Catastrophic bolide impacts on the Earth: Some estimates

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We analyze the impact of large high velocity bodies on the surface of the Earth and obtain estimates of the size of the crater. We show that the atmosphere does not stop large bolides and their mass loss and heating during entry in the atmosphere can be neglected.

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I. INTRODUCTION

The impact of asteroids and comets is an important process that has changed the surface features of most bodies of the solar system due to the formation of craters. There is ample evidence that large impacts on the Earth have produced global catastrophes and sudden changes in the environment that have caused mass extinctions.[1,2] From the point of view of physics, impacts are impressive and dramatic examples of the effects of the dissipation of mechanical energy and illustrate a wide variety of energy transformations.

Impacts are very complicated processes and their detailed and exact description is impossible, as is frequently the case with natural phenomena. In these cases, scientists rely on sophisticated numerical simulations.[3] A reader may ask what is the purpose of the rough estimates that we will present. The answer is that it is impossible to develop numerical codes without having a clear idea of the physics that must be modeled. No simulation can take into account all conceivable processes and effects. Therefore, we must have an idea about what must be included and what can be safely ignored without losing the essentials.

II. HIGH VELOCITY IMPACTS

A variety of cosmic bodies currently impact the Earth and have impacted in the past as shown by the geological record. The largest and fortunately infrequent impactors are asteroids or comets; the smallest are fragments of these bodies, debris from the surface of a planet that has been thrown into space by a previous impact, or primordial bodies. These objects are called meteoroids when they are in the process of colliding with the Earth. The smallest meteoroids are destroyed in the atmosphere and their path gives rise to meteors, such as shooting stars and fireballs. If a meteoroid survives its transit of the atmosphere to come to rest on the surface, the resulting object is called a meteorite. Large meteoroids are also called bolides. In this paper, we shall focus on the impact of bolides whose size is in the range of 100 m to several kilometers, which can produce local, regional, or global catastrophes.

Asteroids that move in orbits near the Earth have velocities v_b of about 30 km/s. Comets can arrive near the Earth with $v_b \approx 40$ km/s. The orbital velocity of the Earth is $v_E = 30$ km/s. The relative velocity v_r of these objects with respect to the Earth depends on the angle between the orbits, so that its value is between $|v_E - v_b|$ and $v_E + v_b$. Upon approaching the Earth, the impactor is accelerated by gravity, and it can be shown using energy conservation that the impact velocity v_i is given by $v_i^2 = v_r^2 + v_e^2$, where $v_e \approx 11.2$ km/s is the escape velocity from the Earth. Thus, v_i can be as low as v_e and as high as ≈ 70 km/s. Average values of v_i are 20 km/s for asteroidal[4] and 56 km/s for cometary impacts on the Earth.[5] For simplicity, we shall assume $v_i = 30$ km/s in our numerical estimates.

The kinetic energy of a high velocity object is huge. The specific kinetic energy $\varepsilon_i = E_i/m_b = v_i^2/2$ is equal to ε_i (MJ kg^{-1}) $= 450V^2$ with $V = v_i$ (km/s)/30. This value is much larger than the chemical energy of an explosive, such as TNT (≈ 4.7 MJ/kg). That is, for the same mass the kinetic energy of a 30 km/s body is 100 times larger than the energy of a high explosive. The comparison is appropriate, because when it hits the ground the bolide liberates its energy by means of an explosion.

It is currently believed that comets consist of a porous mixture of ice and dust particles (bulk density $\rho_b \approx 0.6$ g/cm^3). Most asteroids and their fragments are rocky ($\rho \approx 2.3$–3.5 g/cm^3), but a small fraction of them are metallic (mainly iron, $\rho \approx 7.8$ g/cm^3). Their porosity varies from 0 to 70%, so that their bulk density ranges from $\rho_b \approx 1$ g/cm^3 to $\rho_b \approx 7$ g/cm^3, according to their composition and porosity.[6] The size of these objects can be as large as some tens of kilometers, and their shape is irregular (more information can be found in recent books on asteroids[7] and comets[8].) We assume that the bolide enters the atmosphere at an angle θ from the vertical, and to avoid inessential numerical factors we shall assume that its shape is a cube of side d. We then obtain

$$E_i \approx 108 \rho_b d^3 V^2, \tag{1}$$

where ρ_b is measured in g/cm^3, d in meters, and we express the kinetic energy in terms of tons of TNT.[9]

