SXG390

Tunguska: a cosmic airburst paradigm, how we investigate these phenomena, and the search for viable mitigation strategies

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Abstract

Cosmic airbursts, in which a cometary or asteroidal fragment (50 to 100 m across) enters our atmosphere and explodes before reaching the surface, are the most frequent case of cosmic impacts; therefore, they are more likely to strike in the near future. The blast's energy yield is capable of destroying a major city or disrupting an entire region. This report presents the 1908 Tunguska Event as a cosmic airburst paradigm. To date, research on this topic is very fragmented, thus this report offers the reader a more encompassing view of the issue.

A top-down approach has been used to research the Tunguska Event; starting from broad-ranging books on the asteroid impact topic, technical documents have been sought alongside internet-sourced specialised papers to narrow the study down to airbursts. Further, direct assistance from leading authors has been sought in order to clarify specific details of their scientific work.

Nuclear weapons research stands out as the best tool scientists currently possess to model these phenomena, and clearly supports the standard hypothesis that the Tunguska Event was a cosmic airburst. However, a geophysical alternative hypothesis also fits the field data. The report combines both hypotheses into a new, unified hypothesis based upon an operational military concept, which is capable of accounting for previously contradicting observations.

Although many mitigation alternatives are possible in order to fend off the cosmic impact threat, the report clearly shows that neither we are ready to deflect or otherwise manage the threat, nor international law and political will are mature enough to facilitate the creation of a planetary defence system.

Thus, we conclude that further research and investment into mitigation systems and better political will among the Nations of the Earth is needed if we ever are to survive a Tunguska-level event, or worse… an extinction-level event.

Preface

In an interview, featured in one of the Open University's S283 Course materials [4], the *legendary* Gene Shoemaker remarks that:

> *Maybe it looks obvious now that the craters on the Moon were formed by impact, but in fact, the vast majority of scientists who studied the Moon, astronomers in particular, at the time that I began this work, thought that these craters on the Moon were probably formed by volcanoes. That had been the prevailing idea for a century before…*

Maybe it looks obvious now that the 1908 Event in Tunguska, Russia, was due to the entry of a small asteroid, which exploded above the ground. This has not always been the case, though. As 20^{th} Century Science (and pseudo-science) advanced, many alternative explanations were put forward, including antimatter, UFOs, mini blackholes and Tesla's experiments on electromagnetism – just to mention a few. Most of these hypotheses, although imaginative, have never stood to rigorous scientific scrutiny. Yet, even after a hundred years of intermittent research, some aspects of the Tunguska event in 1908 continue to be open to debate: there is nothing wrong with that. It means we still have not found a full, satisfactory, all-round explanation for it, thus research must continue on.

Abbreviations

Acronym	Full Name
AGL	Above Ground Level
Co	Cobalt
DoD	Department of Defence (United Sates)
ESA	European Space Agency
FY	Fiscal Year
GMC	Giant Molecular Cloud
HQ	Head Quarters
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IEO	Inner-Earth Orbit
K/T-boundary	Cretaceous-Tertiary Boundary
Mt	Megaton
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NBC-war	Nuclear, Biological and Chemical Warfare
NEO	Near-Earth Object
Ni	Nickel
Pd	Palladium
PGM	Platinum Group Metals
PHO	Potentially Hazardous Object
PIXE	Particle Induced X-ray Emission
REE	Rare Earth Elements
TB	Tunguska Body
TE	Tunguska Event
Ti	Titanium
UFO	Unidentified Flying Object
UN	United Nations
USAF	United States Air Force
Y	Yttrium

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1. Introduction

Traditionally, the very large events, such as the K/T-boundary impact, which may have triggered the demise of the dinosaurs, have been the researchers' favourites. Nonetheless, neither we estimate another one of these events is soon to happen, nor there is much we can do about it at present. However, mid-air explosions, like the one that took place in 1908 over the Tunguska River in Siberia, are actually a lot more frequent: perhaps one every 100 to 300 years or so, and there is a great deal more we can do to fend them off.

In this document, we *briefly* describe the sources and the mechanisms that contribute to the Near-Earth Object (NEO) population. We describe the 1908 Tunguska Event (TE), the actual damage and evidence we have for it, and the scientific hypotheses that account for it. We consider and analyse the research methods used to investigate this type of event due to the lack of a crater; especially focusing on the analysis of blast effects, materials from bogs, and the use of hydrocode modelling. We report on the possible mitigation strategies, including deflection and other orbit change techniques, and the level of today's technology readiness to defend against the threat. And finally, we put forward a couple of recommendations for further research. Complementary and interesting, but non-essential, information can also be found in the appendices.

A top-down approach has been used to research the TE; starting from broad-ranging books on the asteroid impact topic, technical documents have been sought alongside internet-sourced specialised papers to narrow the study down to airbursts. Further, direct assistance from leading authors has been sought in order to clarify specific details of their scientific work.

