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Tunguska Workshop: Applying Modern Tools to Understand the 1908 Tunguska Impact

David Morrison
Ames Research Center, Moffett Field, California

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Abstract

A one-day workshop was held at NASA Ames Research Center, January 16, 2018, to re-examine the 1908 Tunguska impact using modern computational tools, many of them developed in response to the 2013 Chelyabinsk airburst. Twelve international experts gave presentations, with another 40 attending in-person or remotely. The most likely models for Tunguska converged on an energy of 10-20 Megatons, released in an airburst at a height of about 10 km. If the Tunguska impactor was a stony asteroid similar to Chelyabinsk, the diameter was roughly 50-80m. A comparison with current understanding of the population of asteroids in this size range indicates that the interval between such events is millennia, not centuries as had been concluded previously. The primary constraints on our understanding of Tunguska are the dearth of quantitative data, not weakness of the computational models. The workshop was sponsored by the NASA Ames Asteroid Threat Assessment Project and supported the NASA Planetary Defense Coordination Office.

Introduction

The 1908 cosmic impact in the Tunguska region of Siberia has intrigued the public and puzzled scientists for more than a century. This event has generally been attributed to the airburst impact of either a comet (an object rich in ice and other frozen volatiles) or a stony asteroid. It has also attracted the attention of fringe enthusiasts, mainly in Russia, who have proposed bizarre explanations including a nuclear explosion, a rare kind of volcanic explosion, an antimatter impact, and the crash of an alien spacecraft.

Unfortunately, no fragments of the exploding object have been recovered, perhaps because it fell in a boggy area, and there is no impact crater. The first scientific survey was not carried out until two decades after the event. The data consist primarily of the distribution of fallen and burned trees and the topography at the site, a handful of eye witness accounts mostly from tens of kilometers (or greater) distance, seismic records, an atmospheric pressure wave (infrasound) that was measured around the world, and an atmospheric phenomenon called light (or white) nights that persisted for several nights in northern Europe.

Now is a good time to re-examine Tunguska. In the twentieth century, it was the only known case of extensive damage from a cosmic impact, with energy estimates between 3 and 20 Mt (Megatons). In 2013, however, the Chelyabinsk bolide provided much more quantitative information on a destructive airburst, although with energy at least an order of magnitude less than Tunguska. The Chelyabinsk airburst has been extensively studied. Models are able to reproduce most aspects of this event, including the altitude where the exploding asteroid deposited most of its energy, the pattern of destruction on the ground, and the observed light curve. The insights and computational tools developed to understand Chelyabinsk can now be applied to Tunguska.

In January 2018, a workshop at NASA Ames Research Center brought together approximately 50 experts on impact airbursts to re-examine the Tunguska event in the light of recent work on Chelyabinsk. Approximately half of the attendance, and three of the presentations, were virtual. Co-Chairs were Donovan Mathias and David Morrison of Ames Research Center. This report briefly summarizes the presentations and conclusions from this workshop.

Background and Previous Work on Tunguska

The history of research in Russia on the Tunguska and Chelyabinsk airbursts was summarized by Natalia Artemieva (Planetary Science Institute), with Valery Shuvalov and Vladimir Svettsov. The primary *in situ* characterization of the Tunguska site was carried out by Leonid Kulik in a series of expeditions in the 1920s and 30s. Analog experiments by Zotkin & Tsikulin (1966) established that the airburst was not a simple point explosion. More recently, beginning with analyses of the 1994 crash of comet Shoemaker-Levy 9 into Jupiter, hydrocode computer models have been used to simulate airbursts, including Tunguska and Chelyabinsk (Artemieva & Shuvalov, 2016).

Russian researchers have characterized the Tunguska event as the oblique atmospheric entry of a stony object, with diameter 30-60 m, releasing an energy of 10-20 Mt. In the models, the projectile does not reach the surface, with total deceleration and vaporization at 6-8 km altitude. The sky was clear, facilitating radiative heating that started forest fires. Ejection of a plume consisting of vaporized rock and entrained atmospheric water to an altitude of about 100 km, together with expected upper atmosphere winds toward the north-west, is consistent with the observations of a bright sky in northern Europe for several nights after the impacts, as also proposed by Boslough and Crawford. Current Russian planetary defense efforts include calculation of hazardous effects on the surface and in the upper atmosphere from impacts by cosmic bodies with diameters from 20 m to 10 km.