For the numerical estimates we shall assume a rocky body with $\rho_b = 2.5$ g/cm^3, $d = 100$ m, $v_i = 30$ km/s, and $\theta = 45°$. The kinetic energy of this object is equivalent to 270 megatons (nearly ten thousand times the combined energy of the atomic bombs dropped on Hiroshima and Nagasaki in 1945). There are many objects of sizes up to several tens of kilometers or larger in orbits that may eventually intersect the Earth's orbit.[10] Because E_i scales as d^3, these objects are extremely dangerous.

A. Ground penetration and slowing down

If (as happens on the Moon) nothing stops the bolide before it arrives at the surface, it will strike the ground with its cosmic velocity v_i. As long as its velocity is larger than the speed c of the elastic waves in the crust (which can transport energy far from the impact region), the impactor interacts only with the material just in front of it. The value of c is usually 3–5 km/s, depending on the materials of the crust. Because $c \ll v_i$, during most of the slowing-down process, no perturbation will propagate to an appreciable distance from the position of the impactor. Then, we can safely assume that during this phase the bolide interacts only with the matter along its path, inside a cylinder of cross section d^2. We call this assumption the "snow-plow" model.

If ρ_c is the density of the upper crust, in the interval Δt, the impactor moving with velocity v sweeps a mass $\Delta m_c = \rho_c v d^2 \Delta t$. This mass acquires the velocity v and thus a momentum $\Delta p_c = \Delta m_c v = \rho_c v^2 d^2 \Delta t$. Conservation of linear momentum implies that during the time Δt, the impactor loses a momentum $\Delta p_b = -\rho_c v^2 d^2 \Delta t$. Thus, the drag force is

$$F_d = \frac{dp_b}{dt} = -\rho_c v^2 d^2. \tag{2}$$

Because $m_b = \rho_b d^3$, the equation of motion is

$$\frac{dv}{dt} = -\frac{v^2}{\lambda}, \tag{3}$$

where we have introduced the characteristic slowing-down distance

$$\lambda = \frac{\rho_b}{\rho_c} d, \tag{4}$$

which corresponds to a thickness such that the swept mass is equal to the impactor mass.

The solution of Eq. (3) is

$$v = \frac{v_i}{1 + v_i t/\lambda}. \tag{5}$$

Thus, v decreases with a characteristic time

$$t^* = \frac{\lambda}{v_i} = \frac{\rho_b d}{\rho_c v_i}. \tag{6}$$

During t^*, the bolide penetrates a distance of the order of λ, its velocity is reduced by a factor of 2, and three-quarters of its kinetic energy is dissipated. Then, if our example bolide impacts on rocky ground ($\rho_c \approx 2.5$ g/cm^3), it will burrow to a depth $\lambda \approx 100$ m in $t^* \approx 3$ ms, dumping an energy equivalent to 270 megatons. During this time, the perturbation in the ground travels a distance of only $ct^* \approx 10$–15 m.

B. Can the atmosphere stop the bolide?

While crossing the atmosphere, an impactor is subject to mechanical stresses due to aerodynamic braking that may result in its breakup and fragmentation when the stagnation pressure[11] $p_s = \rho_a v^2/2$ (ρ_a is the air density) exceeds the mechanical strength Y_b of the bolide (not to be confused with the Young's modulus). For example, if $v = 17$ km/s, $p_s \approx 1.7$ kbar at ground level. The mechanical properties of the impactors are poorly known. Some of these bodies are almost strengthless "rubble piles," but others may have a strength Y_b as large as a few kbars. Some impactors are highly porous, which may affect their deformation and disruption. To keep the discussion simple, we shall not pursue these issues here. We mention that it is widely believed that most small ($d \lesssim 100$ m) stony and cometary bodies break up and dissipate their kinetic energy high in the atmosphere.[12,13] In contrast, small iron objects are able to resist disruption. As a consequence, the reader must be cautious in using our estimates for impacts of bolides in this size range. Beyond this range, breakup can be ignored regardless of the strength of the bolide, because the time scale for disruption increases linearly with d and becomes larger than the time required to cross the atmosphere.[15]

