Tunguska (1908) and its relevance for comet/asteroid impact statistics

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Abstract

During the 1908 Tunguska catastrophe, trees were flattened over an area of more than 2000 Km^2 of Siberian taiga. For several decades, this destruction was thought to be caused by the impact of a sizable meteorite, some 60 m across, and served as a well-defined data point on the terrestrial impact spectrum (i.e. impact rate versus destruction energy). But doubts in the impact interpretation emerged, via a continued absence of detected impact grains, via controversies between the cometary and asteroidal proponents, via the net-zero-momentum treefall pattern with its multiple centers, the three European bright nights (illuminated by scattered sunlight), details of the eyewitness reports, and the geologically preferred site of the destruction, in the Kulikovskii volcanic crater with its intersecting fault lines. In this report, I shall analyze the Tunguska event, compare it with several similar catastrophes, and present more than a dozen criteria that can serve to discriminate between a meteoritic impact and a tectonic outburst (of the kimberlite type). Tectonic outbursts turn out to be (likewise) power-law distributed (as a function of destruction energy), with practically the same spectral slope as the asteroidal impacts, but are more frequent than the latter by a factor of at least 20.

What happened north of the Stony Tunguska river, in the early morning of 30 June 1908?

Depending on distance from the event -- at (101^0 53' 40"E, $60^0$53'09"N) -- the Siberian catastrophe of 30 June 1908 was reported as "*cannon shots*" (barisal guns, brontides: Gold & Soter 1979) and/or "*storms*" followed by "*columns of fire*", also described as "lightning" and "thunderclaps", after which an area of more than 2000 square-kilometers, *diameter* some 50 Km, had its trees debranched, felled, or their tops chopped off, varying with their distance from the center and/or height above the valleys, even with islands of tree survival near the center, and in the valleys. A few tents (tepees), barns (storage huts), and cattle (reindeer) were damaged, hurled aloft, and/or *incinerated*. The haunting took some *ten minutes*, variously reported between 2 min and an hour; one man even washed in the bath house to meet the death clean.

Clearly, the destruction took much longer than the impact time $\Delta l/v$ of a swarm of meteoritic fragments, which measures in seconds. And for an impact, the luminous infall trail would have to precede the sounds of the touchdowns. In his detailed 1966 book `*Giant Meteorites*´, Krinov praises the reliability and uniformity of dozens of eyewitness reports on the Tunguska event, yet has to correct them repeatedly by pointing to the ease at which one's memory can get confused at later times; see also the reports by Gallant (1994), Zahnle (1996), Vasilyev (1996), and Ol'khovatov (1999).

Among the informative eyewitness reports on Tunguska (1908) are the *heat* felt in the faces of inhabitants of Vanavara, the nearest trading post, at a distance of 65 Km from the epicenter. As is known from bonfires, you can only feel the heat of a chemical fire on your skin if a large fraction of the sphere of seeing around you is filled with hot matter (gas) of sufficient column density. The short-lived, narrow trail of a distant impactor cannot be sensed, whereas Km-high gas flames - like occasionally at Baku - can.

Informative are also the `*bright nights*´ in Europe and western Asia, starting late on 29 June, culminating on 30 June, and fading thereafter, witnessed last around midnight of 2 July: the sky did not fall dark, down to northern latitude of Tashkent, 42^0. This phenomenon has only been reported one more time for the 1883 Krakatoa volcanic eruption. It requires transient scatterers of sunlight at great heights, in the thermosphere, above 500 Km, at heights which only methane and hydrogen are light enough to reach in sufficient quantity: molecules whose weight does not exceed that of atomic oxygen. Bronshten (2000) tries to explain these bright nights by softly braked cometary dust, settling to mesospheric heights (50 to 70 Km), but has to make a number of unrealistic assumptions - among them a twofold (in series!) sunlight reflection from dusty clouds - and still falls short of explaining the four successive bright nights which straddle the explosion.