Peter Jenniskens (SETI Institute), with Anna Kartashova, Olga Popova, and Dmitry Glazachev, summarized the injuries and eye-witness accounts from Chelyabinsk and Tunguska. The primary hazards were caused by the shock wave (including collapsed buildings and knocked down trees) and thermal radiation (sufficient, in the case of Tunguska, to start forest fires). In the case of Chelyabinsk, they estimate that 1 percent of local inhabitants were injured (most not seriously), and about 2 percent of those outside in the open were “sunburned” by the radiant heat from the explosion. At Tunguska, which struck in a region of very low population density, fewer than a hundred anecdotal eye-witness reports are available, collected decades after the event. Breaking of windows from shocks was reported out to 200-300 km from impact, and burns to exposed skin out to 50 km. There are fairly reliable accounts of several deaths in nomad camps roughly 25 km from the impact epicenter (Popova, Jenniskens *et al.* 2013).

Sarah McMullan and Gareth Collins of Imperial College London compared three semi-analytical airburst models for both Chelyabinsk and Tunguska-scale impacts. The three models were the pancake model of Chyba *et al.* (1993), the debris cloud model of Hills and Goda (1993), and the chain reaction model of Avramenko *et al.* (2014). The pancake model treats the fragmenting meteoroid as a strengthless liquid, the debris cloud model treats it as an impenetrable cloud of small debris, and the chain reaction model considers a runaway cascade of fragmentation events. The latter model accounts for increasing fragment strength with decreasing fragment size. All models consider mass loss by ablation, but the chain reaction model is the only one to relate the mass loss to the cross-sectional area of the object.

Although the three models predict different rates of asteroid spreading and deceleration after the onset of fragmentation, each one can, with appropriate adjustment of parameters, fit the light curve and other data for Chelyabinsk. However, when scaled up to Tunguska, the results diverge, predicting higher burst altitudes than current estimates, with the pancake model penetrating most deeply. The models can be reconciled if the Tunguska impactor was considerably stronger than Chelyabinsk, and therefore able to penetrate deeper into the atmosphere before it disintegrated. The nature of the impactor and the parameters of the Tunguska airburst (such as height and energy) would need to be better known to differentiate clearly between the models.

Mark Boslough reviewed his previous impact models, calculated mostly before 2007 while he worked at Sandia National Laboratory (Boslough & Crawford, 1997). He abandoned the idea of a point explosion, like a nuclear bomb, and stressed the importance of including the downward momentum of the fireball, and also the production of an upward-moving buoyant plume. He concluded that the yield estimates for Tunguska based on the nuclear test literature may be too high by a factor of 3-4, since the impact fireball moves downward, while the nuclear fireball moves upward. Current simulations discussed below take this downward momentum into account. Boslough's estimate of the yield of Tunguska was (and remains) 3-5 Mt. This is lower than more recent estimates in part because of differences in assumptions about the forest health and the wind speeds required to topple trees.

Boslough noted the importance of considering the local topography and the condition of the forest. The damage estimates from nuclear tests (*e.g.,* Glasstone and Dolan, *The Effects of Nuclear Weapons*) were based on flat terrain and healthy trees. He also noted that there are many century-old trees still standing at Tunguska, and that some of these have retained burn scars from 1908. Further studies of the forest may therefore still be useful. If the coupling of the explosion to the air and ground are dominated by plume ejections and plume collapse as he thinks, the calibration of infrasound data from static nuclear explosions might produce misleading estimates of the energy yield of the Tunguska event.

Current Models of the Tunguska Event

Several presentations described the current work at NASA Ames in applying advanced computer models for asteroid airbursts (supported by access to the NASA Advanced Supercomputing facility). Darrel Robertson and Donovan Mathias began the workshop with a paper titled "Hydrocode Simulations of Airbursts and Tunguska Possibilities". They reviewed the existing information on topography and tree-fall at the Tunguska site, clearly showing the importance of topography, which included hills and treeless swampy areas along two small rivers that cross the impact site.