If we disregard breakup, the effect of the atmosphere on the motion of a high velocity projectile can be estimated by means of the snow-plow model because the thermal velocity of the air molecules (≈ 0.3 km/s) is negligible in comparison with the velocity of the bolide. Then, the stopping power[14] of the atmosphere is $\tau \rho_a h_a / \cos\theta$. Here, we take $\rho_a \approx 1.2$ kg/m^3 to be the density of the air at the ground, $h_a \approx 8.6$ km to be the effective height of the atmosphere, and τ is a coefficient that takes into account the details of the flow. For the speeds of interest, $\tau \approx 0.5$. We shall further assume that the trajectory is rectilinear. The atmosphere stopping power must be compared with $\rho_b d$; the penetrating power of the projectile. The atmosphere will not slow the impactor appreciably if $\tau \rho_a h_a / \cos\theta \ll \rho_b d$. Then, if no fragmentation occurs and if the ratio

$$\epsilon \equiv \frac{\tau \rho_a h_a}{\rho_b d \cos\theta} \ll 1, \tag{7}$$

the bolide will strike the ground without losing a significant fraction of its kinetic energy in the atmosphere. Note that ϵ is inversely proportional to d so that large nonbreaking meteoroids, characterized by $\epsilon \ll 1$ (for example, $\epsilon \approx 0.03$, for our model impactor), are not stopped by the atmosphere. It can also be seen that $\epsilon \ll 1$ implies kinetic energies as least as large as several megatons.

It is easy to estimate the effect of the air on the motion of a large bolide. Because its velocity is almost constant, it will cross the atmosphere in a time $t_a = h_a/(v_i \cos\theta) \approx 0.3/(V \cos\theta)$ s. If we denote the acceleration due to gravity by g, the deviation in radians of the trajectory from a straight line can be expressed as $g t_a \sin\theta / v_i \approx 10^{-4} V^{-2} \tan\theta$, clearly a negligible quantity except for $\theta \approx \pi/2$. We can use Eq. (5) with the substitutions $\lambda \to \rho_b d/\tau\rho_a$ and $t \to t_a$ to show that the impactor will strike the ground with the velocity $v_i(1-\epsilon)$. If there is no loss of mass, the energy dissipated in the atmosphere is then $E_d \approx 2\epsilon E_i$. According to this result, our model bolide will lose $\approx 6\%$ of its kinetic energy; that is, 16 megatons.

We shall not discuss the fate of small meteoroids ($\epsilon \gtrsim 1$) that are either completely vaporized or stopped, mostly in the upper atmosphere.[15] In contrast, the fractional mass loss of the large impactors we are considering is negligible, as we shall show in Sec. III A.

C. Explosion and formation of the crater

Upon striking the ground (after crossing the atmosphere), our model bolide will penetrate it; being slowed down in approximately 3 ms, during which it dissipates 254 megatons in a volume of approximately 10^6 m^3 containing a mass $2m_b \approx 5 \times 10^9$ kg. This kinetic energy is converted to internal energy of this mass and is equivalent to 225 MJ/kg, an amount sufficient to vaporize any material (the latent heat of vaporization of stony material is 8 MJ/kg) and to bring the vapor to a temperature in the range $10^4 - 10^5$ K. Then, the impactor and the swept mass are immediately vaporized. The almost instantaneous delivery of this huge amount of energy produces a pressure in the vaporized medium that can be estimated as $p \approx E_i/d^3 = \rho_b v_i^2/2$, which means the pressure (in Mbar) is $p \approx 4.5\rho_b V^2$. This pressure is larger by several orders of magnitude than the strength of any material. Typical values of the strength Y of the Earth's crust are in the range of 0.2–0.4 kbar. In the following, we shall assume $Y = 0.3$ kbar. Because nothing can contain the vaporized mass, an explosion centered at a depth d occurs, whose magnitude in our example is larger than the most powerful nuclear warhead ever tested.

