Low-altitude airbursts and the impact threat

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Abstract

We present CTH simulations of airbursts in the Earth's lower atmosphere from hypervelocity asteroid impacts. The intent of these simulations was to explore the phenomenology associated with low-altitude airbursts, with the particular goal of determining whether the altitude of maximum energy deposition can be used as a reasonable estimate of the equivalent height of a point source explosion. Our simulations suggest that this is not a good approximation. The center of mass of an exploding projectile is transported downward in the form of a high-temperature jet of expanding gas. The jet descends by a significant fraction of the burst altitude before its velocity becomes subsonic. The time scale of this descent is similar to the time scale of the explosion itself, so the jet simultaneously couples its kinetic energy and its internal energy to the atmosphere. Because of this downward flow, larger blast waves and stronger thermal radiation pulses are felt at the surface than would be predicted by a point source explosion at the height where the burst was initiated. For impacts with a kinetic energy above some threshold, the hot jet of vaporized projectile (the descending "fireball") makes contact with the Earth's surface, where it expands radially. During the time of radial expansion, the fireball can maintain temperatures well above the melting temperature of silicate minerals, and its radial velocity can exceed the sound speed in air. We suggest that the surface materials can ablate by radiative/convective melting under these conditions, and then quench rapidly to form glass after the fireball cools and recedes. Possible examples of such airburst glasses are the Muong-Nong Tektites of Southeast Asia and the Libyan Desert Glass of western Egypt. We suggest an enhancement of entry dynamics models to account for the downward advection of shocked and heated material, and the lowering of the apparent airburst altitude. The actual differences between the effects on the ground from a point source approximation versus a full flow field still need to be quantified by running more realistic high-resolution 3-D simulations with a variety of impact parameters. A re-evaluation of the impact hazard is necessary to properly include this enhanced damage potential of low-altitude airbursts.

Keywords: CTH, hydrocode, airburst, planetology, asteroid.

1. Introduction

Recent work by several researchers has drawn attention to the large amount of energy that is

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coupled directly to the Earth's atmosphere from hypervelocity collisions, and the importance of this interaction, both as a geologic process and as a human hazard. Even for crater-forming impact events, the atmosphere plays an important, if not dominant role. According to recent calculations by Melosh and Collins [1], the iron projectile that formed Meteor Crater (Arizona) deposited more than 2.5 times as much energy directly into the atmosphere than it carried to the surface (the projectile was estimated to have 9.0 megatons of kinetic energy at the top of the atmosphere, and only 2.5 megatons when it struck the surface).* Even more energy is coupled to the atmosphere from the surface explosion and hypervelocity debris that is ejected from the surface impact, [e.g. 2].

The 1994 impact of fragments of Comet Shoemaker-Levy 9 (SL9) on Jupiter underscored the role of atmospheric interactions. Because Jupiter is a gas giant with no solid surface, there was no "impact" in the traditional sense. Nevertheless, at a collision velocity of 60 km/s, the specific kinetic energy density of each fragment was about 2×10^9 J/kg. The amount of energy in a half ton of TNT was carried into the Jovian atmosphere by every kilogram of the comet. When each fragment reached a depth where the density was sufficiently high for the aerodynamic pressure to exceed the strength of the cometary material, it experienced catastrophic breakup which caused an exponentially reinforcing feedback between the radial expansion (which increases drag), and dynamic pressure (which drives radial expansion). As the fragments plunged into the exponentially dense atmosphere, they experienced stresses and strain rates similar to those associated with a hypervelocity impact onto a solid surface. This sequence has come to be known as the "pancake model" in the literature, because of the rapid flattening of the projectile. The rate of conversion from kinetic to internal energy was comparable to chemical energy release from a high explosive, resulting in an event that was indistinguishable from a detonation. The observed phenomena associated with SL9 demonstrated the enormous destructive potential of airbursts from exploding comets or asteroids, and stimulated more research on analogous events in Earth's atmosphere.

The vast majority of objects that collide with the Earth exhibit behavior somewhat like the fragments of SL9—they never reach the ground intact because they are too small. About 50 meteoroids with diameters of larger than 10 cm enter the atmosphere every day [3]. A few of these break up into fragments that are strong enough to be decelerated without exploding, and survive to strike the surface at low velocity as meteorites. Objects larger than about 2 meters enter the atmosphere several times per year. Most of these completely disintegrate in the upper atmosphere, generating a high-altitude airburst with an explosive energy exceeding about 1 kiloton. Only asteroids larger than 20 m or so in diameter are capable to penetrating at hypervelocity into the lower atmosphere (the lower stratosphere or troposphere), where they generate megaton-scale explosions. This happens about once per century on average. Such an explosion could cause property damage or loss of life if it occurred over a populated area, but a recent report suggests that the greatest associated hazard is that it could be misinterpreted as an act of aggression, potentially leading to a dangerous response [4].

The 1908 Tunguska event in Siberia is the only clear example of a megaton-scale low-altitude burst witnessed in modern times, and has provided an anchor point for assessments of the impact hazard. Recent estimates of the Tunguska magnitude have varied widely, from a high value of about 700 megatons [5] to a low value of 3 to 5 megatons [6]. The most widely quoted magnitude range is

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*Units of kilotons or megatons are often used in the planetary impact literature to quantify the initial kinetic energy of projectiles. One megaton is 4.184×10^{15} J.

between 10 and 40 megatons [7] based on historic barograms, seismic records, and forest damage. The yield estimates were derived by comparing data from the Tunguska event to similar data from the nuclear weapons effects literature. For the past 15 years, the consensus has placed the yield at the low end of this latter range–at 10 to 15 megatons–partly because of the low probability of a rare large event happening within the last century. According to Brown et al. [3], only one 10-megaton event should occur per millennium, on average, and a more recent analysis of the rapidly increasing catalog of small asteroids by Harris [8] suggests that the flux of Tunguska-scale objects is even lower, perhaps by a factor of two. This latter result has led the community to be more willing to accept the low-end estimates [4]. For this reason, we have re-examined the physical basis for why the Tunguska event could have been a 5-megaton or smaller airburst.