Their hydrocode simulations used the ALE3D hydrocode from Lawrence Livermore National Laboratory. With an assumed entry angle of 45 degrees, they found many plausible asteroid scenarios, but excluded a long-period comet because it would require implausibly high strength (such as solid ice) to penetrate low enough to match the observations. They utilized data from forestry management sources on the strength of trees and their resistance to uprooting or snapping by wind to estimate that 50 percent treefall requires a sustained wind speed of 35-55 m/s. This is substantially higher than the values used by Boslough discussed above. To make further progress using the treefall to calibrate the impact, we need more information on the composition and health of the forest. Their model fits clustered around an energy of 10-15 Mt, but they stressed that further developments should narrow the range of energies and effective airburst height.

Lorien Wheeler and Donovan Mathias of NASA Ames used their fast-running asteroid impact risk model to perform a broad, stochastic assessment of what combinations of asteroid and entry properties produce Tunguska-like cases, based on our general understanding of the impactor populations (Mathias, Wheeler & Dotson 2017). For each case, their Fragment-Cloud Model (FCM) was used to estimate atmospheric energy deposition and airburst altitude, and the ground damage was computed (Wheeler, Register & Mathias 2017). This allowed a broad probabilistic assessment of what combinations of asteroid and entry properties produce Tunguska-like cases. The FCM provides excellent fits to the light curve of the Chelyabinsk meteor (data we don't have for Tunguska), including three flares with maximum energy deposition at 30 km altitude.

For this study, Wheeler and Mathias ran ten million Tunguska-scale simulations to assess what asteroid and entry properties are most likely to produce the observed damage. They evaluated the distributions of asteroid/entry parameter values among the cases that met various Tunguska-like energies, burst altitudes, and blast damage criteria. They also accounted for the different impact frequencies as a function of size and energy. The results showed:

- Blast damage criteria were more likely met by larger energies and sizes (~20 Mt, 70-90 m diameter) despite their lower impact frequency relative to smaller impactors.
- The most likely burst altitude range for producing Tunguska blast radii was ~8-13 km.
- Entry parameters (velocity and angle) were more influential than compositional parameters (density and strength) in determining airburst altitude and ground damage trends.

Airburst and ground-hazard simulations using different software were presented by Marian Nemec, Michael Aftosmis, and George Anderson of NASA Ames. Their objectives were to confirm and refine energy and burst height estimates using Cart3D, a well-established computational fluid dynamics solver, together with high-resolution models of the local terrain. The atmospheric energy deposition rates used as inputs to the Cart3D blast simulations were calculated using the Ames Fragment-Cloud Model (Wheeler *et al.* 2017), with likely meteoroid properties and entry parameters selected from the ten-million cases considered by Wheeler and Mathias (as discussed above). Specifically, Nemec *et al*. ran high-fidelity simulations of 10, 15 and 28 Mt events, corresponding to meteoroid sizes between 70 and 100 m. The peak energy deposition altitudes were between 10 and 13 km, and the nominal entry angle was set at 45 degrees. The simulations resolved terrain features as small as 40 m using the JAXA digital surface model of the Tunguska region.

The results of the simulations were compared with the unified tree-fall map compiled by Longo *et al.* (2005). They showed that the inclusion of terrain in the simulations increased the maximum overpressure and wind speed by 26% and 21%, respectively, when compared with flat-ground simulations. Moreover, the simulations with terrain closely reproduced the observed north-south asymmetry of the "butterfly" pattern of the forest damage. The maximum ground winds occurred in two locations, to the north and south of the meteor ground track east of the epicenter. For the 15 Mt cases, the maximum winds reached 64 m/s and diminished to about 40 m/s near the edge of the observed butterfly region of forest damage. For the 10 Mt cases, the winds were considerably weaker, peaking at about 45 m/s and diminishing to about 25 m/s at the edge of the tree-fall area. Either increasing or decreasing the entry angle from the nominal 45 degrees did not significantly help the fit. Preliminary conclusions were that the details of the tree-fall pattern are necessary to constrain the meteoroid properties, and that a 15 Mt airburst with an 11.5 km effective burst height seems to be the least unlikely case.