What else is known about the destruction? This part of the Siberian permafrost is not easily accessible; it is snow-covered throughout most of the year, and defended by clouds of mosquitos during the few summer months. The first expedition into the area, in 1910, was carried out by the wealthy Russian merchant and goldsmith Suzdalev who, on return, urged the local inhabitants to keep silent about it. Had he discovered *diamonds*? Thorough investigations of the site, headed by Leonid Kulik, had to wait for 20 years, and were aimed at finding iron-nickel meteoritic debris. According to native reports, a number of funnel-shaped `*holes*´ had been blown on that morning, of diameters $\subseteq$ 50 m, as well as a `*huge dry ditch*´, probably $\supseteq$ 1 Km long, with many small `stones´ in it. That ditch has not been found by later expeditions. For the most conspicuous crater lake in the area, the `*Suslov hole*´, draining revealed a preserved *tree stump* at its bottom, ruling against an impact origin.

Kulik and his followers explored the morphology of the *treefall pattern*. He discerned a central `*cauldron*´, a few Km across, characterized by multiple treefall directions with some *five centers*. In this cauldron were islands of `*telegraph poles*´: trees that had lost all their branches but survived, and sprouted again. Such telegraph poles have meanwhile recurred at Hiroshima, after the nuclear bomb in 1945; they require supersonic blasting, fast enough to break off the branches before the latter can transfer the impacting momentum to the stem. The cauldron had a specific, centered geometry described by Kulik as the `*Merrill circus*´ inside an `*amphi-theatre*´; it can still be recognised today, even on near-infrared satellite photographs. Beyond the cauldron, the treefall pattern is coarsely *radial*, though following the ridges and valleys, see Fig. 2 in (Serra et al 1994), whereby the trees on the ridges tended to be felled, those on the slopes often only lost their tops, and those in the valleys often survived, see Krinov's sketch (1966). Obviously, the stormfield had blown horizontally, not from above.

Remarkably, none of the scientists involved in the reconstruction of the assumed impact seems to have considered momentum balance: an incoming atmospheric shock wave transfers its momentum to the trees. If it enters at a shallow angle, it creates a parallel treefall pattern, not a radial one. In Tunguska, we deal with a *zero-net-momentum* pattern, formed by an explosion at its center. But according to Krinov (1966), explosions after an impact are set up by massive meteorites only, with crater diameters larger than 100 m. This rules against an impact interpretation. Note that a simulation of the destruction by Zotkin & Tsikulin (1966) used an unrealistic input: They built a cable car with low (free-fall) kinetic energy, and ignited a chemical explosion close to the ground. Instead, the evaporation of an icy comet is an endergonic process which taps the huge infall energy.

Vasilyev (1998) discusses another inconsistency of the impact scenario: the various reconstructed *infall directions* do not agree; they range from 95^0 to 137^0, or even 192^0, North towards East, with similar inconsistencies in the inclination angle(!). A strict interpretation of the reports even implies a midcourse manoeuver! He also discusses the "*stony asteroid vs comet alternative*", which has persisted for decades: A stony asteroid would have left craters and debris in the impact area, and certain specific elemental anomalies, whilst a cometary nucleus would have disintegrated too high for the tree destruction, both in intensity and in morphology, also would have been detected weeks before arrival. The suspicion has even shifted to a carbonaceous chondrite as the impactor.

Additional peculiarities of Tunguska's treefall pattern are dozens of detached *root stumps*, with no indication of their origins (pits), some of which still lying around today, as well as *`John's stone´*, weighing 10 tons, which landed on the slope of Mt Stoikevich with at least sonic speed. Such heavy ejecta, hurled through hundreds of meters, argue against an impact interpretation; they require forces familiar from volcanic ejections.

