Possible Explanation of Total Ablation of the 1908 Tunguska Asteroid*

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Abstract

Damage to the Earth's surface from colliding asteroids and comets is of great concern, and first conference on this subject, "Space Protection of the Earth," took place September 26-30, 1995 (Snezhinsk, Chelyabinsk region, Russia). The explosion over Tunguska, Central Siberia, in 1908 is believed to be due to breakup of a stony asteriod. However, because no significant fragments have been located in the area of the explosion, the nature of the object over Tunguska remains to be determined. Recent theoretical models and results of experiments performed to evaluate material erosion in high-heat-load environments are used to analyze the interaction between the Tunguska object and Earth's atmosphere. Models and laboratory experimental data that indicate the possibility of full destruction of such large-sized asteriod objects are presented.

1. Introduction

The Tunguska catastrophe of 1908 and the Shoemaker-Levy comet interaction with Jupiter were events of global scale [1]. In general, the physical phenomena that occur during the interaction between celestial bodies and planets are more or less well understood. Although, the lack of the fragments from the Tunguska object on the Earth's surface remains a mystery. Several full-ablation theories were reviewed in Ref. 2. Recent theoretical models and results from experiments developed to study material erosion in high-heat-load environments, such as those that exist on the first walls of a fusion reactor, are used to analyze the interaction between the Tunguska object and the Earth's atmosphere.

2. Body Fragmentation

The problem of Tunguska body fragmentation was first studied by Grigoryan [3], who assumed deformation and fragmentation due to differential atmospheric pressure across the object. For an object entering the atmosphere at 20 km/s, aerodynamic stresses can reach hundreds of atmospheres, exceeding the characteristic strength (1-50 atm) of a chondritic impactor. Later, the Grigoryan theory was further examined and refined by others [4-6], who took into account the sequence of fragmentation. The theory of branchy fragmentation [6] was confirmed by the observation of meteorite fragmentation in the Earth's atmosphere [7,8] as well as the fragmentation of the Shoemaker-Levy comet due to tidal strength [1]. As follows from the theory of branchy fragmentation, the Tunguska body breaks up to ≈100-cm fragments as a result of many branchy fragmentations in up to 30 steps of fragmentation. Therefore, the problem consists of answering the following question: what mechanisms are responsible for full ablation of these fragments? The problem of full ablation of the fragments is significant because it is only the absence of fragments on the Earth's surface that has led to the conclusion of the comet nature of the Tunguska object [2,9-11]; all other phenomena correspond to a stony asteroid.

It was shown clearly that the radiation flux S_{in} onto the surface of the fragments is not enough to fully vaporize the fragments (see for example Ref. 1). Moreover, the real flux onto the surface of the fragments that takes into account self-absoption of radiation, i.e., the vapor shielding effect [15], is much lower (up to one order of magnitude) than S_{in}, which amounts to some hundreds of kW/cm^2. For these reasons, several authors [4,11] have indicated that other, more effective, mechanisms for ablation should be considered. One of the mechanisms is the blowing-off of the liquid droplets from a molten layer that developed on the stone surface because of hydrodynamic instabilities, such as Kelvin-Helmholtz and Raleigh Taylor instabilities, which result in the formation of capillary surface waves. In this case, the ablation energy q decreases from tens of kJ/g (solid vaporization) to only a few kJ/g (liquid splashing); therefore even lower radiation power of $<1\ MW/cm^2$ is enough for full ablation. The existence of this splashing mechanism is confirmed by the discovery of many microsized particles (aerosols) trapped in the resin of trees that survived the Tunguska catastrophe [13,14].