Earth and planetary scientists are beginning to recognize the role that airbursts may have played in geologic history. Tunguska-scale airbursts do not leave any obvious traces in the geologic record. Had Tunguska not been witnessed, it may have never been recognized and studied by the scientific community in later years. Strong and dense asteroids in this size range can reach the ground with more than half of their initial velocity, even while dissipating more than half their kinetic energy into the atmosphere. In this sense, the Meteor Crater event can be considered as a low-altitude airburst, which happened to include a residual ground impact at low velocity, with a fraction of its initial kinetic energy and mass [1]. Airbursts much larger than Tunguska are sufficiently energetic to melt surface materials by radiative heating [9]. Several researchers have suggested that melting and rapid quenching may have left evidence in the form of layered tektites or Libyan Desert Glass [10, 11] or other fused materials that have not yet been recognized by geologists because they are not associated with impact structures. Putative impact glasses continue to be discovered, [e.g. 12, 13]. These glasses may have also been formed by airbursts. We have performed preliminary numerical simulations intended to provide insight into the phenomenology associated with large low-altitude airbursts.

2. Tunguska

The explosive yield of the Tunguska event has been estimated from observational data and is constrained by nuclear tests, laboratory experiments, and numerical models. Primary observational data include 1) the extent and pattern of treefall, 2) seismic records, 3) barograph records, and 4) extent of burned area. The nuclear weapons effects literature [e.g. 14] has provided the principal means for determining the magnitude of a point-source explosion that would be required to generate the observed phenomena. Chyba et al., [15] used the pancake model [16] to constrain the range of impactor size, strength, and kinetic energy based on the physics of atmospheric entry, ablation, deformation, and fragmentation. Taken together, the published evidence all appears to be consistent with a 10 to 15 megaton event. However, high-resolution hydrocode simulations have provided the means to discover and examine emergent phenomena–i.e. effects that may not be obvious from first principles considerations–that had not been considered by previous workers. The results of simulations, combined with a reexamination of the surface conditions at Tunguska in 1908, reveal that several assumptions from the earlier analyses have led to erroneous conclusions, resulting in an overestimate of the size of the Tunguska event. We argue that the yield could actually be 5 megatons or lower.

One of the assumptions has been that Tunguska can be treated as a point-source explosion, and that nuclear weapons effects provide good calibration. This assumption would seem to have good justification: observations and models of atmospheric entry demonstrate that energy deposition is sharply peaked and concentrated within a scale height of the atmosphere [15]. However, the wake of the entry creates a low-density, high-pressure channel from the point of maximum energy all the way out of the atmosphere, so the explosion is highly anisotropic and directed upward and outward. The resulting high-velocity plume can rise hundreds of kilometers into space for a Tunguska-scale impact [6] much like the plumes that were generated by the impact of fragments of Comet Shoemaker-Levy 9 on Jupiter in 1994 [e.g. 17]. A second (implicit) assumption has been that downward advection of the explosion can be neglected. In the pancake model, the energy deposition is sharply peaked because of the exponentially reinforcing effects of impactor deformation and atmospheric drag. This peak has been called "airburst height" [15] and is generally considered the altitude at which a point source explosion of the same yield would have a similar effect on the ground. This assumption neglects the fact that the mass of the projectile is still traveling downward at a significant fraction of its initial speed at the time of its maximum energy loss. Simulations demonstrate that the resulting fireball continues to descend rapidly through the atmosphere, driving a shock wave ahead of it as it moves downward at supersonic velocities. In some simulations, a ring vortex forms, reducing drag forces so that the fireball continues descending, carrying high temperature air and vaporized meteoritic material to much lower altitude than the simple point source assumptions would suggest, before it loses its remaining momentum and begins to rise due to buoyant forces. Sufficiently large impactors penetrate the atmosphere so deeply before deforming, fragmenting, and exploding, that the resultant fireball reaches the surface before losing the remainder of its momentum (shown schematically in Fig. 1).

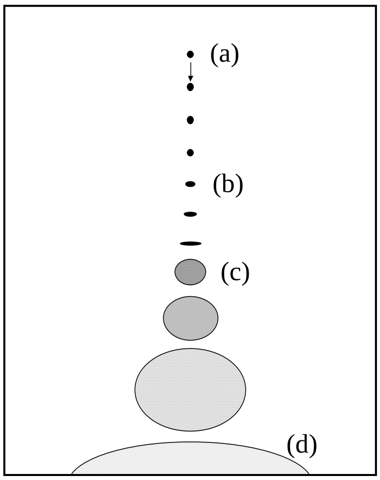

Fig. 1. Schematic diagram of a low-altitude airburst. (a) Asteroid enters the upper atmosphere and is subjected to aerodynamic drag and ablation; (b) Aerodynamic stress exceeds asteroid strength, deforming it and increasing its cross-sectional area; (c) Asteroid breaks into fragments which rapidly ablate, forming a high-temperature fireball; (d) Fireball continues to descend to surface where it is held in contact for some period of time by its own inertia.

Boslough and Crawford [6] listed several reasons to be skeptical of estimates that are based on comparisons between the observed damage to the forest at Tunguska and the criteria for blast effects established by the nuclear weapons literature. Yield estimates based on treefall are too high because they account neither for topography nor forest health. Comparison to nuclear weapon effects is a reasonable approach, but it is important to recognize the limitations associated with using the weapons tables for treefall, which apply to living coniferous forests and implicitly assume that the surface is flat. Scientific and popular accounts of the Tunguska event state that the forest was flattened over an area of 2000 km^2. However, old photographs of the destruction show that many trees were left standing. These photographs, as well as contour maps, also reveal that slopes of 15º and greater are typical of the terrain around the impact site (Fig. 2).