2. The Source of the Cosmic Impact Hazard

2.1 The Near-Earth Object Population

As Bottke [1] explains, there are four families of *asteroidal* NEOs: Apollos and Atens have Earth-crossing orbits, Amors and Inner-Earth Orbit asteroids (IEOs) could acquire such orbit easily. Objects in the Asteroid Belt may collide and break apart; a combination of Yarkovsky thermal forces and gravity-related motion resonances eject some of the fragments into the inner Solar System, where they settle in orbits that may cross a planet's path. The υ_6 secular resonance with Saturn and the 3:1 resonance with Jupiter are highlighted as contributing most effectively to turning such fragments into NEOs.

A second source of NEOs can be found in the Kuiper Belt. These are short to mid-term comets (e.g. Halley's). Jupiter influences their lifetimes and, eventually, either they smash into the giant planet (e.g. Shoemaker-Levy 9) or they are given a *gravity assist* out of the Solar System. But a few of these may settle in the inner Solar System.

A Giant Molecular Cloud (GM) is an interstellar cloud of gas and dust that, if stressed by gravitational interactions, will contract to produce a cluster of new stars. Mazeeva [3] points out that the Sun crosses the galactic plane, that is, the galaxy's *equator*, every thirty million years. In doing so, there is a 25% probability that it will encounter a dense GMC; thus, an encounter with a GMC can be expected every 120 million years. Mazeeva concludes that the tidal influence of GMCs on the Oort Cloud, which is the outer layer of the Solar System, causes the injection of comets with high orbital eccentricities into the inner planetary system. This 120-million-year GMC collision interval could be very significant as NASA's [5] latest estimate for extinction-class events is also of around 100 million years.

Asteroidal NEOs, which constitute the largest population of NEOs (~90%), are thought to have *median* lifetimes in NEO space between 2×10^6 and 7×10^6 years [1, 10]; lifetimes vary depending on the gravitational source that placed them in NEO space, which also dictates the probability of an encounter with one of the inner planets. According to Bottke [1], these probabilities vary from 0.2 % to 1.0%.

3. The Tunguska Event: The Effects of an Airburst

3.1 The Standard Hypothesis

The Tunguska Event (TE) refers to an explosion over Tunguska, Siberia, which took place on the 30th of June, 1908. The currently accepted hypothesis argues that a small NEO (30 – 60 m) entered the atmosphere and *exploded* before reaching the surface. Shuvalov and Artemieva [8] argue that, on the basis of numerical models, it is not possible to specify if the Tunguska Body (TB) was a stony asteroid or a comet. Dr Artemieva [personal communication] explained that current numerical models only exclude metallic asteroids from being TB candidates.

Longo [2] explains that both *seismic and barometric* readings of a large explosion were recorded in the aftermath of the Event. The phenomenon of *bright nights*, in which it was possible to read a newspaper at midnight without artificial light, was reported as from July, 1st, lasting a fortnight or so. *Eyewitnesses* spoke of an object that flew overhead before an explosion. There was *no* photographic evidence. There was *extensive damage to the local Tunguska forest* over an area of around 2000 km^2. A large number of trees were uprooted and thrown across the landscape, yet others at the epicentre were left standing, with their branches either bent down or severed.

In 1927, Leonid Kulik discovered that there was a central point from which an outward pattern of fallen and burnt trees could be observed. Nevertheless, systematic analysis would have to wait until the 1960s, when several Russian scientists, notably V.G. Fast, mapped the tree fall pattern and produced the first numerical data catalogue. In 2008, Longo *et altri* [7] put forward a revised version of Fast's tree fall maps. Longo's team's new map incorporates data from University of Bologna's 1999 ground and aerial surveys. A summary [2, 7] can be found in Table 1.

Parameter	Estimated Value
Coordinates of Epicenter	60°53' N, 101°54' E
Height of Explosion	6000 to 10000 m AGL
Trajectory Azimuth	If single body: ~110°; If multiple bodies: ~135°
Inclination of Shockwave Axis	30° to 50°
Centers of Wave Propagation	2 or 4
Energy Emitted by Blast (Fast's Estimate)	10 to 15 Megatons

Table 1: Recent (2005 - 2008) TB parameter estimates by Longo *et altri*.

In the 2008 map (Figure 1), the reliability of the data has been colour-coded: the darker areas represent the most reliable data sets. The map resembles a butterfly, and the estimated epicentre and flight path are marked. The tree fall pattern represents the prevailing *dynamic* pressures away from the centre, thus it is the basis for a *dynamic* pressure scalar field. Longo's team superimpose isobars onto the map as a function of the damage observed on the field. The isobars show a horizontal *dynamic* pressure gradient, which increases from the epicentre outwards and then decreases again. Dr Natalia Artemieva explains [personal communication] that these isobars were calculated around fifteen years ago by Korobeinikov at Tomsk University. However, they were based on a model for nuclear explosions on the surface rather than nuclear airbursts; cylindrical symmetry was used and, *with some trick*, dynamic pressure distributions were deformed to obtain non-circular isobars.

