorite is not significant compared to this leading edge so that the average interior pressure is $-¼\, dv^2C_D$. The asteroid will explode in the air if the shock wave created by the pressure has enough time to travel the length of the asteroid. We can calculate this time from $t = L/c$, where L is the length of the meteorite and c is the speed of sound (for these solids we've estimated 2000 m/s, but of course other values can be tried).[3] One problem is that we do not know enough about the speed of these shock waves in meteorites because their density and composition is largely unknown. Moreover, fragmentation speeds up the breakup of the meteorite. The great benefit of the spreadsheet is the ability to change a value like this and instantly view the results. So if we wish to investi-

Table I. Spreadsheet Examples.

	1	2	3	4	5	6	7	8	9	10	11	12	13
A	**Stone**												
B	Angle	**L**ength	**D**ensity	velocity	**A**rea	**Q**	**E**nergy	**M**ass	**g**	C_d	C_h	Yield Strength	Time
C	degrees	m	kg/m^3	m/s	m^2	J/kg	J	kg	N/kg			N/m^2	s
D													
E	45	100	3.50×10^{3}	15000	L^2	8.00×10^{6}	$\frac{1}{2}mv^2$	$D \times L^3$	9.6	1.5	0.1	1×10^{7}	L/2000
F													
G		.								.			
H	Altitude	density	average	velocity	Drag	Mass loss	**t**ime	**m**ass	Weight	Total Force	acceleration	**p**ressure	Alt
I	km	of air	**d**ensity		$\mathbf{F_{drag}}$	Rate (**mR**)			$F_g \sin\theta$	F_{total}			
J		kg/m^3	kg/m^3	m/s	N	kg/s	s	kg	N	N	m/s^2	N/m^2	km
K													
L	100	1.00×10^{6}		1.50×10^{4}				3.50×10^{9}	2.38×10^{10}	2.38×10^{10}	9.6		
M	90	3.00×10^{6}	$\frac{(d_1 + d_2)}{2}$	$\sqrt{v^2 - 2ax}$	$\frac{-dv^2ACd}{2}$	$\frac{-(C_h dAv^3)}{2Q}$	$\frac{d}{v}$	m - mR * t	mg	$F_{drag} + F_g \sin\theta$	$\frac{F_{total}}{m}$	$\frac{F_{total}}{A}$	95
	100 m stone												
N	100	1.00×10^{6}		1.50×10^{4}				3.50×10^{9}	2.38×10^{10}	2.38×10^{10}	9.6		
O	90	3.00×10^{6}	2.00×10^{6}	1.50×10^{4}	-1.27×10^{6}	4.22×10^{2}	0.94	3.50×10^{9}	2.38×10^{10}	2.38×10^{10}	6.79	6.34×10^{1}	95
P													
Q	10	4.14×10^{-1}	3.90×10^{-1}	1.50×10^{4}	-1.76×10^{11}	8.28×10^{7}	0.09	3.43×10^{9}	2.34×10^{10}	-1.52×10^{11}	-4.42×10^{1}	8.78×10^{6}	10.5
R	9	4.67×10^{-1}	4.41×10^{-1}	1.50×10^{4}	-1.98×10^{11}	9.36×10^{7}	0.09	3.42×10^{9}	2.33×10^{10}	-1.75×10^{11}	-5.08×10^{1}	9.90×10^{6}	9.5
S	8	5.26×10^{-1}	4.96×10^{-1}	1.50×10^{4}	-2.23×10^{11}	1.05×10^{8}	0.09	3.41×10^{9}	2.32×10^{10}	-1.99×10^{11}	-5.82×10^{1}	1.11×10^{7}	8.5
	1 m stone												
T	100	1.00×10^{6}		1.50×10^{4}				3.50×10^{3}	2.38×10^{4}	2.38×10^{4}	9.60		
U	90	3.00×10^{6}	2.00×10^{6}	1.50×10^{4}	-1.27×10^{2}	4.22×10^{-2}	0.94	3.50×10^{3}	2.38×10^{4}	2.36×10^{4}	6.75	6.34×10^{1}	95.0
V	15	1.95×10^{-1}	1.42×10^{-1}	1.38×10^{4}	-7.00×10^{6}	2.55×10^{3}	0.50	1.03×10^{3}	7.02×10^{3}	-6.99×10^{6}	-6.76×10^{3}	3.50×10^{6}	17.5
W	11	3.65×10^{-1}	2.80×10^{-1}	1.07×10^{4}	-7.88×10^{6}	3.24×10^{3}	0.46	0.00	0.00	-7.88×10^{6}	Burned	3.94×10^{6}	13.0
X	10	4.14×10^{-1}	3.90×10^{-1}	1.07×10^{4}	-8.94×10^{6}	3.01×10^{3}	0.13	0.00	0.00	-8.94×10^{6}	Burned	4.47×10^{6}	10.5

gate how any changes to this model might affect the breakup of the meteorite, we can enter "what if" values to test our model. Nevertheless, in this case, the breakup of the meteorite occurs very rapidly, and hence we have an explosion. Cases where the meteorite does not break so rapidly might explain crater-strewn fields on Earth.