Eric Stern (NASA Ames) and Chris Johnston (NASA Langley) discussed the influence of detailed radiation modeling on the Tunguska interpretation. They presented high-fidelity aerothermodynamic models to explore the heating of the meteoroid and predict the expected ground thermal pulse, using a chemically reacting, Navier-Stokes flow solver to simulate the environments for Tunguska-class impacts. The ablation products absorb a significant amount of radiation from the shock, reducing the rate of mass loss during entry. The effect is to lower the airburst altitude by 2-3 km for Tunguska-class impactors.

Radiant exposure of the ground is computed through post-processing of the entry flowfield solutions. They find that the majority of thermal irradiance emanates from the wake behind the meteor, with more oblique entry angles producing greater thermal exposure. Ablation products act to slightly reduce the thermal pulse at the ground due to absorption of radiation in the wake. Comparisons between simulations of carbonaceous and ordinary chondrite meteoroids show minimal sensitivity to chemical composition. For a notional trajectory of the Tunguska event, they calculate an approximately 10 km radius for the tree burn area, with the location of maximum thermal exposure located about 5 km up range from the airburst location.

Additional Topics

Jay Melosh (Purdue University) discussed another factor that may be important for understanding high-speed meteoroid behavior. If there is sufficient porosity, some hot air from the leading side may be able to penetrate the object, destabilizing it and leading to a breakup faster than calculated based only on the basis of mechanical and thermal stress. He concludes that this percolation of hot, high-pressure air into the body of entering meteoroids is a previously unrecognized process that may greatly enhance their fragmentation and dispersion. This phenomenon may explain why the ~100m diameter Tunguska object disintegrated so completely before reaching the surface, suggesting that the Earth's atmosphere may be a better screen against small impacts than previously recognized.

The Tunguska strike was first detected by its low-frequency infrasound pressure wave observed by detectors in Russian Siberia and Europe, and its seismic signal recoded at Irkutsk, about a thousand kilometers south of the impact point. These sources provide independent measures of the energy of the airburst. Peter Brown (University of Western Ontario, Canada), with his students Nayeob Gi and Kimberlee Dube, presented a paper "Infrasound Detection of Bolides: Tunguska Re-examined". Brown's current summary of the infrasound and seismic data is based primarily on two good-quality micro-barograph records. He finds that comparison with nuclear weapons tests are consistent with Tunguska energy yields substantially less than 30 Mt. Rayleigh waves from seismo-acoustic coupled waves detected for Chelyabinsk and Tunguska and analyzed in the same way are consistent with an explosion energy on the order 15 Mt. Therefore, the best energy estimate from combined infrasound and seismic data is 10-20 Mt. This value is consistent with most modern modeling of the airburst as constrained by the ground data on treefall and burn distribution. The equivalent size for the Tunguska meteoroid (assuming similar composition to the 20m-diameter Chelyabinsk impactor) is roughly 50-70m.

One interesting implication of current studies of Tunguska is a revised estimate of the expected frequency of such events. Alan Harris (formerly at JPL) presented the most recent data on "The Population and Impact Frequency of Tunguska-size NEAs" (Harris & D'Abramo, 2015; Stokes *et al.,* 2017). Although current surveys of near-Earth asteroids are far from complete in the Tunguska size range, a modest extrapolation from larger size can be made with some confidence to estimate the number as a function of absolute magnitude (H). Conversion of the population estimate based on H magnitude to a size-frequency distribution in terms of diameter includes uncertainty in albedo distribution of NEAs and an offset of the survey H magnitudes from precisely measured H magnitudes. Population as a function of diameter is therefore uncertain by a factor of 2 or more. As noted above, for an impactor similar to Chelyabinsk, we estimate a Tunguska diameter of roughly 50-70 m, implying an absolute magnitude H between 24 and 25. The frequency of impacts on the entire Earth by a Chelyabinsk-size asteroid is about once per century, and for a Tunguska object with energy 10-20 Mt is roughly between 2000 and 4000 years, using the most recent calibration. For a land impact the recurrence intervals are about a factor of three longer.