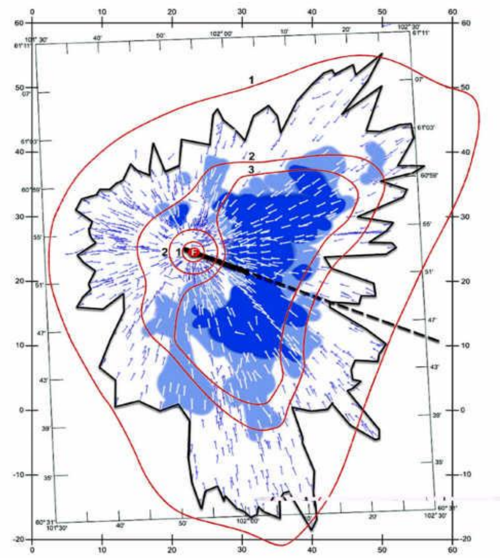

Figure 1: A map of tree fall in the Tunguska area. Credits: Longo et altri / Universities of Bologna and Tomsk.

3.2 A *Fitting* Alternative Hypothesis

The only serious challenge to the standard hypothesis comes from Prof. Kundt [11], who proposes the *tectonic hypothesis*. Kundt argues that, as the tree fall pattern is clearly inhomogeneous, that is, there are groups of trees that remained upright in addition to the ones that were vertically severed; this suggests there were multiple, smaller blast sources, possibly related to funnel-shaped structures identified in the local swamps. Besides, there is no TB debris on the surface. In addition, the Tunguska area is both rich in natural gas resources and had been tectonically and volcanically active in the past. Kundt also notes that some witnesses spoke of columns of fire rising from the ground, and that some witnesses reported tremors before the actual explosion. Consequently, Kundt concludes that, the TE must have been tectonic in origin: an earthquake gave rise to a violent natural gas outflow. On venting, the liquefied gas expanded, escaped supersonically and formed a giant mushroom cloud. The surrounding air was pushed outwards in the form of a big storm field. The expanding gas combined with oxygen and ignited.

The 1994 Cando Event, in Spain, is the most recent piece of evidence to support this alternative hypothesis. The investigators, Docobo et altri [15], concluded that a sudden release of natural gas through a fissure created a rising gas bubble. The explosive gas release dug a crater and uprooted trees. The gas formed a convection cell that climbed to stratospheric levels and ignited. On its way down, it was perceived by all witnesses as a burning meteorite. When it reached the surface again, the searing gas burned the forest surrounding the crater area.

3.3 Nuclear Airbursts and Dynamic Pressure

As explained in a NATO NBC-war defence manual [16], for a nuclear airburst, around 50% of the energy is projected as a blast shockwave and some 35% as thermal radiation, leaving 15% as nuclear radiation. An airburst implies that the fireball will not touch the ground. As a result of the very high temperatures at the point of detonation, the hot gases move radially outwards at hypervelocity. The material forms a thin, but dense shell known as the hydrodynamic front. This front compresses the surrounding air and transfers its energy to the atmosphere creating the shockwave. The work done by the explosion on the terrain below has two components. There is damage due to *static overpressure*. This is the damage caused by the sharp increase in pressure due to the thick wall of air that comprises the advancing shockwave. In addition, damage is caused by *dynamic pressure*. In passing through the atmosphere, the blast wave imparts its energy to the molecules in the air, setting them in motion in the direction of the advancing shock front. The motion of these air molecules is manifested as the blast winds. These push, tumble and tear apart objects and cause their violent displacement.

The static pressure of a gas is a measure of the average momentum of its molecules. But, if a body of gas is moving, then we also define its *dynamic pressure* as *pressure-force*, which depends on the body’s velocity, and is perpendicular to the surface it acts on:

$$q(Nm^{-2}) = \frac{\rho v^2}{2} \quad \text{(Eqn.1)}$$

where, q is the dynamic pressure, ρ is the air density and v the gas velocity. Atmospheric pressure is static and in equilibrium: we experience the same pressure from all directions, thus, we are not affected by weather-related atmospheric pressure changes. However, *dynamic* pressure is a hazard because it is directional and creates pressure differences. For example, we cannot survive a tornado, yet using Eqn. 1, we see that:

$$|\mathbf{q}| = \frac{(1.3kgm^{-3})(130ms^{-1})^2}{2} m^{-2}$$
$$|\mathbf{q}| = 10985Nm^{-2} \approx 0.11bar$$

The dynamic pressure is only: 0.11 bar; for comparison, ordinary car tyres work at 2 bar! Yet, due to the dynamic pressure difference, say, between the front and the back of a farm building, an approaching tornado will tear it apart.

3.4 Hydrodynamic Code Models *Fully* Support the Standard Hypothesis

Artemieva and Shuvalov [6, 8, 9], who have recently produced hydrodynamic code models of the TE based on nuclear airbursts, model the entry of a Tunguska-like body as follows (Figure 2):

a) At an altitude of 30000 m AGL, the projectile starts to deform under increasing aerodynamic loading.

b) At an altitude of 20000 m AGL, a pancake-like structure is formed. Hydrodynamic instabilities, which eventually break the body apart.

c) At an altitude of around 15000 m AGL, the body turns into a jet of material made up of vapours, solid projectile fragments and shock compressed air.

d) At about 8000 m AGL, a gaseous jet consisting of vaporized materials and very hot compressed air forms.