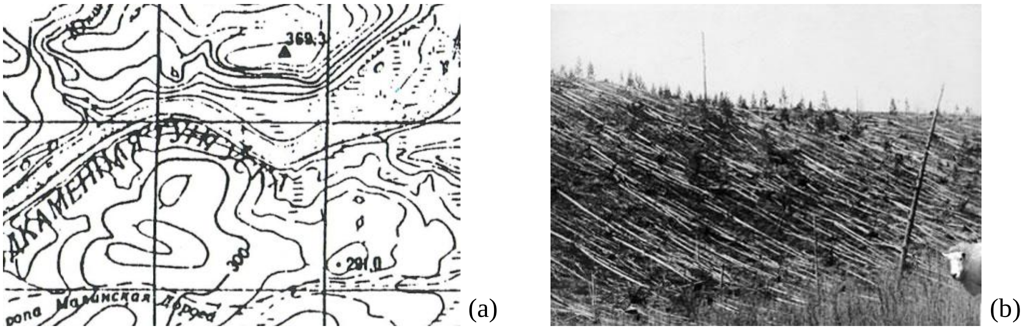

Fig. 2. (a) Area near Tunguska epicenter shows significant topographic variation (b) the most dramatic photographs from the 1927 Tunguska expedition showed treefall along ridges.

The topography at Tunguska would naturally lead to concentrations of blast wave energy far beyond the distance that would be calculated assuming flat terrain. To illustrate this phenomenon, we ran a simulation of a 5 megaton point source at an altitude of 10 km, and compared the resulting wind speed at the top of a 115-m high ridge compared to that on flat ground on either side (Figs. 3, 4).

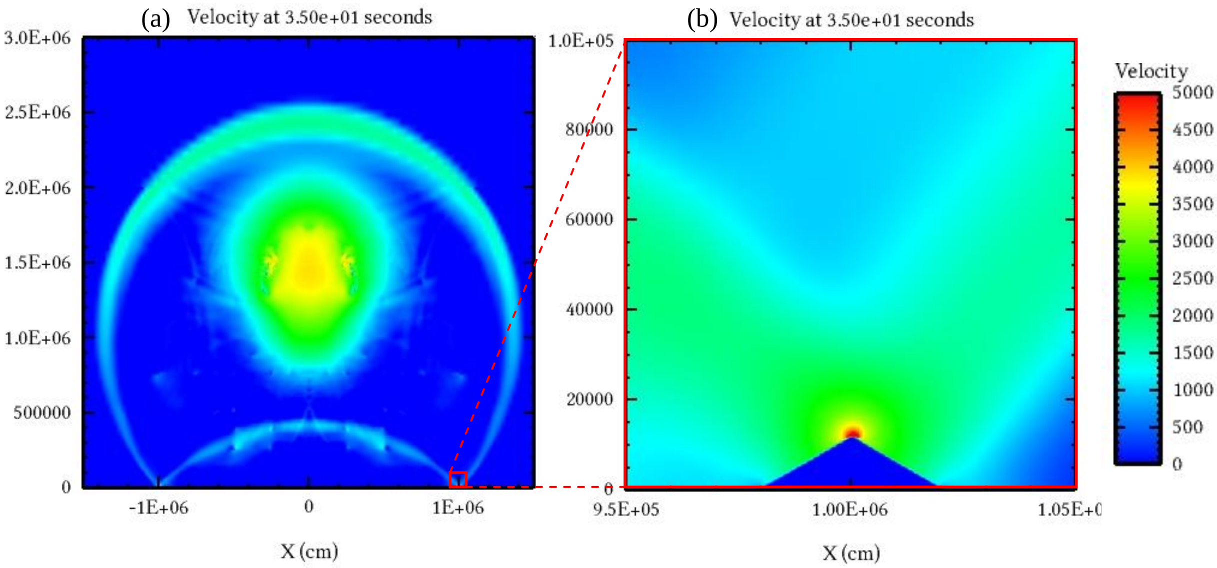

Fig. 3. (a) Five megaton point-source explosion, 35 seconds after initiation at 10 km (velocity scale is cm/s). Primary and reflected shocks are visible, and fireball has risen buoyantly to 15 km. (b) Ridge effect at 10 km from ground zero, as primary and reflected waves pass over a ridge, wind speed (and dynamic pressure) are enhanced.

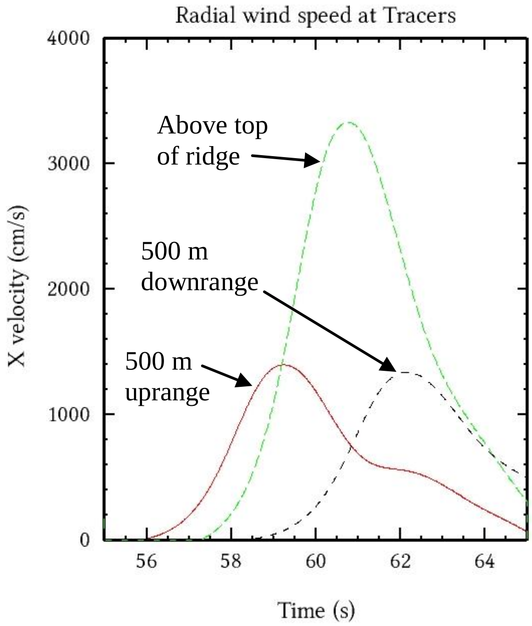

Fig. 4. Wind velocity histories for three locations near a ridge 20 km from ground zero. Wind speed peaks at 33 m/s above ridge (sufficient to blow over weak trees), but only 14 m/s for a point 500 m closer to epicenter.