Conclusions

The 2018 Tunguska Workshop clarified the current status of airburst modeling and identified the primary sources of uncertainty in describing this event. The results from four different modern computer codes were in general agreement, and they converged on a most likely (or least unlikely) energy for Tunguska in the range of 10-20 Mt, corresponding to a diameter of 50-70 m if a composition similar to Chelyabinsk is assumed, or a wider range when different compositions and entry velocities were considered.

These results agreed with recent simulations in Russia, and with the conclusions by Peter Brown from reanalysis of the seismic and infrasound data. However, the energies are significantly higher than those derived by Mark Boslough a decade ago. They also do not account for the suggestion by Jay Melosh that percolation of hot gas through the asteroid during its plunge might accelerate its breakup. Little modern effort has been applied to simulating the upward plume of material ejected from the explosion (Artemeva *et al.* 2019, in press), and most Tunguska simulations are constrained primarily by the tree-fall pattern, without explicit consideration of the data on burned trees.

The primary uncertainties in these results reflect the limited data on the Tunguska event. Stress was placed in several presentations on the influence of forest health and topography, which had not been considered in many earlier studies. Assumptions about the wind speeds necessary to knock down trees on the varied topography of the Tunguska site can substantially influence estimates of the energy of the airburst. There are also uncertainties in how an impact airburst of this size couples to the ground for its seismic signal, or to the atmosphere to create the infrasound signal. It was also noted that most simulations assumed a 45 degree entry angle, but it would be valuable to try to determine this parameter independently from the eye-witness observations. Results of the work presented at the Workshop suggest such events may occur at intervals on the order of millennia rather than centuries.

The convergence of a variety of models for the Tunguska event is encouraging (although the 2008 work by Boslough and Crawford remains at the low end of estimates). What the models yield is basically the energy of the explosion, which cannot be translated into impactor size without assumptions about the density and trajectory of the object. Estimating average recurrence intervals for the whole Earth for such impacts is harder yet, since the astronomical surveys do not directly measure asteroid size or mass, and the population data for Tunguska-class impactors from these surveys is limited. While it is possible to estimate probable values, the uncertainties in impactor sizes and impact frequencies that match the Tunguska data are quite large. The addition of better knowledge of the health of the forest, the use of burn data, and additional study of infra-sound and seismic signals should strengthen the Tunguska models in future, but are unlikely to greatly improve estimates of impact frequency for Tunguska-class events.

Program of the January 2018 Tunguska Workshop

8:00 Introductory Comments on Goals of Workshop
Lindley Johnson, David Morrison, Donovan Mathias

8:30 Hydrocode Simulations of Airbursts and Tunguska Possibilities
Darrel Robertson and Donovan Mathias

9:00 Energy Deposition and Risk Modeling of Tunguska-Scale Impacts
Lorien Wheeler and Donovan Mathias

9:30 A Comparison of Semi-analytical Airburst Models of the Tunguska Event
Sarah McMullan & Gareth Collins

10:15 Influence of Detailed Radiation Modeling on Tunguska Interpretation
Eric Stern and Chris Johnston

10:45 Entry and Ground Hazard Simulations for the Tunguska Meteor
Marian Nemec and Michael Aftosmis

11:15 Group Discussion of Modeling Results
Donovan Mathias, facilitator

1:15 Arguments for a Smaller Tunguska Airburst
Mark Boslough

1:45 Enhanced Breakup of Entering Meteoroids by Internal Air Percolation
Jay Melosh

2:15 Infrasound Detection of Bolides: Tunguska Re-examined
Peter Brown, Nayeob Gi, and Kimberlee Dube

3:00 Injuries and eye-witness accounts at Chelyabinsk and Tunguska
Peter Jenniskens, Anna Kartashova, Olga Popova, and Dmitry Glazachev

3:30 Recent Tunguska and Chelyabinsk Airbursts Research in Russia
Natalia Artemieva, Valery Shuvalov, and Vladimir Svettsov

4:00 Population and Impact Frequency of Tunguska-size NEAs
Alan Harris

4:15 Group Discussion of a Possible Consensus on the Tunguska Event
David Morrison, facilitator

Relevant Tunguska Publications

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