3. Dynamics of Asteroid/Earth-Atmosphere Interaction

Figure 1, an illustration of an asteroid interaction with the Earth's atmosphere, shows the stages of the interaction: stage a is shock wave formation a distance L from the fragment cloud, $L \sim D$, where D is the cloud size; stage b is body fragmentation, and stage c is radiation transfer from shock-wave-heated air to the body (cloud fragments) surface. Figure 2 shows the altitude dependence of parameters as given by Ref. 4, with explosion-like energy release ("fireball") at $\mathbf{H} \cong 10$ *km* for a short time of $\approx$1 s. The space dependence of the heated air temperature and radiation fluxes is shown in Figure 3 for the region between the shock wave and the body surface. The air pressure after the shock wave front reaches high values of hundreds of atmospheres because of high ram pressure, $P = \rho V^2$ =1000 atm, and air temperature T increases up to 10 eV. In the deceleration region, $5 < \mathbf{H} < 20$ *km*, the particle path length, $l_p \cong 10^{-4}$ cm, and the Rooseland mean path length of radiation, $l_\upsilon = 0.1$ cm, are $<L$ therefore, all physical processes can be studied under the assumptions of hydrodynamics and radiation heat conduction. In earlier papers, mass losses due to vaporization were estimated with this maximum temperature. But, because of self-absoption of radiation, i.e., the vapor shielding effect, radiation fluxes both into the body surface and outside of it decrease significantly [15].

The problem of decreasing radiation fluxes was studied in detail when we were evaluating the erosion and lifetime of candidate materials for fusion reactor first walls. It was shown that the radiation flux to a target surface is determined by the radiation flux from a depth where the

Rooseland path length of radiation is comparable to the characteristic length dx/d log(T), i.e., from layers where radiation becomes transparent. This phenomenon is widely known, for example, in determining solar corona parameters. The temperature of solar radiation T_b is ≈6000 K, and the maximum radiation temperature of strong shock waves in air T_b is 1.5-1.7 eV or = 17000-20000 K. This T_b is governed by the ionization temperature, i.e., $T_{ion} = T$ (of Z ~ 1). Therefore, the radiation flux into the surface is limited by the value $S_{in} = \sigma T^4 = 400$ kW/cm^2, $T_{ion} \cong 1$ eV, which corresponds to the ionization temperature of stone elements. The radiation flux to the outside S_{out} is limited by the ionization temperature of the air, $T_{ion} \cong 1.5$ eV; therefore, S_{out} is <1 MW/cm^2. Thus, measurements of fireball radiation from the surface of the Earth cannot be used to estimate the actual temperature inside the fireball. Such limitation of S_{out} would result in an increase in the duration of the luminescence of the fireball. It is known that, explosion of ≈ 15 x 10^6 mt, the size of the fireball can reach a radius R of ≈ 500 m. Therefore, the cooling time of the fireball can be estimated as $t_s = E/(4\pi R^2 \sigma T^4) = 5$ s which exceeds the asteroid deceleration time of ≈ 1 s.

4. Full Ablation Due to Splashing and Stationary Wave of Splashing

The rate of mass loss due to liquid splashing can be estimated as $U_a = S_{in}/q$, where the value of the ablation energy q depends on the ablation mechanism [15]. Two main mechanisms are responsible for liquid splashing: the above-mentioned Kelvin-Helmholtz and Raleigh-Taylor instabilities, and volume bubble boiling, illustrated in Figure 4. These mechanisms were studied in detail both theoretically and experimentally [15]. The capillary surface waves excited by plasma wind along the stone surface soon reach a nonlinear stage when the combs of the waves become very sharp and, because of the capillary force, are divided into droplets that are blown off by the wind. In this case, the ablation energy can be estimated as $q = c_v T_m + q_m + q_{kin}$, where c_v is the specific heat, T_m is melting temperature, q_m is heat of fusion, and q_{kin} is the kinetic energy of the droplets. For chondritic stone with a density of 2 g/cm^3, the ablation energy can be estimated as ≈1.25 kJ/g or 2.5 kJ/cm^3.