Another reason to be skeptical of treefall-based yield estimates is that none of them take into account the pre-impact condition of the Siberian forest at the site of the explosion. One result of K.P. Florenskiy's 1961 expedition to the site was that "the region of the forest flattened in 1908 was not one of homogeneous primeval intact taiga," and that "…the region of meteorite impact in 1908 was basically a fire-devastated area… a partly flattened dead and rotting forest was standing in this area…" According to Florenskiy [18], "…an estimate of the force of the shock wave that is based on the number of flattened trees must necessarily take into consideration the condition of the forest at the time." If the requisite wind speeds are reduced to be consistent with Florenskiy's dynamometer measurements, then the necessary point-source yield is reduced to 3.5 megatons [6].

Energy estimates based on coupling to seismic and air waves can be grossly in error if naive assumptions are made. The source of seismic waves from Tunguska is estimated to be a vertical point impulse of 7×10^{18} dyn s [19]. Turco et al. [5] assumed that this entire pulse of momentum had to be attributed as the momentum of the impacting body, leading them to the conclusion that the impactor energy was about 700 megatons. By contrast, Ben-Menahem [19] arrived at 12.5 megatons by equating the vertical impulse to that from a nuclear explosion (the explosion itself conserves momentum, but the downward directed impulse is coupled to the seismic wave). Momentum multiplication is a well-known effect for crater-forming impacts on a solid surface, given that the ejected material provides a reaction force in addition to the stopping of the projectile [e.g. 20]. Momentum enhancement can also be an effect of large impact-produced airbursts, because the ejection of a hypervelocity plume of air into space creates a transient load on the surface that can also couple to seismic waves. Boslough and Crawford [6] suggested that a 3 megaton plume-forming impact could generate a sufficiently large impulse to generate the seismic signal from Tunguska.

Shoemaker [21] likewise assumed a point source explosion approximation to estimate the yield based on inertia-gravity waves in the atmosphere. For Tunguska, the collapsing plume would couple approximately the same momentum back into the atmosphere that the plume originally coupled to seismic waves when it was ejected (but about 10 minutes later, and over a much different time and spatial scale). Boslough and Crawford [6] also suggested that the bright skies widely observed over Europe and Asia following the Tunguska explosion provides independent evidence for a collapsed plume. Artemieva and Shuvalov [22] have performed simulations that support this view, but it has not yet gained full acceptance. For example, Bronshten [23] still prefers the long-standing hypothesis that the bright nights were caused by a comet tail associated with the impact.

3. Tunguska Simulations

The primary motivation for revisiting Tunguska with new simulations is the expectation that significant impact energy is advected downward within the exploding fireball. A simplified pancake model (ignoring gravity and Earth's curvature) is described by a set of coupled differential equations for the aerodynamic drag, heat transport and ablation, and hydrodynamic deformation of the projectile:

$$m\frac{dv}{dt} = -\tfrac{1}{2}\, C_D \rho A v^2 \qquad (1)$$

$$q\frac{dm}{dt} = -\tfrac{1}{2}\, C_H \rho A v^3 \qquad (2)$$

$$\mathrm{r}\frac{d^2 r}{dt^2} = -\tfrac{1}{2}\, C_D \frac{\rho}{\rho_m} v^2 \qquad (3)$$

where m, v, A, q, and ρ_m are the instantaneous mass, velocity, cross-sectional area, heat of ablation, and density of a projectile, and ρ is the atmospheric density (which falls off exponentially with altitude). C_D and C_H are the drag coefficient and heat transfer coefficient, respectively. We solved these equations numerically for a stony asteroid using the parameters of Chyba et al. [15] for the stony asteroid they believe comes closest to consistency with the observations at Tunguska. An initial velocity of 15 km/s, radius of 29 m, and density of 3.5 g/cm^3, and entry angle of 45º (representing a 15 megaton impact for the right circular cylindrical geometry assumed by the pancake model), yields the energy deposition and velocity curves of Fig. 5. The maximum energy deposition of about 2 megatons/km is reached at about 9 km above the surface, at which time the asteroid is still descending at a velocity of about 9 km/s.

Our series of Tunguska-scale airburst simulations used the Eulerian shock-physics code CTH. The primary goal of this research was to explore parameter space in an effort to develop a qualitative understanding, from which new models can be developed that more properly capture the physics. We ran dozens of simulations in which we varied size, impact energy, and material properties (strength and density) over a wide range of values. We used adaptive mesh refinement to sufficiently resolve the entry dynamics while still spanning the entire atmosphere of interest. We performed simulations using

2-D axial symmetry, which allowed the quick turn-around times needed for scoping and sensitivity analysis. We found phenomena that emerged regardless of the assumptions, over a large range of realistic values. We have selected three representative simulations to present here. In all these illustrative cases, we modeled the asteroid as a porous dunite sphere that vertically enters the gravitationally stabilized Earth atmosphere. These simulations all used an entry velocity of 20 km/s. Initial masses were adjusted so that initial kinetic energies were 3.0 megatons.

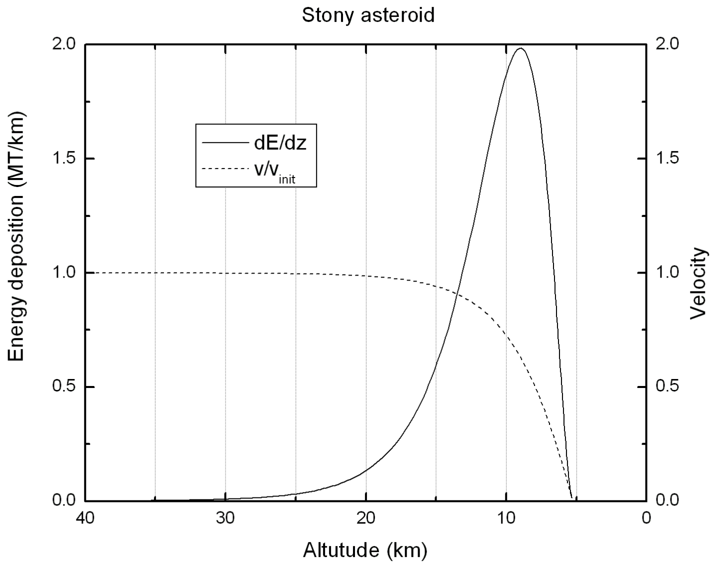

Fig. 5. Results of pancake model calculation for a 15 megaton stony asteroid showing maximum energy deposition at 9 km altitude. As the crushed asteroid explodes at this “airburst altitude” it is still moving downward at 9 km/s (60% of its initial velocity).

