Possible Explanation of Total Ablation of the 1908 Tunguska Asteroid*

A. Hassanein
Argonne National Laboratory, Argonne, IL, 60439, USA

V. A. Alekseev, A. I. Konkashbaev, I. K. Konkashbaev, and L. B. Nikandrov
Troitsk Institute for Innovation and Fusion Research, 142092, Troitsk, Russia

January 1998

Presented at the Second International Aerospace Congress (IAC'97), August 31- Sept. 5, 1997, Moscow, Russia.

*Work supported by the Civilian Research & Development Foundation (CRDF) for the Independent States of the Former Soviet Union.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

 Portions of this document may be illegible electronic image products. Images are produced from the best available original document.
Possible Explanation of Total Ablation of the 1908 Tunguska Asteroid


*Troitsk Institute for Innovation and Fusion Research
142092, Troitsk, Russia

**Argonne National Laboratory, Argonne, IL. 60439, USA

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 asteroid. 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 asteroid 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 \( \approx 100 \)-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-absorption 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/cm². 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/cm² 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 \( H \leq 10 \text{ km} \) for a short time of \( \approx 1 \text{ s} \). 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, \( P = \rho V^2 = 1000 \text{ atm} \), and air temperature \( T \) increases up to 10 eV. In the deceleration region, \( 5 < H < 20 \text{ km} \), the particle path length, \( l_p \approx 10^{-4} \text{ cm} \), and the Rooseland mean path length of radiation, \( l_o = 0.1 \text{ cm} \), 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-absorption 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 \( \approx 6000 \) 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., \( T_{\text{ion}} = T \) (of \( Z \sim 1 \)). Therefore, the radiation flux into the surface is limited by the value \( S_{\text{in}} = \sigma T^4 = 400 \text{ kW/cm}^2 \), \( T_{\text{ion}} \approx 1 \) eV, which corresponds to the ionization temperature of stone elements. The radiation flux to the outside \( S_{\text{out}} \) is limited by the ionization temperature of the air, \( T_{\text{ion}} \approx 1.5 \) eV; therefore, \( S_{\text{out}} \) 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 \( S_{\text{out}} \) would result in an increase in the duration of the luminescence of the fireball. It is known that, explosion of \( \approx 15 \times 10^6 \) 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 \( t_c = \frac{E}{(4\pi R^2 \sigma T^4)} = 5 \) s which exceeds the asteroid deceleration time of \( \approx 1 \) 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 \( U_a = S_{\text{in}}/q \), 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
\( \approx 1.25 \text{ kJ/g} \) or \( 2.5 \text{ kJ/cm}^3 \).

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 \( q = c_v T_m + q_m + q_{kin} = 1.75 \text{ kJ/g} \) or \( 3.5 \text{ kJ/cm}^3 \). 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 \( U_e = S_{in}/q \) 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 $S_m$ (hundreds kW/cm$^2$) in a time $t_a = (S_m/l_d q_v)^{1}$, where $q_v$ is the vaporization energy. For $q_v = 20$ kJ/cm$^3$, in a time of $\approx 1$ s, particles up to a few cm can be vaporized as estimated by $l_a = S_m t_a / q_v$. 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 $h_m = (2 \cdot \kappa / c_v)^{1/2} = 0.2$ cm, which is considerably less than the $\approx 100$ 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 $V_d = (2 \cdot \kappa / c_v t)^{1/2} = 0.2$ cm/s, the radiation flux will interact with the target surface directly, so the temperature gradient will be large, i.e., $dT/dx = S_m / \kappa >> T_m / h_m$. 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 (self-similar) solution, \( T(x) = T_s \exp(-\xi \cdot U_s \cdot c/\kappa) \),
\[ \xi = x-U_s \cdot t, \quad U_s = S_{in}/(c_s \cdot T_s), \]
where \( T_s = (T_m T_f) \) is the temperature of the target surface. The characteristic value of the heat skin depth is given by \( l_s = k/(c_r U) = k \cdot T_s / S_{in} \equiv 10^{-4} \text{ cm} \). 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 asteroid. 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 occurred 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.

References


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 $S_{\text{in}}$ and $S_{\text{out}}$.

Figure 4  Illustration of splashing mechanisms due to Kelvin-Helmholtz instability and volume bubble boiling.
Fig 3

Sout

P_d V^2

T_{\text{max}}

T_{\infty}

S_{\text{in}}

cloud of debris

shock wave

L
KELVIN-HELMHOLTZ INSTABILITY MECHANISM

VOLUME BUBBLE BOILING MECHANISM

DROPLETS

LIQUID STONE

STONE

Fig 4