The last possible scenario for our Earthly intruder finds the meteorite making it through the atmosphere without burning up or exploding. In this case, it will impact the ground with a kinetic energy of $\frac{1}{2}mv^2$. Such an impact is a potential extinction event.

Impact Scenarios/Spreadsheet

Table I illustrates how you can build a spreadsheet program to model the asteroid event. Rows A to E represent the initial conditions of our asteroid, and rows G to M represent the calculations we must make for a typical example. In rows E and M, we have generically coded the formulae that must be entered in those cells, and the symbols used in the formulae are bolded in the column headings. Rows N to S depict some sample calculations for our example. For a quick start, if you do not wish to build your own spreadsheet, you can download a sample spreadsheet (in Quattro Pro format) from the website http://www.uwinnipeg.ca/~metz.

In the specific example shown, we follow Chyba's model of a stone asteroid of length 100 m, entering the Earth's atmosphere with an approach angle of 45° at 15 km/s. The stone has density 3.5×10^3 kg/m^3 and heat ablation 8.0×10^6 J/kg. Its yield strength is 1.0×10^7 N/m^2. Air densities for various altitudes (10-km intervals) are entered (L2) from standard tables. The drag coefficient is 1.5 and the heat transfer coefficient is 0.1. For a 100-m asteroid, the break time is 100/2000 or about 0.05 s. Remember that to change the model, any of these initial conditions can be modified at any time and the spreadsheet will automatically recalculate the event conditions.

Rows N to S show the calculation for a few intervals. From Eq. (1), the average drag force acting on the asteroid for the first interval is -1.27×10^6 N. For a 100-m stone asteroid, the interior pressure exceeds the yield strength (1.0×10^7) at an approximate altitude of 9 km (R12, S12). At this time the asteroid still has a velocity of 1.5×10^4 m/s (R4) and it will travel about ¾ km in the time it takes the asteroid to break up. In other words, the asteroid will explode at approximately 8 km above the Earth. This is exactly the height that the Tunguska asteroid was estimated to have exploded.

Let's try some other "what if" scenarios. What happens to a 1-m stone asteroid entering the atmosphere with an approach angle of 45° at a velocity of 15 km/s? If we enter 1 in cell E2, the spreadsheet recalculates and we notice that the asteroid burns up completely (mass = 0) before the critical pressure is achieved (columns T to X). Now try a 1.5-km asteroid entering the atmosphere with an approach angle of 45° at a velocity of 15 km/s. If we enter 1500 in cell E2, the spreadsheet recalculates and we notice that the pressure exceeds the yield strength at approximately 10 km, similar to the 100-m asteroid. However, the time for the shock wave to spread across the asteroid is 1500/2000 = 0.75 s. By this time, the asteroid has impacted on the ground with a tremendous kinetic energy.

We can also change the composition of the asteroid by changing the density in cell E3 and the yield strength of the material in cell E12. For example, a carbonaceous asteroid would have a density of approximately 2.2×10^3 kg/m^3 and a yield strength of 1.0×10^6 N/m^2. An iron asteroid would have a density of about 7.9×10^3 kg/m^3 and a yield strength of 1.0×10^8 N/m^2. We find that carbonaceous asteroids explode at higher altitudes above 20 km and that the iron asteroids tend to make it through the atmosphere.

Changing the Spreadsheet

A modeling process such as the Earth-asteroid collision is an excellent way for students to be exposed to authentic problems and real-life science. Like most simple models, anomalies can be found. For example, we can generate an inconsistency by considering a 2-m asteroid moving at 15 km/s. Students are now challenged to explain the error condition in the spreadsheet. It is not difficult to determine that the spreadsheet is trying to calculate the square root of a negative number in formula M4. This leads us to a discussion of terminal velocity and how we can account for it in the spreadsheet. Further discussion can lead us to consider the drag force in relation to the changing area of the asteroid, the relative size of the intervals, and the mass rate change for low velocities. Melosh[4] adjusts the mass rate change (formula M6) for low velocities using a cutoff function $(v^2 - v_{cr}^2)/v^2$, where v_{cr} is the critical velocity below which the mass rate change decreases to zero. We have included a second spreadsheet on the website that includes these modifications and, using these variations, we now find that our 2-m stone asteroid traveling at 15 km/s just makes it through the atmosphere, which more closely reflects reality.