The second mechanism of ablation of molten material is due to the volume bubble boiling that is a result of overheating a surface, i.e., $T > T_v$, where T_v is the temperature at which the saturated vapor pressure exceeds the external pressure. In this case, the liquid material is splashed by bubble explosion. Because of the grain structure of the stone, pores between grains contain enough absorbed gases for initial bubble nucleation. The ablation energy can then be estimated as $q = c_v T_m + q_m + q_{kin}$ = 1.75 kJ/g or 3.5 kJ/cm^3. The important role of pores in the ablation process was noted in Ref. 10.

During the interaction of an asteroid with the atmosphere, both mechanisms, i.e., hydrodynamic instabilities as well as volume bubble boiling take place. Therefore, mass losses can be calculated from the equation $U_a = S_{in}/q$ using the appropriate value of q taking into account both mechanisms. The total erosion rate or splashing velocity can then be estimated as to be = 30

-100 cm/s. Similar calculations for aluminum target exposed to laboratory heating are in a good agreement with experimental data [16]. The characteristic time of splashing t can be estimated as $t_a < t < t_c$, $t_a < 1$ s, $t_c < 5$ s, where t_a is slowing-down time and t_c is fireball lifetime. This is reasonable because t_a during the deceleration stage is valid and during the fireball cooling-time t_c is suitable. It follows that fragments up to 100 cm can be fully splashed. Consequently, the splashed droplets that are less than tens of micrometer in size can be fully vaporized by the radiation flux S_{in} (hundreds kW/cm^2) in a time $t_a = (S_{in}/l_a q_v)^{-1}$, where q_v is the vaporization energy. For $q_v = 20$ kJ/cm^3, in a time of ≈ 1 s, particles up to a few cm can be vaporized as estimated by $l_a = S_{in} t_a / q_v$. Therefore, most of the droplets (aerosols) are vaporized and only a small remainder are not fully vaporized and can fall onto the surface of Earth [13].

For a heat conduction coefficient of $\kappa = 0.02$ J/(cm·s·K), $c_v = 1$ J/cm^3, and $t = 1$ s, the skin depth determined without taking into account any mass losses is small and is on the order of $h_m = (2 \cdot \kappa \cdot t / c_v)^{1/2} = 0.2$ cm, which is considerably less than the ≈ 100 cm that is the characteristic size of the fragments. However, taking into account the fast blowing-off of the molten layer with a velocity that exceeds that of the diffusion velocity $V_d = (2 \cdot \kappa / c_v \cdot t)^{1/2} \approx 0.2$ cm/s, the radiation flux will interact with the target surface directly, so the temperature gradient will be large, i.e., $dT/dx = S_{in}/k >> T_m/h_m$. The numerical simulation using the SPLASH code predicted that, after some transition time, the depth of the molten layer and the erosion depth grow linearly with time; therefore, a stationary splashing wave with constant velocity is formed [16]. This can be easily shown for the limiting case of $q_m + q_{kin} = 0$. In this case, the heat propagation equation with full blowing-off of the molten layer has a stationary (selfsimilar) solution, $T(x) = T_s \exp(-\xi \cdot U_s \cdot c_v/k)$, $\xi = x - U_s \cdot t$, $U_s = S_{in}/(c_v \cdot T_s)$, where $T_s = (T_m, T_v)$ is the temperature of the target surface. The characteristic value of the heat skin depth is given by $l_s = k/(c_v \cdot U) = k \cdot T_s/S_{in} \cong 10^{-4}$ cm. Thus, as a result of fast erosion of the molten material, "thawing" of the stone takes place with a splashing velocity that is much greater than the heat diffusion velocity.

5. Summary

Models and experimental data are presented to explain the possibility of total ablation of the 1908 Tunguska asteriod. The following statements can be made from the above considerations.

1. The Tunguska object was in the form of a stony asteroid.

2. The asteroid was broken into fragments, with sizes on the order of meters, by branchy fragmentation due to the differential atmospheric pressure that exceeded the yield strength.

3. These macroscopic fragments were further reduced to microsized particles during splashing of the molten layer that develops on the solid surface by two main mechanisms: hydrodynamic instabilities and volume bubble boiling.