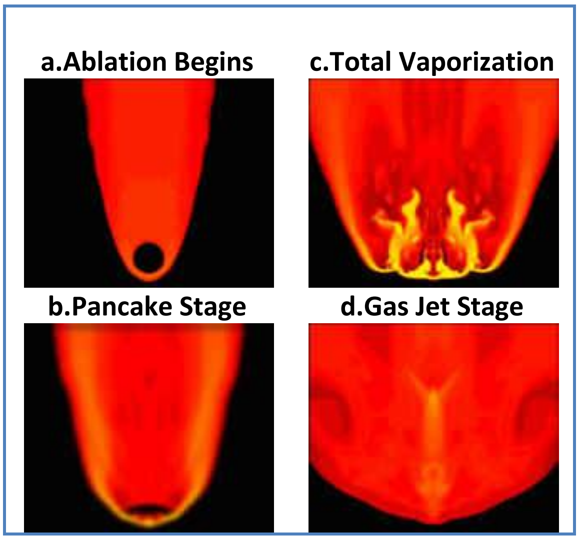

Figure 2: Credit: Shuvalov & Artemieva 2002 – 2008 Tunguska-like airburst hydrocode numerical simulations.

Once all the material has vaporised, the gaseous jet decelerates to a complete stop and ignites. The temperatures are very high and all the materials become buoyant. A plume forms and the jet reverses its direction to flow upwards. A very dense air bubble forms. Gas density in the bubble exceeds that of the surrounding air by several orders of magnitude and it explodes: an airburst. This generates a huge shockwave (static overpressure), which will subsequently advance accompanied by blast winds (dynamic pressure).

Dr Artemieva [personal communication] explains that the shock front strikes the surface vertically, as if it were a wind column, followed by the blast winds, which have certain spherical symmetry and velocity components along both polar directions: this *sphere* hits the ground and begins to spread over the landscape (Figure 3).

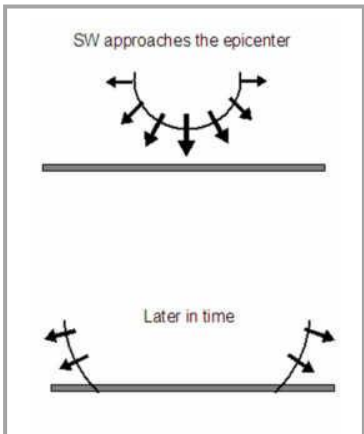

Figure 3: Credit: Dr. Artemieva

Dr Artemieva [6] presents a map (Figure 4) which shows lines of equal wind speeds, which increase from the centre to a distance of 10 km, and then progressively decrease out to distances beyond 40 km from the epicentre. This map also portrays a horizontal *dynamic* pressure gradient, which increases from the epicentre outwards and then decreases again. Using Eqn.1, the wind speeds can be translated into *dynamic* pressure isobars (Table 2); these are the *dynamic* pressures responsible for the tree fall pattern.

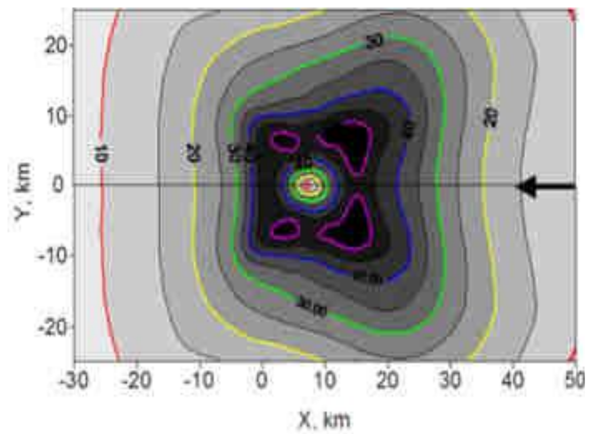

Figure 4: A map of wind speeds. Credit: Dr Natalia Artemieva

Wind Speed ($m\ s^{-1}$)	Dynamic Pressure ($N\ m^{-2}$)
10	61.50
20	246.00
30	553.50
40	984.00
50	1537.50

Table 2: Dynamic pressure isobaric values based on Artemieva wind speeds.

Rearranging Eqn.1 and substituting for the density, we obtain an expression that shows that the *dynamic* pressure can be considered to be a measure of the energy per unit volume:

$$q = \frac{\rho v^2}{2} = 0.5\rho v^2 = 0.5\frac{m}{vol}v^2 = \frac{0.5mv^2}{vol} = \frac{E_{kin}}{m^3} \qquad \text{(Eqn.2)}$$

Therefore, the energy delivered to the landscape by the blast winds is proportional to the dynamic pressure due to each cubic metre of rushing air:

$$E_{kin} = q \times m^3 \quad \text{(Eqn.3)}$$

Dr Artemieva [personal communication] explained that her dynamic pressure isobars differ from Longo's by an order of magnitude or so, therefore, Eqn.3 implies that the total energy yield will differ too. The total energy release in the TE was around 5 Mt, which is around 2.2 x 10^{16} J. The NATO NBC document [16] indicates that a 1 Mt nuclear explosion yields an effective blast damage radius of 3 km from detonation point; consequently, a 5 Mt burst would have an effective blast damage radius of around 15 km. Dr Artemieva's map (Fig. 4) shows that the strongest wind speeds spread 10 to 20 km at either side of the epicentre, so a 5 Mt yield is a reasonable computation.