The effect of the explosion generates a strong shock wave that, as it expands about the point of impact, shatters and pulverizes the crust, throwing part of the fragments up and to the sides, thus leaving a cavity called the transient crater. This excavation process goes on until the shock wave is sufficiently attenuated and can no longer fracture the soil rocks, after which it propagates as a seismic wave.

We can estimate the diameter D of the transient cavity by comparing the energy E_i of the explosion with the energy E_c needed to fracture the crust rocks and with the gravitational potential energy E_g that must be provided to the fragments to eject them from the crater. The order of magnitude of E_c is the product of Y times the volume of a half-sphere of diameter D, that is,

$$E_c = Y(2\pi/3)(D/2)^3 \approx YD^3/4. \tag{8}$$

We can similarly estimate E_g as the weight of the object contained in a half-sphere of diameter D, multiplied by its average depth $3D/16$. We find

$$E_g = \rho_c g(2\pi/3)(D/2)^3(3D/16) \approx \rho_c g D^4/20. \tag{9}$$

The ratio E_c/E_g is

$$\frac{E_c}{E_g} \approx \frac{5Y}{\rho_c g D} = \frac{5h^*}{D}, \tag{10}$$

where $h^* \equiv Y/\rho_c g \approx 1.2$ km.

The parameter h^* is the height for which the gravitational potential energy is equal to the cohesion energy. There will be two different scalings depending on whether E_c or E_g dominates the process.

1. Cohesion scaling

If $D \ll 5h^* \approx 6$ km, we have $E_c \gg E_g$, and if we equate E_i with E_c, we obtain the scaling law

$$D = (4E_i/Y)^{1/3}. \tag{11}$$

For $Y = 0.3$ kbar, we find D (km) $\approx 0.81[E_i(\text{megatons})]^{1/3}$. If we substitute into Eq. (11), the value of E_i given by Eq. (1), we obtain $D/d \approx 39\rho_b^{1/3}V^{2/3}$. According to this scaling, the model impactor will produce a 5.3 km diameter transient cavity.

2. Gravity scaling

If $D \gg 5h^*$, we have $E_g \gg E_c$, and if we equate E_i with E_g, we derive the scaling law

$$D = (20E_i/g\rho_c)^{1/4}. \tag{12}$$

From Eq. (12), we obtain D (km) $\approx 1.74[E_i(\text{megatons})/\rho_g]^{1/4}$. We substitute Eq. (1) into Eq. (12) and find

$$\frac{D}{d} \approx 138 d_{\rm m}^{-1/4}(\rho_b/\rho_c)^{1/4}V^{1/2}. \tag{13}$$

For impacts on the Earth, the transition between cohesion and gravity scaling occurs for impactor energies of about 400 megatons.

Note that the scalings we have just discussed refer to the transient cavity, which does not coincide in size and shape with the final impact structure. The latter is determined by various processes that depend on the magnitude of the impact, and include the slumping of the transient cavity walls, the partial filling of the cavity by the infall of debris, the formation of central peaks and rings, and the effusion of magma. We shall not pursue these matters further, and the interested reader is referred to Ref. 16. We also mention that most of the material ejected by the explosion is cool. The mass that is heated and vaporized is a tiny fraction, of the order $(d/D)^3$, of the total mass involved in the formation of the transient crater.

The scalings we have obtained do not take into account the porosity of the target medium. This effect can be safely ignored when considering large impacts on the Earth, but should be taken into account for the case of the cratering of very porous asteroids and comets.