In order to examine the post-airburst hydrodynamics, we added an additional internal energy source term that initiated the explosion at a prescribed altitude. Over the span of several computational time steps, we added 2.0 megatons to the asteroids, bringing the total energy associated with the impacts to 5.0 megatons. The resulting energy density of the asteroid causes it to instantly vaporize, lose strength, and expand as a fireball while maintaining its downward momentum. We chose to detonate the asteroid in this way because it provided an extreme case to provide a bound on phenomena associated with rapid fragmentation, ablation, and explosion of the object. The justification for a nearly instantaneous conversion of kinetic to internal energy of the disintegrating body is made by Svetsov [24], who showed that a Tunguska-scale stony asteroid can be disrupted by the peak aerodynamic load into fragments smaller than 10 cm, which are totally ablated by the high-temperature fireball.

As the fireball descends at hypersonic speed, its translational motion continues to drive a downward bow shock, which is reinforced by its radial expansion. This contrasts with descriptions in much of the Tunguska literature, which describe a “ballistic wave” (the bow shock) and “explosion wave” as being two distinct phenomena [e.g. 25]. In reality, there is only one wave but it obtains its energy from both directed and radial components of kinetic energy. Fig. 6 shows snapshots for each of the simulations, a few seconds after the explosion energy was sourced at the specified altitude. At this time, the explosion-reinforced bow shock takes on a spherical shape, which can be used to determine the apparent airburst altitude (as opposed to the altitude where the explosion was initiated). In all cases the height of the apparent airburst is significantly lower than the point of maximum energy deposition. Notably, the fireball penetrates more deeply for the 15 km explosion than for the 10 km explosion.

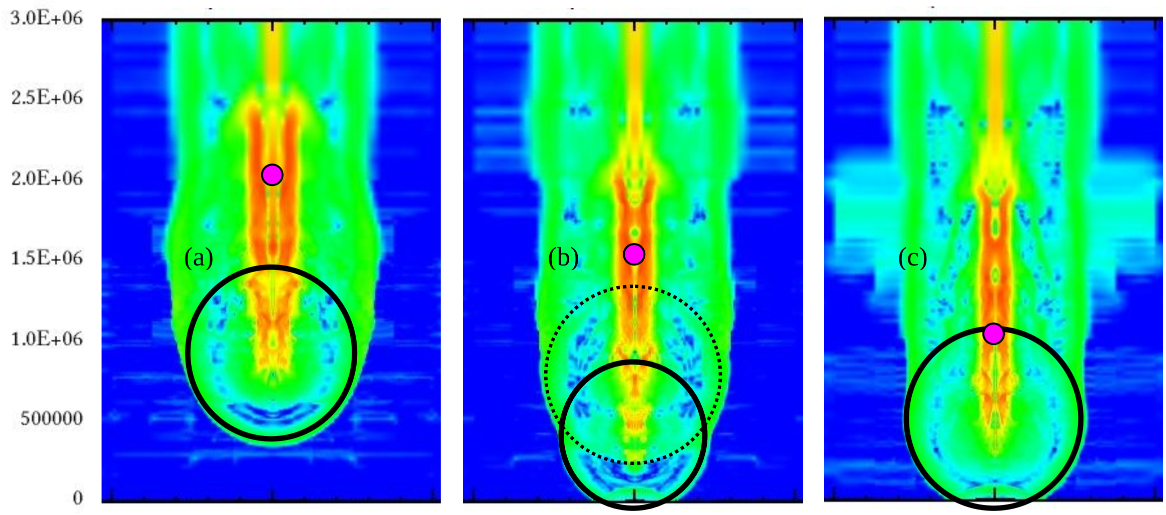

Fig. 6. Snapshots from three simulations of 5-megaton bursts where asteroid explodes at (a) 20, (b) 15, and (c) 10 km about the surface. Magenta dot marks locations at which 2.0 megatons of energy was sourced. Spherical shape of low-altitude blast wave is centered on apparent airburst altitudes of 9, 4, and 5 km, respectively. In some cases, such as (b), there are multiple apparent burst altitudes. Velocity shading is used to enhance visibility of shock wave.

One unanticipated result is the formation of a large ring vortex, which is initiated by the rapidly descending air mass in some cases. When such a vortex forms, it reduces the aerodynamic drag between the fireball and the surrounding air, allowing the hot mass to reach a lower altitude before stopping. It appears from our preliminary simulations that vortex formation is related to perturbations in the large-scale hydrodynamic flow, and may be chaotic in nature. If this is true, then the effects on the ground may strongly depend on the chaotic nature of the fragmentation process that determines the macroscopic flow pattern, adding to the inherent statistical uncertainties in the hazard associated with low altitude airbursts. These results suggest that the pancake model needs to be modified to include a "post-burst" phase that more properly accounts for the reduced drag on a rapidly expanding, rapidly descending fireball.