4. Final destruction of the asteroid material occured by vaporization of aerosols from radiation of the fireball.

For a more detailed analysis, special experiments on the interaction of high-power plasma flows of real meteorite material are required to determine the splashing velocity, which depends on the meteorite material. Also required full, comprehensive, numerical calculations that takes into account all of the physical phenomena and various hydrodynamic instabilities that occur during the asteroid/Earth-atmosphere interaction.

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Figure Captions

Figure 1 Schematic illustration of asteroid fragmentation, fireball, and shock wave formation.

Figure 2 Variation of asteroid energy E, velocity V, pressure P, breaking power S, and shock wave temperature T as a function of altitude Z.

Figure 3 Generation of the radiation fluxes S_{in} and S_{out}.

Figure 4 Illustration of splashing mechanisms due to Kelvin-Helmholtz instability and volume bubble boiling.

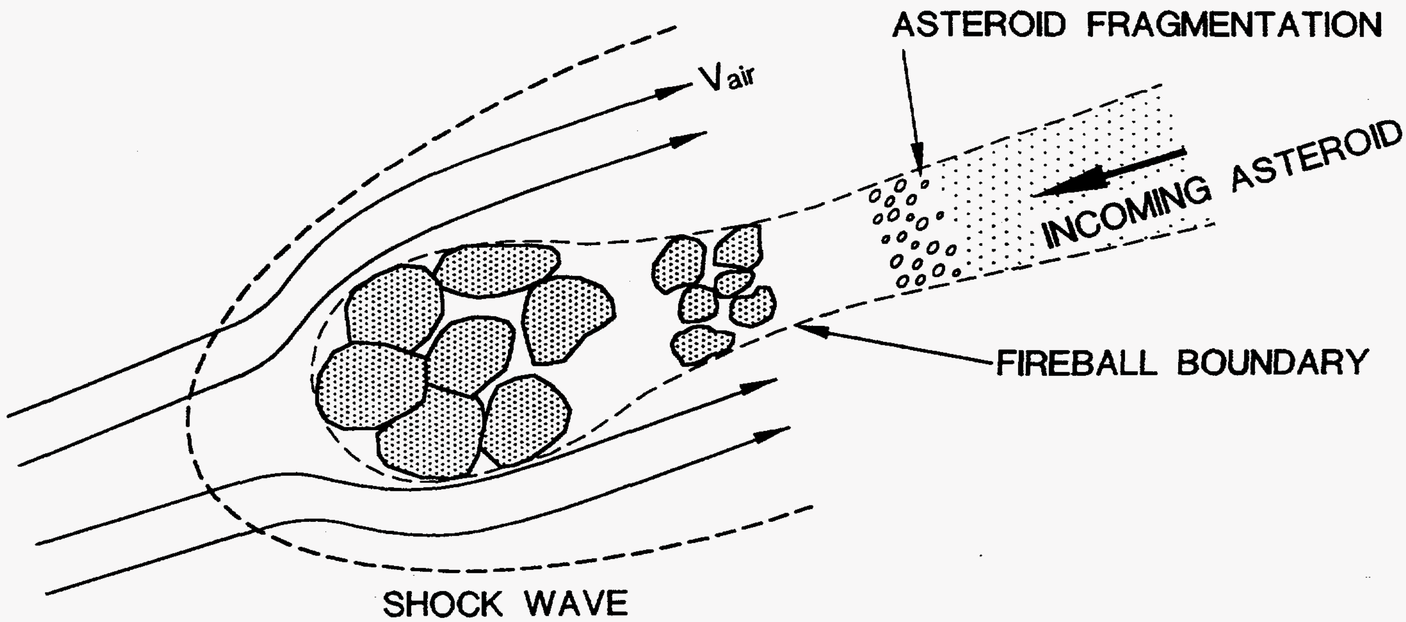

Fig. 1

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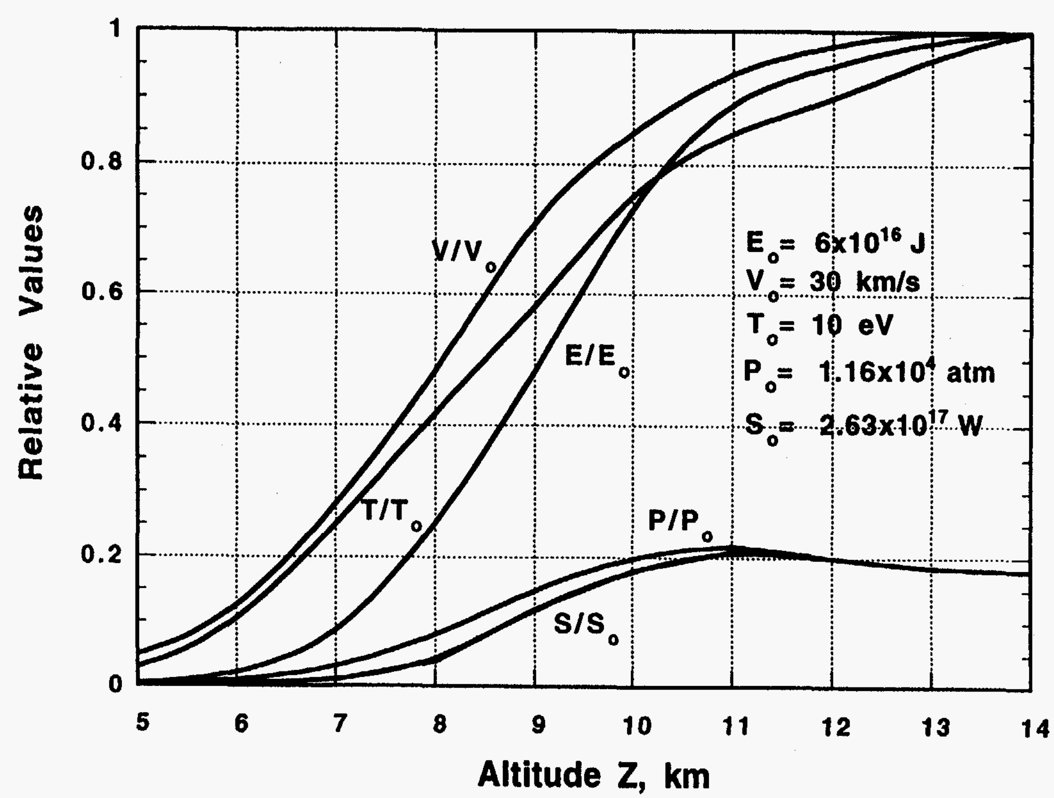
Relative Values
Altitude Z, km
V/V$_o$
T/T$_o$
E/E$_o$
P/P$_o$
S/S$_o$
$E_o = 6 \times 10^{16}$ J
$V_o = 30$ km/s
$T_o = 10$ eV
$P_o = 1.16 \times 10^4$ atm
$S_o = 2.63 \times 10^{17}$ W