III. MASS LOSS AND HEATING DURING ENTRY IN THE ATMOSPHERE

The physics of meteoric entry in the atmosphere is complex. A simple approximate analytical treatment can be found in Ref. 15, where the key physical phenomena involved are discussed. For a large meteoroid ($\epsilon \ll 1$) further approximations can be made to obtain estimates, because such a body traverses the atmosphere losing only a small fraction of its velocity as shown in Sec. II B. Notice, however, that this fact does not mean that the energy dissipation in the atmosphere is of no consequence. The power dissipated, the forces, and the accelerations involved are huge. The magnitude of the aerodynamic drag varies with height. At ground level, we have

$$F_d = \tau\rho_a d^2 v_i^2 \approx 1.1 \times 10^9 \tau d_m^2 V^2(\text{N}). \tag{14}$$

The power dissipated can be estimated as

$$W = F_d v_i = \tau\rho_a d^2 v_i^3 \approx 32\tau d_m^2 V^3(\text{TW}). \tag{15}$$

This magnitude can be compared with the total electric generating power of the United States, which is of the order of 1 TW.

The energy dissipated during entry is transferred to the atmosphere in three ways: (1) A shock wave develops in front of the bolide and the air is adiabatically heated in crossing the shock; (2) the surface of the impactor is heated by radiation from the shock-heated air, producing the melting and vaporization of the material; and (3) the material that is lost from the bolide ultimately loses its energy to the atmosphere.

A. Mass loss

Let us estimate the mass loss of a large meteoroid due to evaporation. The strong shock wave that develops in front of it dissociates and ionizes the air. These processes consume most of the energy dissipated and, as a consequence, the temperature of the shocked gas tends to stabilize. In this condition, it can be shown[17] that, independently of v_i, the radiation emitted by the heated air corresponds to a temperature $T \approx 20\,000$ K (T depends on the mixture of gases involved in the process). This radiation dominates the bolide heating so that the power it absorbs does not depend on its velocity. This regime is not discussed in Ref. 15, and is not attained by small meteoroids that dissipate most of their energy in the high atmosphere. The power absorbed by a large impactor is then[18]

$$W_a = 6d^2 c_a \sigma T^4, \tag{16}$$

where $c_a \leqslant 1$ is the absorption coefficient and σ is Stefan's constant. This absorbed power heats the material of the surface, which melts and vaporizes so that the surface temperature cannot exceed the boiling temperature of the material. Then, the flux F_m of the evaporated mass is

$$F_m = W_a / 6d^2 L, \tag{17}$$

where L is the latent heat of vaporization (2, 8, and 5 MJ/kg for ice, rocks, and iron, respectively). From Eqs. (16) and (17), we find $F_m = c_a \sigma T^4 / L$. The mass evaporated during the time t_a it takes the bolide to cross the atmosphere is $\Delta m = 6d^2 F_m t_a$. Then, the fractional mass loss is

$$\frac{\Delta m}{m} = \frac{6 c_a \sigma T^4 h_a}{L \rho_b v_i d \cos\theta} \approx \frac{2.27 c_a}{\tau V L} \epsilon. \tag{18}$$

Notice that $\Delta m / m$ is inversely proportional to d. For our model bolide with $c_a = 1$, we obtain $\Delta m / m \approx 0.027$. This result justifies the previous assumption of negligible mass loss for large bodies.

B. Heating

It can be shown that the heat absorbed does not penetrate to a significant depth in the impactor. From dimensional considerations, we find that during the time t_a heat penetrates to a depth $\delta \approx (K t_a / C \rho_b)^{1/2}$, where K is the thermal conductivity and C is the specific heat of the medium. If we use the parameters for our model bolide and assume $K \approx 20$ J/m s K and $C \approx 420$ J/kg K, we obtain $\delta \approx 3 \times 10^{-3}$ m. This estimate indicates that the inside of the bolide remains cold (independently of d), while its surface layers are ablated, that is, lost by evaporation.