4. Large glass-forming airbursts

Most natural glasses are volcanic in origin and have chemical compositions consistent with equilibrium fractional melting. The rare exceptions are tektites and glass in melt sheets formed by shock heating associated with the hypervelocity impact of a comet or asteroid. Recent work has explored the possibility that large low-altitude airburst explosions have been responsible for creating deposits of enigmatic glass that appears to be produced by impact but does not seem to be melted by high-pressure shock waves. Unlike most tektites, which exhibit aerodynamic shapes consistent with hypervelocity traversal of the atmosphere, the Muong-Nong tektites of Southeast Asia and the Libyan Desert Glass of western Egypt have a layered structure, suggesting that they experienced laminar flow and sedimentation, and probably formed in place. The chemical composition of these glasses eliminates any possibility of a volcanic origin, and the large areal extents (690,000 km^2 for the Muong-Nong tektites and up to 6500 km^2 for the Libyan Desert Glass) had been somewhat of a mystery. If they had formed as a coherent melt sheet by the process of direct shock melting, their area would be limited to the size of the crater in which they formed. Moreover, no impact structure has been found in association with either of these glass deposits, although it is not unreasonable to expect that a crater could be eroded or buried under sediment.

Wasson [11] considered the possibility of large aerial bursts in the range of 10^{19} to 10^{20} J (roughly 10^3 to 10^4 megaton). One impact of that magnitude takes place every hundred thousand years or so on average [8]. By estimating the amount of energy necessary to provide sufficient heat to the atmosphere, Wasson suggests that the Muong-Nong (layered) tektites would require an impactor energy of 6.5×10^{21} J and all of it would have had to be coupled directly to the atmosphere. Wasson cites constraints on impactor size provided by Ir concentrations in the fallout from this event, concluding that this projectile would have had to be a comet. In Wasson's scenario, a combination of an oblique entry angle and low strength would be necessary conditions for most of the comet's energy to be deposited in the atmosphere. However, observations of Earth-crossing comets suggest that they do not impact the Earth frequently enough to make this plausible for an event that happened less than a million years ago (the age of these tektites is only 0.78 Ma). Only 3 comets cross Earth's orbit every year, on average, most of which are in the 1-2 km diameter range required by Wasson. This flux is consistent with an impact frequency of only one per 150 million years [8]. A low-probability oblique impact reduces the likelihood of such an event even further, virtually eliminating it as a plausible explanation.

Wasson's assumption, however, was that the entire atmosphere would have to be heated–from top to bottom–over a significant fraction the entire area of the melt sheet to a temperature of 2500 K. However, if the requirement is a radiatively-melted surface, there is no need for the atmosphere to be at high temperature of the entire area simultaneously. When the high-temperature fireball produced by a low-altitude airburst expands, it temporarily displaces the colder, higher-density atmosphere. Moreover, the most common elevation angle for an asteroid impact is 45º, and our airburst simulations suggest that the fireball will retain a significant fraction of the initial momentum of the asteroid (perhaps in a low-drag configuration enhanced by a ring vortex). In this way, the expanding fireball can move horizontally for a long distance, passing over and heating an area many times larger than itself. Perhaps a better estimate of the magnitude of the required yield would be from the mass of the glass itself. Wasson estimated the mean thickness of the sheet to be about 4 mm, with a total mass of about 10^{16} g, which would require the influx of roughly 10^{19} J to heat and completely melt. A chondritic asteroid with a mass of 1.5×10^{15} g is consistent with the Ir concentrations [26]. The impact frequency for asteroids of this size is about one per million years, so the likelihood of an oblique impact at 0.78 Ma is reasonable. An asteroid of that size impacting at 20 km/s would only need to transfer 3% of its kinetic energy through the atmosphere into the ground as heat to melt the requisite volume. Significantly, such a small fraction of energy required for coupling to the atmosphere does not eliminate the possibility of a crater-forming event that was accompanied by an airburst.

The 29 million-year-old Libyan Desert Glass (LDG) represents another candidate material that may have formed by radiative melting from a low-altitude airburst. Unlike the SE Asian tektites, LDG fragments have probably been transported laterally over long distances since they were formed, so it is not necessary to invoke a hot atmosphere that spans the entire area in which they are found. The LDG is composed of 98% SiO_2 and has a composition similar to that of the sandstone bedrock and dune sands of the Great Sand Sea where it is located. The physical structure of the glass fragments provide clues to how it was formed, and do not appear to be consistent with either shock melting at high pressure or hypervelocity traversal of the atmosphere. Some fragments are yellow-green and highly transparent with embedded bubbles that are highly elongated along an apparent flow axis, while others are opaque and white, giving the appearance of foam (Fig. 7). Microscopic examination of the white glass reveals dense spherical bubbles about 100 microns in diameter, suggesting that air was injected during frothy, turbulent flow of a very low-viscosity liquid. Many pieces show streaks of darker material, often aligned in the apparent flow direction. Koeberl [27] has shown that at least some of this darker material has a meteoritic component.

Fig. 7. Examples of clear and frothy specimens of Libyan Desert Glass

There is no known impact structure in the immediate vicinity of the LDG. However, Kleinmann et al. [28] have shown that local sandstones have been strongly shocked, so there is unambiguous evidence for a solid crater-forming impact. The question is whether the surface impact represented a significant fraction of the energy deposition and if it had anything to do with glass formation. To help answer this question, we performed CTH simulations with adaptive mesh refinement of the atmospheric entry of a 120-meter-diameter sphere of dunite. With an initial velocity of 20 km/s, the asteroid had a kinetic energy of about 108 Megatons. Even at vertical incidence, most of the energy is coupled directly into the atmosphere as the asteroid ablates and explodes before it hits the ground. In this case, the resulting fireball (which contains air and ablated meteoritic material at temperatures exceeding the melting temperature of quartz) makes direct contact with the surface over a 10 km diameter area for more than 10 s after the explosion (Fig. 8). Where the fireball comes into contact with the ground, wind velocities exceed the sound speed for tens of seconds.