3.5 Is Kundt's Hypothesis Simply a Phenomenological Fit?

Kundt argues the tree fall pattern is clearly inhomogeneous. But hydrocode models can account for this as follows: Since the shock front descends vertically, but the *dynamic* pressure winds spread over the surface, this is why we have vertically damaged trees at the epicentre and fallen trees further afield due to the *dynamic* pressure winds. Since the TB may have entered the atmosphere at around Mach 98 (Appendix A), a powerful hypersonic shockwave would have been generated along the path, which would have been directed to the ground; this Mach-related wave would have been recorded by seismographs before the explosion: this explains the earth tremors before the explosion. In addition, Boslough and Crawford [12] mention that the Tunguska topography is not flat. Shockwaves and blast winds are bound to be deflected by terrain gradients, thus protecting some tree groups placed behind hills that can offer some shelter. Local topography may have combined with the fact that some tree species were healthier than others, hence not all trees were brought down.

3.6 A Possible Unified Hypothesis

Although we can counter Kundt's arguments, a violent outflow is *not* unthinkable either. Longo [2] suggests that the heat from the airburst might have released the natural gas locked in the local permafrost: subarctic permafrost is a good sink of atmospheric methane. I would like to put forward a stronger case for a unified hypothesis, which can be substantiated by a military concept. Aerial bursts have a *remarkable* phenomenological resemblance to conventional mid-air detonated weapons. Dr Artemieva [personal communication] agrees the resemblance stands to reason. In contrast with ground-penetrating bombs, above-ground detonated bombs are designed not to dig a crater, so that energy is not wasted in making a hole. During the Vietnam War, and more recently in Afghanistan, the US Air Force (USAF) deployed the 15000 lb, BLU-82B (Appendix B), aerial ordnance weapon. The purpose of this massive unit is to clear the surface of trees and to detonate any buried land mines in order to produce safe landing areas for transport helicopters and to establish artillery positions. The shockwave is horizontal and all of the momentum is transferred to the surface, thus sweeping across the landscape [14].

The TE shock front would have reached the ground and shaken it, hence seismic-like shocks were recorded after the explosion. It is possible that shallow natural gas deposits could have broken through weak or fractured thin rock layers aided by the shockwave, just like the BLU-82B would explode buried mines and underground fuel stores. Around the epicentre, the temperatures would have been very high, thus, as the subsurface gas was being jettisoned upwards, it could have ignited too. This could explain why witnesses recalled both the flight of a burning object and columns of fire from the ground.

4. Can We Protect Ourselves from a Tunguska-level Event?

4.1 Eventually, This Will Happen Again

Nuclear weapons are a helpful indicator of the effects of the blast wave from the TB should it have fallen on a city. Based upon Okmanech and Lowell's data [30], we extrapolate the following *approximate vales* for a 5 Mt blast:

Distance (miles)	Overpressure (PSI)
0.2	>400
0.5	400
1.0	84
2.0	34
5.0	8

Table 3: Wave blast overpressures

According to these authors the overpressure values translate to damages as follows:

Wave Overpressure	Resulting Damages
20 PSI	Even reinforced-concrete buildings are destroyed.
10 PSI	Will collapse most factories and commercial buildings, as well as wood-frame and brick houses.
5 PSI	Flattens most houses and lightly constructed commercial buildings.
3 PSI	Suffices to blow away the walls of steel-frame buildings.
1 PSI	Will produce flying glass and debris sufficient to injure large numbers of people.

Table 4: the effects of different overpressure values on the landscape

Clearly, Table 4 shows a future Tunguska-level impactor bursting over a large city will do a lot of damage. Duncan Steel [31] mentions that when a 3 to 4 m NEO exploded over Dubbo, Queensland; the emergency services were alerted as houses shook and windows shattered.

4.2 Reducing the Risk of Impact

Sommer [32] reminds us that for most of mankind's history, we have not been seriously harmed by the NEO threat, thus doing nothing about it is one possibility. However, Sommer suggests that, because the World Trade Centre events of September 11th, 2001 were found to be an unacceptable loss, public opinion and policy-makers are now more likely to demand some form of insurance against unforeseen hazards. NASA [5] indicates that a coping strategy will depend on NEO size, budgets, public will, cost-benefit analysis, etc. If we have months or years to act, cost-benefit analysis will dictate our actions. NASA's report [5] estimates the development and testing of a nuclear interceptor to cost around 2.5 billion USD, plus an additional 1 billion USD per attempt. Consequently, we could argue an interception mission is *financially* advantageous if we can estimate an impactor may generate in excess of 4 or 5 billion dollars of damages, otherwise evacuating might be more cost-effective.