The biggest problem for the impact interpretation has always been a complete *absence of debris*, by a factor of $10^{-8\pm2}$ in mass: The estimated kinetic energy in the storm field that felled the trees, $10^{24\pm0.3}$erg, would correspond to an impacting mass of some 0.4 Mt (Svetsov 1996, Foschini 1999). This mass would have left a several-mm-thick layer in the epicenter area if distributed uniformly, easy to detect. (Debris have been found for impactors weighing much less than a ton. For the 1947 Sikhote-Aline meteorite, one third of its mass was recovered within less than four years). Because of this absence of debris, alternative interpretations have been proposed over the decades, such as impacting antimatter, a low-mass black hole, solar transients, extraterrestrials, or mirror matter (Foot R 2001), none of them without problems. In their estimate of "the possible origin of the TCB", Farinella et al (2001) leave these problems unsolved.

There has been an intensive search for chemical, and isotopic anomalies in the Tunguska area, in *magnetic microspherules*, *sphagnum peat* columns, and *resin* layers, for essentially all the chemical elements from hydrogen (deuterium), carbon, and nitrogen all the way up to the platinum group elements (including iridium), with small enhancements around 1908 found for most of them, and a depression for deuterium, and with sometimes surprising inhomogeneities for different sites (Kolesnikov et al 1999, Hou et al 2004). None of them have been able to give an unequivocal answer for the complete evidence, in particular to discriminate against terrestrial outgassing (Longo et al, 1994). Vasilyev (1998), after a careful presentation, summarizes the evidence by "To this day, the matter which might be unambiguously assigned to the Tunguska Meteorite has not been found".

Among the further recorded evidences on the Tunguska event are an atmospheric *shock wave* racing around the globe, local *magnetic-field disturbances* lasting for more than 4 hours, many small local *earthquakes* thoughout the year, and optical anomalies measured by disturbances in the normal run of *Arago* and *Babinet neutral points* lasting for weeks. Their (long) durations favour a tectonic origin, but the evaluations are less straight-forward than those of the earlier facts.

The tectonic interpretation of the Tunguska catastrophe

Once we have appreciated the many *difficulties* of the impact interpretation - viz the (i) sounds before the lights, (ii) their duration (several 100 times too long), (iii) columns (not streaks) of fire, (iv) discrepant infall directions, (v) heat sensible at large distances, (vi) four bright nights, (vii) radial tree-fall pattern (viii) following the surface topography, (ix) cauldron structure, (x) hurled root stumps and John's stone, (xi) absence of impact craters, but (xii) formation of funnel-shaped holes, and (xiii) absence of meteoritic debris - why not follow Ol'khovatov (1999) and Yepifanov (2002), and pursue the other alternative, a tectonic outburst?! Knowing from Shoemaker, and Alvarez (1997) that there is only one impact crater for 30 *volcanic craters* on Earth, this re-interpretation of Tunguska cannot even be considered unlikely, except for the missing lava.

But *volcanism* has many different faces, ranging from supersonic ejections, plate tectonics and the formation of mountains, \`maars´, and kimberlites through lava flows, mud volcanoes, burning torches, and solfataras to quasi-steady outgassings, depending on the *viscosity* of the magma, on the magma supply rate, and on the transmissivity of the surface layers. Driving - in all cases - is *natural gas*, dissolved in liquid magma, often from as deep as the molten core of Earth (Kundt & Jessner 1986, Kundt 1991, 2001, Gold 1999). Highly viscous (acid) magma leads to explosive eruptions (like Mt. St. Helens) whereas in rising low-viscosity (mafic) magma, the natural gas often separates from the melt before reaching the surface, forming a *mystery cloud*. In all likelihood, this is what happened at Tunguska.