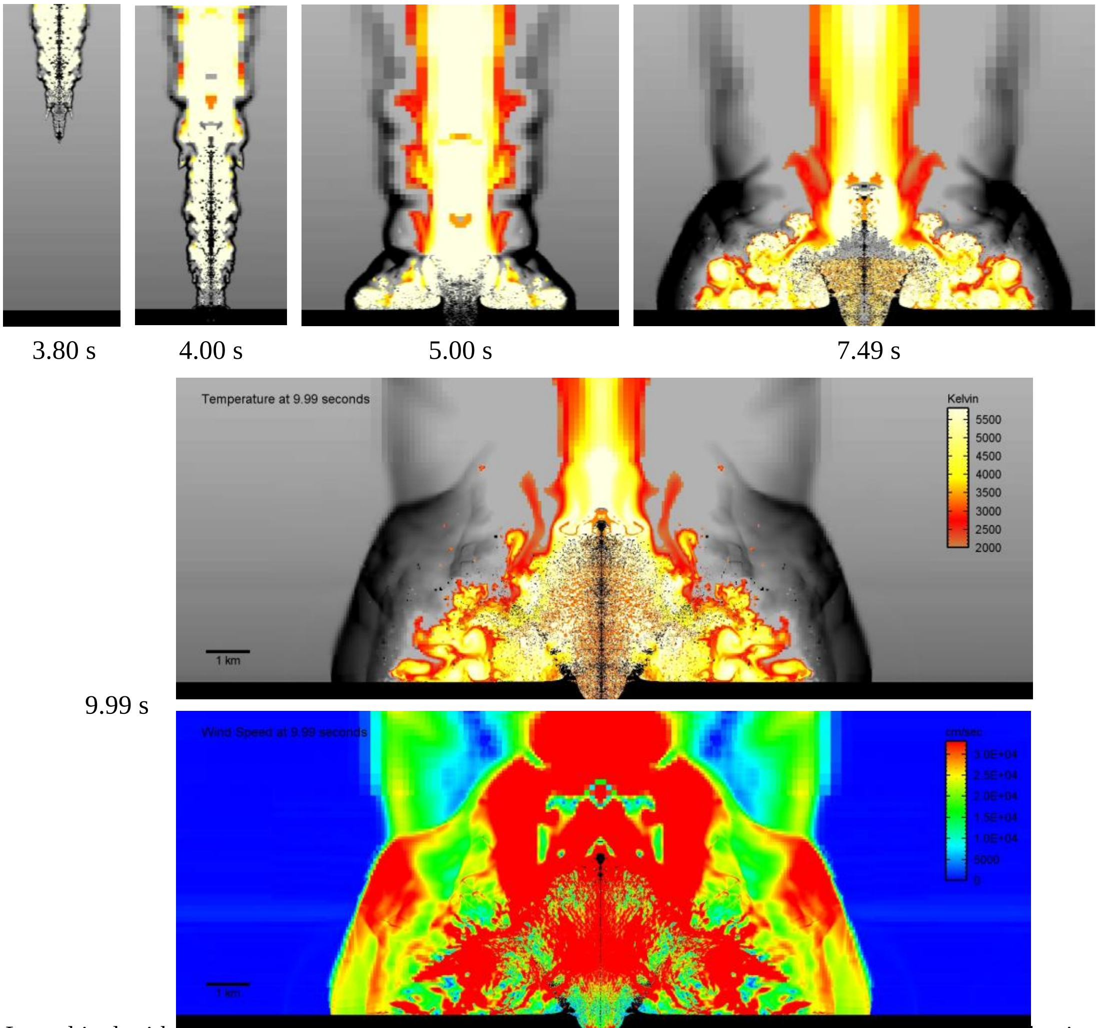

Fig. 8. Low-altitude airburst for which the fireball descends to the surface. Top two rows show temperature and density shading. White represents 5800 K, the approximate surface temperature of the sun. Red represents 2000 K, the approximate melting temperature of quartz. Bottom image shows particle velocity. Red represents supersonic wind speeds.

The results of this simulation seem to provide answers to two oft-cited objections to the airburst hypothesis. First, is the question of how bubbles of significant size could have escaped a viscous fluid (LDG is nearly pure silica, which is remains highly viscous at elevated temperature). Friedman and Parker [29] measured the high-temperature viscosity of LDG and calculated that bubble removal would require a temperature of 1600 ºC for 47 days, 1800 ºC for 0.5 day, or 2000 ºC for 2 minutes. They preferred and explanation that invoked a very high temperature for a very short time. Since the postshock temperatures in silica can achieve these high levels for a hypervelocity impact [e.g., 30] the preferred explanation has remained with direct shock melting. However, direct exposure to a 5000 K fireball would raise the temperature of the melt beyond those considered by Friedman and Parker [29], further lowering its viscosity and easing the constraint on time required, The second objection is that the observed sizes of LDG fragments (>10 cm) greatly exceeds the thickness of silica that could be heated by a 10 second pulse of radiation. A simple diffusion calculation suggests that a layer of only a few mm could be heated above the silicate melting temperature [e.g., 9] However, this calculation neglects the fact that in a low-altitude airburst, the surface materials will be subjected to supersonic winds at the same time as the thermal pulse, and any melt layer will be ablated. Repeating the diffusion calculation, discarding any material above the melt temperature and re-applying a flux condition to the new boundary suggests that several cm can be ablated. It is reasonable to expect that melt would blow downrange where it would collect in pools and form glass with larger dimensions.

5. Conclusions

Low-altitude airbursts are by far the most frequent impact events that have an effect on the ground. The next impact on Earth that causes casualties or property damage will almost certainly be a low-altitude airburst. The simulations and interpretations presented here suggest that current models for effects on the ground from such events are inadequate, and that low-altitude airbursts are more damaging than point-source estimates and comparison to nuclear weapons effects would indicate. Hydrocode simulations have identified emergent phenomena, such as downward-directed ring vortexes and upward-directed atmospheric plumes that need to be included in models to fully assess both the impact hazard and the evidence in the geologic record. The pancake model can be extended to account for ring vortex formation, buoyant forces, and surface interactions of the fireball, from which better estimates of air blast and radiative damage zones can be made over the range of possible airburst scenarios. The capability of high-performance computers will soon make new research possible, such as a full 3-D simulation of various Tunguska scenarios using a high resolution model of the actual topography of the site. Comparing simulated damage maps to the actual data should provide much tighter and more convincing constraints on the low-altitude airburst at Tunguska.