4.3 Are We Actually Ready?

In an internal USAF paper [34], Garretson and Kaupa point out that we have no off-the-shelf contingency plans, no standard operational procedures and no hardware for a mitigation mission; no-one is in charge and nobody has ever been assigned the planetary defence mission either. And brilliantly (or worryingly) add:

> *The F-22 fighter aircraft alone has taken nearly 25 years to evolve from a list of requirements to initial operational capability.*

New generation jet fighters are built upon known air combat principles, but a Planetary Defence System is a new challenge and may take longer to develop. Major Kaupa, USAF, is also involved with the Planetary Society. Kaupa explained [personal communication] that:

> *[Future] recon missions need to determine PHO's orbit, spin rate, composition and density. If a recon probe is launched and the asteroid is not determined to be an issue, we still can gleam important data. Of course, who will fund these missions? Mitigation is the next tricky part. Why build an asteroid diverting craft if it is not needed in the next 30-40 years? We can't answer this question until we find a threat. Budgeting is the issue, especially with today's economy and the years needed to recover.*

4.4 Deflection Technologies

NASA [5] groups deflection technologies into two categories. Impulsive techniques change the velocity of a Potentially Hazardous Object (PHO) instantaneously. Instead, slow-push techniques attempt to progressively change a PHO's orbit. Impulsive concepts include nuclear weapons and kinetic impactors. These techniques are regarded as having a high level of technological readiness and effectiveness. Slow-push concepts include gravity tractors, mass drivers and space tugs. These techniques are regarded as having a low level of technological readiness and effectiveness, unless they can be applied over long periods. NASA's 2006 report [5] offers a very comprehensive description of these technologies.

4.5 Viable Strategies

At the time of writing, the only workable mitigation option we have is to use nuclear weapons. Theoretical studies show this is the most effective too. However, there are four or five different UN treaties that forbid the presence, let alone the use, of nuclear weapons in outer space; chiefly, the Outer Space Treaty of 1967. A country's airspace can be thought of as a column of air above its territory, whose upper boundary is set at 100,000 m above sea-level. Because the radioactive fallout from a nuclear detonation in space will not respect national airspace boundaries, a country's actions in space cannot be allowed to affect another country: hence the ban.

As NATO currently has many world-wide non-member partners, including Russia and some Arab States, and considers geophysical issues as an integral part of its global security strategy to maintain regional stability, I contacted General C. King (*Dean of Academics, US Army Command College, and a speaker at NATO HQ conferences*) to discuss NATO taking a leading role in developing a nuclear interceptor. In summary, General C. King categorically pointed out that "*as international law establishes, no-one should be firing any nuclear arms into space"*.

This offers a tough legal challenge. I contacted ESA's legal team and was referred to a UK representative. Dr Sa'id Mosteshar, at Mosteshar Mackenzie, is a partner in this London-based legal firm specializing in space law. I posed the question of working around the stalemate situation, whereupon the space treaties could be amended regardless of the vetoing ability of the permanent members of the UN Security Council. Dr Mosteshar replied that:

> *To alter international law is, as you imply, a slow and deliberate process. The Security Council cannot override international law. Its remit is specifically to act in accordance with the law. However, it is not inconceivable that a General Assembly Resolution could be passed distinguishing the actions contemplated from those forbidden by Treaty. Any such Resolution needs to be tabled well in advance to allow for the procedural requirements of the UN. The General Assembly does have powers to pass interpretive resolutions construing treaty provisions. In fact this has been proposed in some of the debates surrounding weapons in space.*

There are non-nuclear options. These are more expensive to develop and nobody knows how well they would really work. However, it is believed that kinetic-energy weapons and space tugs could cope with (the smaller) TB-sized objects.

NASA [5] considers the use of a kinetic impactor as the next best option. A kinetic impactor is a mass-to-target weapon. In short, a mass is directed to a target to change its course. The momentum transferred, and the direction of such momentum, must be optimised in order to correct the target's course and speed as desired. However, NASA [5] points out this method requires much better characterization studies of a target, because a kinetic impactor would be ineffective against a loosely bound asteroid, since the impactor may just pass through it. On the other hand, this technology is somewhat more mature because of NASA's Deep Impact mission and the embryonic development of this type of weapons for military use. Yet, once again, we run into international political difficulties. Sommer [32] reminds us that while the White House may be concerned with reducing the risk of a NEO impact, President Clinton in 1997 vetoed the Clementine II asteroid interceptor program to avoid space weaponization. Clementine II was a program to test out asteroid deflection technologies. However, a senior USAF / DoD officer, whose name I am not at liberty to mention, explained [personal communication] that "*USAF / DoD maintains an interest in planetary defence as part of its larger mission of Space Situational Awareness, which aims to improve our ability to understand and act upon whatever is in near-Earth space: man-made or otherwise*".

Funding for projects that would help better characterize the impact threat may be difficult to come across until we find an asteroid heading our way. But… could the space tug be the exception? A space tug is a vehicle that would dock with a PHO and push the object in the desired direction. NASA [5] estimates developing the concept may cost around ten billion dollars. Nevertheless, the space tug may have commercial value too; so that a return on the development investment may be found in using this technology to capture NEOs for mining purposes. Ross [36] estimates the market value of metals in an average metallic asteroid to be in excess of thirteen billion dollars (FY'97). Becoming experienced with moving around small asteroids could be the key to developing a non-nuclear PDS. However, Dr Mosteshar [personal communication] points out that outer space has the character of Antarctica, thus asteroids are free for exploration and use by all countries on a similar basis to Antarctica. Consequently, it is at present too difficult to determine who should be granted rights of exploitation.