More specifically, Tunguska may have been the present-day formation of a kimberlite. *Kimberlites* are called after the south-African town of Kimberley, where diamonds and gold have been found by digging. They are huge, narrow funnels, growing in diameter from a few meters, at a kilometer's depth, to a dome-shaped tuff ring at the top, some Km across, and occasionally enclosing a shallow crater lake (Dawson 1980, Haggerty 1994). They occur in all continents, lie at the intersection of major fracture zones, in old, stable cratons, are intruded by ultra-alkaline rock types containing high amounts of volatiles, and show several spasmodic, often cold intrusions. An explosive injection from great depth is indicated, driven by volatiles. In Russia, the \`*Zanitsa pipe´* was discovered in 1954, in the headwaters of the Markha river in Siberia. Gold (1999) mentions that there is no evidence of frozen lava in kimberlites.

In the case of Tunguska, I have estimated a natural-gas mass of 10 Mt, required both for blowing the funnel-shaped \`holes´ (like the Suslov hole; and the ditch?), ejecting the *root stumps*, and for setting up an overpressure dome - the cauldron - big enough to drive the storm field for felling the trees out to some 30 Km distance (Kundt 2001). On venting (through some five of these holes), this expanding, initially liquidized gas - some 80% *methane* - escapes supersonically, thereby creating the \`*telegraph islands´*, until it has sufficiently expanded to be stalled by the ambient air mass. It then shoots up vertically, again supersonically, in the form of a giant *mushroom*, many times higher (200 Km) than the mushrooms of nuclear explosions (30 Km) because of its much lower molecular weight m and lower adiabatic index κ (both of which enter as $1/m[\kappa-1]$), whilst the surrounding air mass is pushed radially outward, in the form of a big storm field. This same gas will *burn* partially whenever it gets mixed with ambient oxygen and ignited (by self-generated lightning), and will continue burning at great height whenever it meets the surrounding atomic oxygen, thereby heating up and rising further. The newly formed water vapour will freeze out and remain frozen even when embedded in the hot thermosphere, because it gets radiatively cooled by seeing the cold night sky. In this way, snow clouds can reach the exosphere, and give rise to the bright nights, for a few days.

This alternative explanation of the Tunguska explosion - as the present-day formation of a kimberlite - is supported by the facts that (j) its epicenter coincides with the 250 Myr old *Kulikovskii volcanic crater,* forming a part of the *Khushminskii* tectono-volcanic complex, (jj) it lies near the crossing point of a number of *tectonic fault lines*, one of them running towards lake Baikal, (jjj) it sits at an Asian *geomagnetic* maximum, and also *heat flow* maximum, surrounded by ringlike *Moho isohypses* (Jerebchenko IP, Kochemasov GG 2001), and (jv) it is located above a thick, sealing *basalt layer* (Yepifanov 2002), near the center of the Siberian *craton*. Moreover, (v) during their 1999 expedition to (the near) lake Cheko, Longo's group recorded a local *radon* outburst lasting four hours. And as mentioned above, (vj) tectonic outbursts are at least 20 times more *frequent* than meteoritic impacts at the same destruction energy (Kundt 2001, 2002).

Finally, (vjj) the *mystery clouds* mentioned above are likely to form the low-intensity, more frequent end of the tectonic methane-outburst distribution, observed at a rate of many clouds per year - by airplane pilots and by satellite photography - and indirectly as `*pockmarks*´on 6% of the sea floor (Walker 1985, Kundt 2001, May & Monaghan 2003). The clouds rise rapidly from an unresolved spot on the surface - land or water - expand, hence cool, and bend downwind as they rise, looking whitish by condensing water vapour on their periphery. They tend to ignite near the ground when escaping from land, due to self-generated lightning, but rise unburnt when issuing from the sea, probably causing a threat to commercial sea and air traffic, at a rate of more than once per year.