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References

[1] Melosh HJ, Collins GS. Meteor Crater formed by a low-velocity impact. *Nature*, 2005; **434**: 157.
[2] Schultz PH. Atmospheric effects on ejecta emplacement. *J. Geophys. Res*., 1992; **97**: 11,623-11,662.
[3] Brown P, Spalding RE, ReVelle DO, Tagliaferri E, Worden SP. The flux of small near-Earth objects colliding with the Earth. *Nature*, 2002; **420**: 294-296.
[4] 2007 Planetary Defense Conference White Paper: Summary and Recommendations, http://www.aero.org/conferences/planetarydefense/documents/WhitePaper.pdf, 2007.
[5] Turco RP, Toon OB, Park C, Whitten RC, Pollack JB, Noerdlinger P. An analysis of the physical, chemical,

optical, and historical impacts of the 1908 Tunguska meteor fall. *Icarus*, 1982; **50**: 1-52.

[6] Boslough MBE, Crawford DA. Shoemaker-Levy 9 and plume-forming collisions on Earth. *Near-Earth Objects, Annals NY Acad. Sci.*, 1997; **822**: 236-282.

[7] Vasilyev NV. The Tunguska meteorite problem today. *Planet. Space Sci.*, 1998; **46**(2/3): 129-150.

[8] Harris A, personal communication, 2007.

[9] Svetsov VV. Thermal radiation on the ground from large aerial bursts caused by Tunguska-like impacts (abstract). *Lunar and Planetary Science XXXVII*, Lunar and Planetary Institute, Houston, 2006.

[10] Wasson JT, Boslough MBE. Large aerial bursts; an important class of terrestrial accretionary events (abstract). *LPI Contribution 1053: Catastrophic Events and Mass Extinctions: Impacts and Beyond*, Lunar and Planetary Institute, Houston, 2000; 239-240.

[11] Wasson JT. Large aerial bursts; an important class of terrestrial accretionary events. *Astrobiology*, 2003; **3**(1): 163-179.

[12] Schultz PH, Zárate M, Hames WE, Harris RS, Bunch TE, Koeberl C, Renne P, Wittke J. The record of Miocene impacts in the Argentine Pampas. *Meteoritics*, 2006; **41**(5): 749-771.

[13] Osinski GR, Schwarcz HP, Smith JR, Kleindienst MR, Haldemann AFC, Churcher CS. Evidence for a ~200–100 ka meteorite impact in the Western Desert of Egypt. *Earth Planet. Sci. Lett*, 2006; **253**(3/4), 378-388.

[14] Glasstone S, ed. *The Effects of Nuclear Weapons*, U.S. Dept. of Defense/Dept. of Energy, Washington DC, 1977; 653 pp.

[15] Chyba CF, Thomas PJ, Zahnle KJ. The 1908 Tunguska explosion: Atmospheric disruption of a stony asteroid. *Nature*, 1993; **361**: 40-44.

[16] Zahnle KJ. Airburst origin of dark shadows on Venus. *J. Geophys. Res*., 1992; **97**(E6): 10,243-10,255.

[17] Crawford DA. Comet Shoemaker-Levy 9 fragment size estimates: how big was the parent body? *Near-Earth Objects, Annals NY Acad. Sci.*, 1997; **822**: 155-173.

[18] Florenskiy KP. Preliminary results from the 1961 combined Tunguska meteorite expedition. *Meteortica*, 1963; **XXIII**: 3-37.

[19] Ben-Menahem A. Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations. *Phys. Earth Planet. Inter*., 1975; **11**(1): 1-35.

[20] Lawrence RJ. Enhanced Momentum Transfer from Hypervelocity Particle Impacts. *Int. J. Impact. Engng.*, 1990; **10**: 337-349.

[21] Shoemaker EM. Asteroid and comet bombardment of the Earth. *Ann. Rev. Earth & Planet. Sci.,* 1983; **11**: 461-494.

[22] Artemieva N, Shuvalov V. 3D effects of Tunguska event on the ground and in atmosphere (abstract). *Lunar and Planetary Science XXXVIII*, Lunar and Planetary Institute, Houston, 2007.

[23] Bronshten VA. Nature and destruction of Tunguska cosmical body. *Planet. Space. Sci*., 2000; **48**(9): 855-870.

[24] Svetsov VV. Total ablation of the debris from the 1908 Tunguska explosion. *Nature*, 1996; **383**: 697-699.

[25] Zotkin IT, Tsikulin MA. Simulations of the explosion of the Tungus meteorite. *Sov. Phys. Dokl., English Translation*, 1966; **11**: 183-186.

[26] Schmidt G, Zhou L, Wasson JT. Iridium anomaly associated with the Australasian tektite-producing impact: Masses of the impactor and of the Australasian tektites. *Geochim. Cosmochim. Acta*, 1993; **57**: 4851-4859.

[27] Koeberl C. Confirmation of a meteoritic component in Libyan Desert Glass from osmium isotope data (abstract). *63rd Annual Meteoritical Society Meeting*, 2000.

[28] Kleinmann B, Horn P. Langenhorst F. Evidence for shock metamorphism in sandstones from the Libyan Desert Glass strewn field. *Meteoritics & Planet. Sci.*, 2001; **36**: 1277-1282.

[29] Friedman I, Parker CJ. Libyan Desert Glass: its viscosity and some comments on its origin. *J. Geophys. Res*., 1969; **74**: 6777-6779.

[30] Boslough, MB. Postshock temperatures in silica. *J. Geophys. Res*., 1988; **93**: 6477-6484.