Thus, we see that organizing a Planetary Defence System will not only take time, but global political consensus and large sums of money.

5. Geophysical Issues Open to Further Research

5.1 Lake Cheko

Lake Cheko is a lake along the Kimchu River, which flows through the TE epicentre. In his report in 1963, Koshelev [20] explains that Lake Cheko forms an oval, conical funnel, which resembles a meteoritic crater, but there are no *obvious* signs of an impact.

But, after considering many alternative explanations, Gasperini *et altri* [17] concluded, in 2008, that a bit of the TB broke off and survived. Ground Penetrating Radar (Figure 5) suggests a crater-like structure and the presence of a compact object at the bottom. Collins *et altri* [18], question Gasperini's proposal reasoning that the impactor was too weak to reach the surface: there is no evidence for high shock pressure, no evidence of meteoritic material, the lake is significantly elliptical, there is no rim, and no ejecta apron. Gasperini *et altri* [19] reply that the impactor could have come in at a very shallow angle, explaining the oval shape, and that the surface materials were very soft, thus, the rim may have collapsed altogether.

Figure 5: Gasperini argues that if we emptied the lake, we would see a tilted round crater. Credit: University of Bologna.

One possible model of formation of the Asteroid Belt suggests a planetary embryo was disrupted by Jupiter's gravitational influence; this embryo would have broken apart. Some element *differentiation* may have taken place during its formation. This model makes possible for NEOs to have a dual stony-iron composition: lumps of metal surrounded by stone. If the TB were a fragment of a disrupted planetary embryo, then perhaps the iron component of the TB could have detached during the early stages of atmospheric entry as the stony part boiled away.

Further research should be conducted to establish beyond *any* reasonable doubt whether this is an impact crater and whether it is due to the 1908 Event.

5.2 No Impactor Debris

Impactors can be traced by looking for unusual concentrations of platinum-group metals (PGMs) and Rare Earth Elements (REEs) in the stratigraphic record. Asteroids contain several orders of magnitude more PGMs than terrestrial sedimentary materials and basalts [29]. Because of this, and because extraterrestrial materials are known to show different isotope ratios of any one element, extraterrestrial PGMs stand out. Tunguska researchers traditionally have worked with peat cores. A 60 cm core from the peat bogs *may* represent a time span of around 150 years at this site; but Tositti [23] points out that this is not an established rule of thumb yet [personal communication].

Based on fieldwork carried out before 2001, Kolesnikov *et altri* [21, 22] presented their final findings in 2004, in which they argued that, because the concentrations of Pd, Ni, Co, Ti, Y and REE in the event and lower layers are much more than the background values for the upper layers, these would suggest there is strong geochemical evidence for an impact as the cause of the TE.

On the other hand, Tositti *et altri* [23] performed similar fieldwork and filed their final report in 2005. Laura Tositti [personal communication] explained that, in summary, her team neither found anomalous radioactive levels in the materials that represent the 1908 Event, nor did they find anomalous traces of PGMs. Therefore, peat sample analysis *alone* cannot support the TE's extraterrestrial origin. Notwithstanding the aforementioned conclusions, Tositti's research team conducted a palynological (pollen and spore count) analysis. This showed an atypical injection of pollen, spores, and so on into the peat in 1908. Tositti concludes that this is consistent with the effects of unusually strong winds, perhaps caused by a shockwave.

Kolesnikov's team used ICP-MS (Inductively Coupled Plasma Mass Spectrometry). ICP-MS is a destructive method. It requires the samples to be pre-treated and then converted into an aerosol. Subsequently, the samples are introduced into ionizing plasma, which has a temperature of 6000 K to 10000 K. Wolf [24] warns that, due to the ionizing nature of the plasma, atomic species may form during the analysis, which may interfere with detection. Incidentally, Kolesnikov's team pre-treated the samples in a manner terribly akin to industrial extraction of PGMs from terrestrial ores, *perhaps* increasing the original concentration of all the samples [22, 26].

Tositti's team used PIXE instead (Particle Induced X-ray Emission). PIXE [25] is a non-destructive method in which high-energy protons are fired onto a target sample. Bombardment displaces the inner shell electrons of atoms, causing outer shell electrons to replace them. These transitions produce unique X-ray emissions for each particular atom (emission spectra as they lose energy), and this allows the composition of a sample to be determined. Tositti [personal communication] explains that her team could have pre-concentrated the samples, but they chose not to.

From the above, it can be seen that different geochemical analysis techniques can easily yield different results. Besides, Kolesnikov presents a most peculiar graph of PGM and REE concentrations (Figure 7). This graph shows a progressive build-up during the years running up to 1908. This is not what we would expect to see in the graph should the PGMs had been introduced all at once. Instead, there should be a single sharp spike centred on 1908 only; this has been agreed by Tositti in personal correspondence.