(Other) Recorded Impact Events

What do we know about terrestrial impacts? Their *rates* have been estimated between monthly and 10^8-yearly events for impact masses between 10^{-1}t and 10^{12}t , in (Kundt 2001, 2002), collected from Ol'khovatov (1999), Krinov, and other recordings. Well-studied cases are *Sikhote-Aline* (Siberia, 1947), *Wabar* (Saudi-Arabia, ≈ 1800), *Gibeon* (Namibia, < 1838), *Barrington* crater (Arizona, - 50 Kyr), and *Chicxulub* (Yucatán, - 65 Myr; Alvarez 1997, Melosh 1997), the latter's age being recently somewhat controversial. The list does not include *cometary* impacts, because they are estimated to be rare, and would likely not cause any lasting damage to the surface of Earth. Yet there is the 1994 crash of comet Shoemaker-Levy 9 onto Jupiter, whose probability must be multiplied by a factor of $10^{-5.0}$ when compared with terrestrial events - for equal embedding fluxes - because accretion rates scale as the square of the accretor's mass. As the best-studied case, I now turn to Sikhote-Aline.

On 12 February 1947, at 10:30 local time, an iron meteorite struck the easternmost edge of Siberia, in the western part of the *Sikhote-Aline* mountain range. Eyewitnesses reported a bolide crossing the atmosphere within ≤ 5 s, though noises were heard for (10±5) minutes (Krinov 1966). The bolide left a gigantic trail, or smoke band which got increasingly wiggly but disappeared only towards the evening. According to eyewitnesses, the bolide split up successively at the four heights of 58, 34, 16, and 6 Km, towards a final diameter of 0.6 Km. From infall channels in the ground and tree destructions, its infall angle could be measured as (30±8) deg w.r.t. the vertical.

Within the four succeeding years, over a hundred small *craters* were detected in that area, the largest of diameter 26.5 m. They formed three concentrations, spread over an ellipse of diameters 1 and 2 Km. All craters were formed by meteoritic fragments whose impact channels penetrated between 1 and 8 m into the ground, depending on their shape and orientation. The summed weight of all the collected iron-rich fragments was 23 t, and estimates yielded about 70 t total for the impacted mass, corresponding to an iron bolide of diameter 6 m, some $10^{-3.5}$ in mass of the hypothetical Tunguska bolide. Even if a comparable amount of rocky material had been left behind in the atmosphere, in the shape of the dust trail, the Sikhote-Aline meteorite was still some 1000 times lighter than Tunguska's hypothesized one. No *impactites* were found at Sikhote-Aline: explosions after impact tend to occur (only) for crater diameters ⊇ 100 m. Telegraph poles and snapped-off tree tops were plentiful. Trees were felled radially around craters, but only in directly adjacent ringlike domains, of width $\subseteq$ 30 m. Some of them took bizarre shapes.

(Likely) Tectonic Outbursts

The list of internal (tectonic) outbursts is less uniform than that of external (impact) catastrophes. It contains *volcanic eruptions*, like Mt. St. Helens (1980), Krakatoa (1883), Tambora (1815), and Santorin (Thera, 1400 BC), with their large outcrops of lava, in excess of Km^3 per event. It also contains the mountain-forming activities of the Eifel (- $\subseteq$ Myr), still ongoing, and of the Alps (- $\subseteq$ 10 Myr). The disappearance of *Sodom and Gomorrah* at biblic times may also be due to tectonic events, making the two cities slide to the bottom of the Dead Sea. Finally, among the smaller, more recent events - compiled by Ol'khovatov (1999) - there are *Cando* (NW Spain, 1994), *Allende* (Mexico, 1969), the *Zanitsa pipe* (Siberia, $\subseteq$ 1954), and *Tunguska* (1908). These events are distributed between occurrence *rates* of yearly and millennial, and liberated energies corresponding to impact masses between 10^2t and 10^6t. (Impact velocities tend to be at least 10 times higher than outburst velocities, hence correspond to destruction energies at least 100 times larger [than outburst energies] for a given mass).

Let us now look at the *Cando* outburst, a more recent miniature Tunguska event. A destruction energy comparable to Sikhote-Aline was liberated by the bolide of 18 January 1994, seen and heard at 7:15 UT in the parish of Cando, NW of Spain, (Docobo et al 1998). It took three months until a newly formed crater was reported, of size 29 x 13 m, 1.5 m deep, whose former (big) pine trees were hurled downhill through 50 to 100 m. An in-between road remained clear of soil from the ejection, eliminating the possibility of a landslide - which did, however, occur on the same day 300 m NW of the main crater, knocking down two pines. No meteoritic debris were recovered. The authors prefer a high-speed gas-eruption explanation.