Fig ②

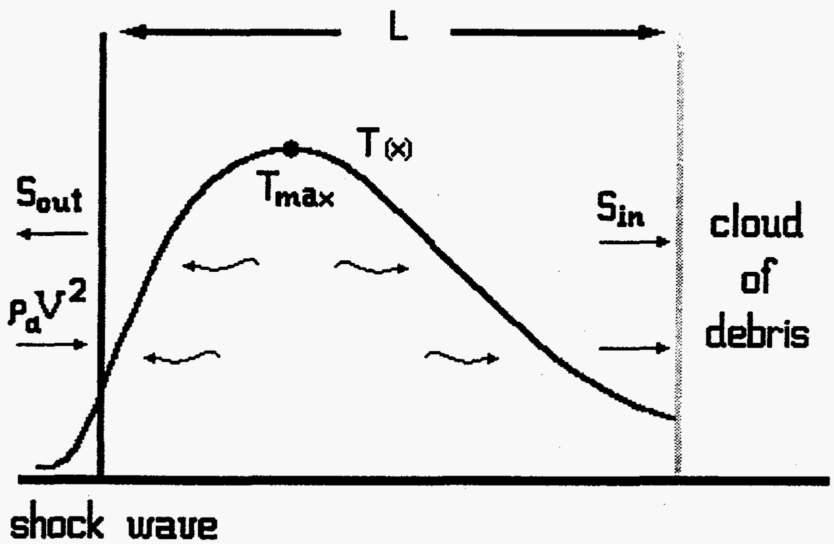

Fig ③

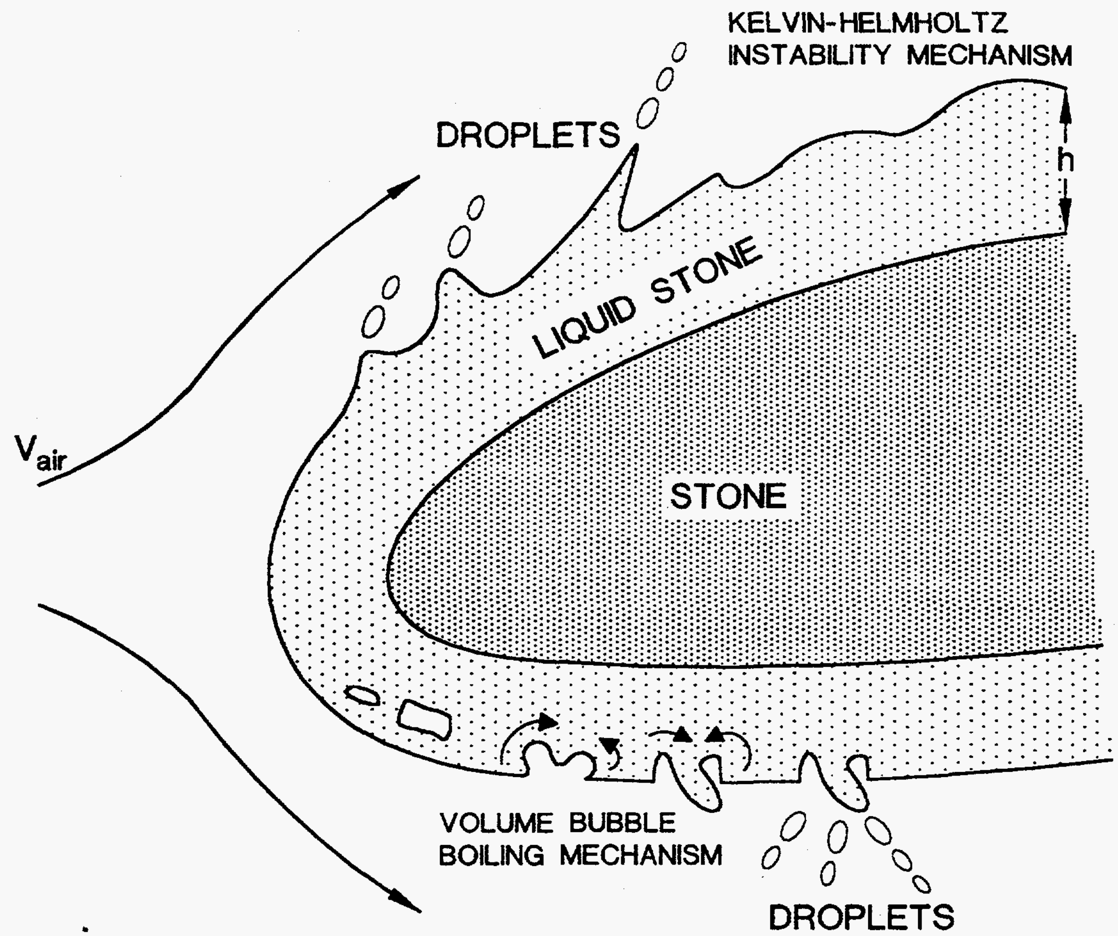

Fig 4

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