Students can also add further modifications to the spreadsheet by changing the formulae in the cells. For example, to model the asteroid as something other than a cube, the area formula (E5) would be changed, as would the volume used in the mass calculation (E8) and the drag coefficient (E10). Any formulae that include these factors (like the drag force) will automatically use the new values in any calculation, so no further change is necessary.

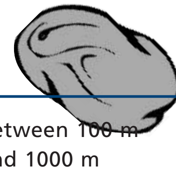
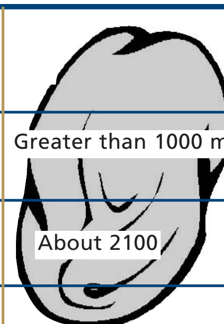
Other more complex factors also affect the descent of the asteroid. In our calculation of the mass loss rate, we used a coefficient of heat transfer of 0.1. Chyba reports that $C_h = 0.1$ above ~30 km and varies inversely as the meteorite descends to lower altitudes. Consequently below ~30 km, the rate of mass loss stays constant until the cutoff velocity is reached. We have also assumed that the angle of trajectory stays constant during the descent. Students might want to consider how the angle actually changes for small and large asteroids at various speeds. We've left these modifications for the more interested and capable student.

Comments

The physics of small meteorites is well known, and for large bodies of 1 km and up, the atmosphere does not present a great barrier. They come through without a significant loss in speed, suffering very little deceleration on the way down or sometimes even accelerating to greater speeds. These large bodies do not explode even when encountering the high density at about 10 km. The main reason for this is that the shock waves produced when the body meets the denser part of the atmosphere do not have enough time to cross the body before it reaches the ground.

We have summarized the behavior of different sizes of asteroids in Table II. Very small particles (the size of dust, 10^{-6} to 10^{-4} m) decelerate slowly and reach the ground intact; the larger particles, from about 1-mm

Table II. Asteroid-Earth Collisions.[5]

			
Diameter: Less than 10 m	Between 10 m and 100 m	Between 100 m and 1000 m	Greater than 1000 m
Number: billions	150 million	300,000	About 2100
Collision rate: Constantly	Every decade for the small end of the scale; every few centuries for the large end of scale	Every 5,000 years	Every 500,000 to 1,000,000 years
Result: The small ones burn up in the atmosphere. A few metallic ones reach the Earth's surface. There are recorded instances of humans being injured by pebble-sized fragments of larger objects.	Most of the asteroids in this size range burn up in the atmosphere, and no damage occurs on the ground. The larger size ones tend to disintegrate close to the ground. Examples: The Tunguska Event and the Arizona collision (Barringer crater). Energy equivalent is between 10–100 Hiroshima nuclear explosions.	These reach the ground intact and explode with enormous energies produced. The craters produced are about 10 km across. The energy of the explosion is of the order of thousands of nuclear bombs. The asteroid that hit in Sudbury is of this magnitude.	These explode with the energy equivalent of millions of nuclear bombs and leave craters 10–15 times their diameter. The 15-km asteroid that collided in the Yucatan peninsula about 65 million years ago left a crater about 200 km across.

grains to 1-m boulders, burn up and little or no solid material is left; and those above 100 m reach the ground virtually at the same speed as their entry speed into the atmosphere. Poorly understood is the behavior of bodies between about 10-m and 100-m diameter. These bodies require more research in order to understand what happens to them when they enter the atmosphere at hypersonic speeds. Did an asteroid impact cause the extinction of the dinosaurs 65 million years ago? And what caused the devastation at Tunguska? Are there other answers or can we pronounce the asteroid guilty as charged? Scientists solve these types of mysteries by first proposing a model and then facing the predictions of their model as their model develops into a more sophisticated one and accounts for a wider range of observations. We suggest that students will find this type of modeling activity motivating and interesting.

References

1. D. Fernie, "The Tunguska Event," *Am. Sci.* **81**, 412–415 (1993).
2. C. Chyba, P. Thomas, and K. Zahnley, "The 1908 Tunguska explosion: Atmospheric disruption of a stony asteroid," *Nature* **361**, 40-44 (1993).
3. See element E13 in the spreadsheet (Table I).
4. H.J. Melosh, *Impact Cratering* (Oxford University Press, 1989).
5. Adapted from Steel and Duncan, *Rogue Asteroids and Doomsday Comets* (Wiley, New York, 1995).