How to discriminate between Impacts and Outbursts?

Tunguska, Sikhote-Aline, and Cando are three catastrophical events of the last century - the first of them some 10^3 times more energetic than the two others - which have found quite different explanations in the literature. Whereas Krinov (1999) spends 129 pages of his 397-page book on giant meteorites on the "Tunguska meteorite", Ol'khovatov (1999) prefers a tectonic interpretation. Even Sodom and Gomorrah have been recently interpreted as former cities on the SE bank of the Dead Sea, blown up and/or slid to the bottom of the Sea by a volcanic eruption. How can we *discriminate* between the extraterrestrial and the terrestrial interpretation?

Whereas with the latter interpretation you can be rejected from peer-reviewed journals, even when based on sober and friendly arguments, the former interpretation may only apply to a 3% minority of all events. Eyewitnesses speak of bolides - or fireballs - in all cases, and of barisal guns lasting for many minutes. Trees are felled, or debranched, or their tops chopped off, craters are formed, and fires are ignited in all cases. What differs are the *details*, of which I have listed some 20 above, each of which can be used for a discriminaton. They read:

Volcanic *flames* in the sky can last for up to an hour whereas a meteoritic infall trail flashes only for a few seconds, and its *heat* cannot be sensed in the faces of eyewitnesses, because of too small an extent in space and time. But a meteoritic *trail* tends to stay visible for hours, unlike volcanic flames. *Barisal guns*, on the other hand, are heard for comparable times in both cases by distant eyewitnesses (d $\supseteq$ 70 Km) because sound echos from warm layers above the stratosphere take that long. For tree falls, their *pattern* matters: Absorbed *momentum*? How many *centers*? Telegraph poles require strong shock waves, hence trace the *supersonic* domain. *Craters*, if blown from below, can contain tree stumps, whereas those formed by infall show an impact channel plus debris. Volcanic outblows can *throw* trees, or root stumps, or rocks through several hundred meters, whereas non-explosive infalls (with small craters) redistribute the impacted soil in their immediate surroundings ($\subseteq$ 30 m). Meteoritic *debris* tend to be recovered for impact masses in excess of fractions of a ton.

There are additional criteria. Volcanic blowouts require pressurized vertical exhaust pipes from a deep-lying fluid reservoir, which have their imprints on the local *geography*, like the Kulikovskii crater. Moreover, when megatons of natural gas - mainly methane - are suddenly released into the atmosphere, they will rise, burn, and form *clouds* in the thermosphere for several days, at heights above 500 Km, where they scatter the sunlight. Such scattered sunlight at night is known as the bright nights of both Krakatoa (1883) and Tunguska (1908). We live on a tectonically active planet.

How to evaluate the impact risks? None of the published repetition rates I have seen have attempted to *discriminate* between external and internal hazards. Rather, a power law has been fitted through Tunguska (1908) and Chicxulub (-65 Myr), starting with Shoemaker (1983), and continuing through Chapman & Morrison (1994), Jewitt (2000), and Atkinson (2001). Note that a determination of the density of near-Earth objects (*NEOs*), as by Rabinowitz et al (2000), cannot reliably predict the collision rates with Earth because of the unknown transfer function, which depends on their orbital parameters, in particular on their orbital inclinations. I therefore made an attempt in (Kundt 2001, 2002) to estimate the independent statistics of extraterrestrial and terrestrial events, and came up with a much less pessimistic prediction for the likelihood of harmful future impacts -- in line with the fact that life on Earth has not been erased for much more than a Gyr. Even the great "*mass extinctions*" of the past were, in reality, only extinctions of species, not extinctions of life as a whole.

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