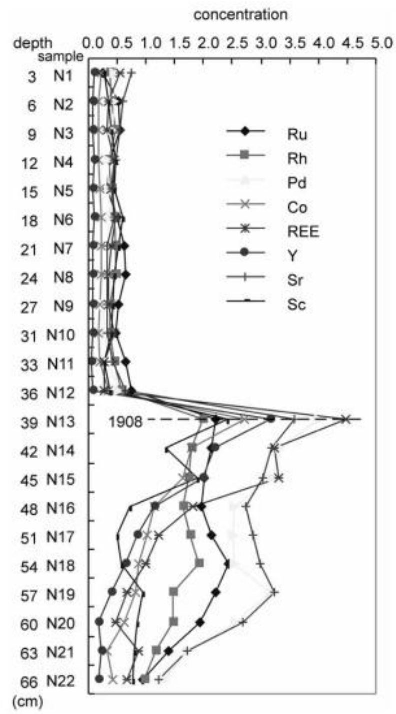

Figure 8: Elemental abundances in the peat column from the epicentre of the Tunguska catastrophe. Credit: Kolesnikov et altri.

On the other hand, Tositti's analyses agree with all recent hydrocode models of the Event. Dr Artemieva [6, personal communication] has repeatedly pointed out that the TB completely vaporised in mid-air, and that all of its material was subsequently dispersed, with the finest particles reaching out to a radius of a thousand miles from the epicentre: no *significant* geochemical evidence can possibly be found in the local Tunguska peat.

Therefore, undertaking a further study of Tunguska peat samples would be extremely advisable in order to further validate Laura Tositti’s and Natalia Artemieva’s matching results.

6. Conclusion

Having achieved the goals of presenting the TE as a natural airburst paradigm, explaining the effects and how we model these phenomena, and briefly detailing possible strategies for mitigation, I conclude that the TE was a cosmic airburst which, with the use of research on nuclear weapons technology, can now be reasonably understood; however, further research on the presence of chemical signatures on the ground and further investigating Lake Cheko are needed. The presence of a NEO population suggests that another Tunguska-like event can be expected in the future. Therefore, research and development of mitigation technologies is desirable, including the creation of a stable and sustainable planetary defence system, which could also instigate the preservation of Earth's natural resources, further advance our knowledge of the Solar System, bring about new space lift and travel technologies and robotic systems, and ultimately promote better international relations among all the Nations. Due to the many international legal and political obstacles to developing a planetary defence system, we would also like to recommend supranational organizations, such as the United Nations, NATO, etc, take the lead in working towards protecting our planet from this threat.

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Appendix A

TB's Entry Mach Number Calculation

In aeronautical terms, and following [28], the Mach number is the ratio of the speed of an aircraft to the *local* speed of sound. When the Mach number is well below unity, flight is subsonic. When the Mach number is well above five, flight is hypersonic. The Mach number, M, is:

$$M = \frac{v}{a}$$

In this expression *v* is the aircraft's speed and *a* is the local speed of sound. TB flight path hydrocode simulations generally begin at an altitude of around 30,000 m AGL and with an entry speed of around 30,000 ms^{-1}. To calculate the TB's entry Mach number, a model of the upper stratosphere (above 25,000 m AGL) is needed. Our model [27] calculates the temperature of the air as:

$$T / ^{\circ}C = -131.25 + 0.00299h$$

In this expression, *h* is the relevant altitude AGL. Using h = 30,000 m, we obtain:

$$T = -41.51^{\circ}C$$
$$or$$
$$T = 231.59K$$

Subsequently, we approximate stratospheric air to a perfect gas, and use the following expression to calculate the relevant, local speed of sound:

$$a = \sqrt{\gamma RT}$$

In this expression, γ is the ratio of specific heats, *R* is the gas constant and *T* the temperature of the air. Using the following values,

$$\gamma = 1.406$$
$$R = 287 Nmkg^{-1}K^{-1}$$
$$T = 234.59K$$

We obtain

$$a = \sqrt{\gamma RT} = 305ms^{-1}$$

Therefore, the Mach number is:

$$M \approx \frac{\sim 30000}{\sim 305} \approx 98$$

A shockwave forms and travels ahead of an object when it moves across the atmosphere with Mach > 1. The higher the Mach number, the more energy the shockwave has. This shockwave eventually reaches the surface and transfers its energy to the landscape. For this reason, jet fighters in air shows are not clear to supersonics speeds in low level flight, otherwise the spectator's car windscreens would probably shatter, etc. Banking on these well-known effects, today's scientists use seismographs around the world to detect the hypersonic booms from incoming larger meteorites.

Appendix B

BLU – 82B

The BLU-82B/C-130 weapon system[14], nicknamed Commando Vault in Vietnam and Daisy Cutter in Afghanistan, is a high altitude delivery of a 15,000 pound conventional bomb, delivered from an MC-130 (Hercules cargo plane) since it is far too heavy for the bomb racks on any bomber or attack aircraft. Originally designed to create an instant clearing in the jungle, it has been used in Afghanistan as an anti-personnel weapon and as an intimidation weapon because of its very large lethal radius (variously reported as 300-900 feet) combined with flash and sound visible at long distances. It is the largest conventional bomb in existence, but is less than one thousandth the power of the Hiroshima nuclear bomb.