Note also that

$$\frac{W_a}{W} = \frac{6 c_a \sigma T^4}{\tau \rho_a v_i^3} \approx 1.7 \times 10^{-3} \frac{c_a}{\tau V^3}, \tag{19}$$

so that in the present regime a very small fraction of the power dissipated during entry is absorbed by the bolide.

IV. COMMENTS

We have shown that the basic physics of catastrophic bolide impacts can be described by simple models that allow us to derive scaling laws for the transient craters. The atmosphere does not stop a large impactor or significantly reduce its mass by ablation. However, while crossing the atmosphere, an impactor is subject to mechanical stresses that may result in its breakup and fragmentation for $d \lesssim 100$ m. We leave the discussion of these issues to a future paper.

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APPENDIX: SOME PROBLEMS

We suggest a few activities whose goals are to develop students' skill with back-of-the-envelope estimates and to gain familiarity with the scale of impact phenomena.

1. For an oceanic impact, find the conditions that must be satisfied to ensure that the impactor produces a crater in the seabed.
2. Estimate the evaporated mass of water during the entry in the sea.
3. Compare the energy involved in the high velocity impact of a large bolide with other catastrophic events, such as earthquakes, tsunamis, hurricanes, and a large-scale nuclear war.
4. Compare the present back-of-the-envelope estimates with the results of more accurate simulations.[19]

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[9]By definition, 1 megaton $= 4.184 \times 10^{15}$ J. The megaton is approximately equivalent to the energy released in the detonation of 10^6 tons of TNT.

[10]See ⟨http://neo.jpl.nasa.gov/neo/⟩ for updated information on near-Earth objects.

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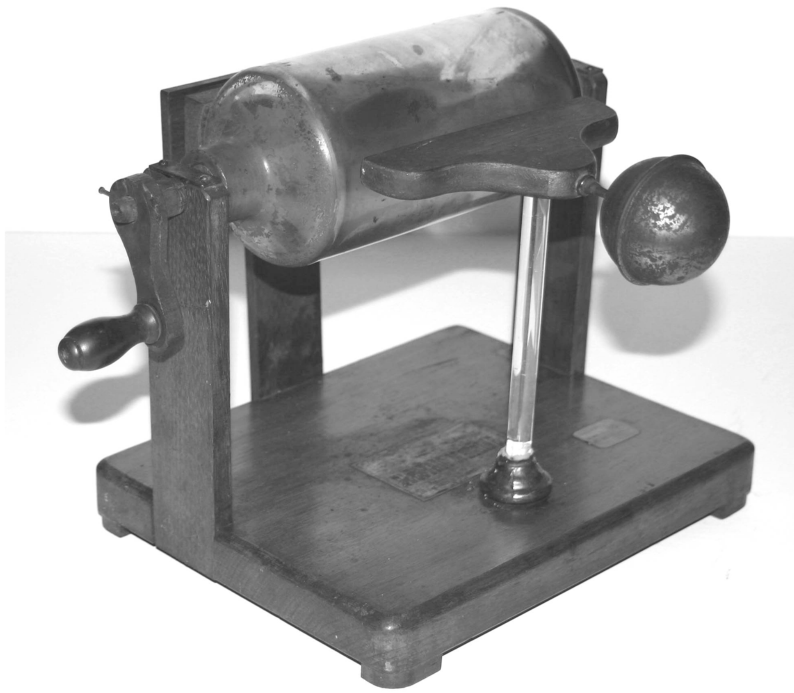

Cylinder Electrostatic Machine. The British physicist John Tyndall lectured to large audiences in the United States in the 1870's and excited considerable interest. The 1885 catalogue of Curt W. Meyer of New York City lists a complete set of apparatus to accompany Tyndall's 1875 book "Lectures in Electricity." The complete set of nearly 60 items cost $65; the cylinder electrostatic generator shown here was, at $8, the most expensive item. It is tiny; the cylinder is only 15 cm long. (Photograph and Notes by Thomas B. Greenslade, Jr., Kenyon College)