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The Tunguska event

Chris Trayner

The Tunguska event of 1908 is reviewed. The event, its location, effects, eye-witness reports, apparent trajectory and probable nature are described. The importance and growing availability of Russian research are mentioned. It is concluded that the event was probably caused by the collision of a comet or asteroid with the Earth, but that it is not yet certain which.

Introduction

In Siberia early this century, a sizeable meteor was seen over an area 2000km across. The body responsible, the Tunguska Cosmic Body (TCB) to use the Russian term, exploded high above the forest. It left no crater and no meteorites have been found. The site was first scientifically investigated in 1927 by Leonid Kulik. Despite extensive research since then, the nature of the bolide and many details of the event are uncertain. It was probably a small comet or asteroid, or a fragment of one. The event was presumably nothing exceptional on geological or astronomical time-scales, but is possibly unique in our historical and scientific experience. (A similar event may have occurred in the Brazilian jungle in 1930.[1]) The last five years have produced many theoretical advances in our understanding of meteoritics and the Tunguska picture is slowly clarifying. This *Journal* published a good review some years ago;[2] the present one attempts to enlarge upon it and bring it up to date. Like probably all western Tunguska reviews it does no more than scratch the surface of the Russian-language literature on the subject.

Geography of the area

The Tunguska event occurred in a remote part of Siberia (Figure 1). It is about 700km northwest of Lake Baikal and about 70km from Vanavara, 30 minutes by helicopter. The traditional route is along the Tropa (pronounced 'trappa') Kulika, the Kulik Route, a journey of 2½ days on foot. The event is named after the Podkammenaya Tunguska River, not to be confused with the Nizhnaya Tunguska further north. Apart from a few small towns, this area is sparsely populated and is mainly forest negligibly disturbed by human activity. The ground underneath the bolide's explosion is termed the epicentre; this term is used both for the exact point and for the general area, perhaps 3–5km across. The epicentre comprises gently undulating hills and valleys, about a hundred metres from top to bottom, with bogs in the hollows and woodland above (Figure 2). The forest ecotype is Taiga, also known as Northern Coniferous Wood[3] which in fact comprises mixed coniferous and deciduous trees (Figure 3). There is an undergrowth which is scrubby and can be walked through with ease. The bogs are divided into two distinct areas: wet swamp and raised peat mounds. The former is structurally weak and can only be walked on in a few places; elsewhere a researcher or meteorite would go straight through the vegetation (Figure 4). Part of the main swamp was found to be 25 metres deep.[4] It is in the nature of peat bogs that dead vegetation does not decay completely but accumulates, building the surface level up to generate peat mounds. These are firm enough to walk upon and support a scrubby herb layer, occasional trees and abundant lichen (Figure 5). The epicentre has one main bog (Figure 6). It is possible that before the explosion the Southern Swamp was solid peat bog rather than swamp.[5]

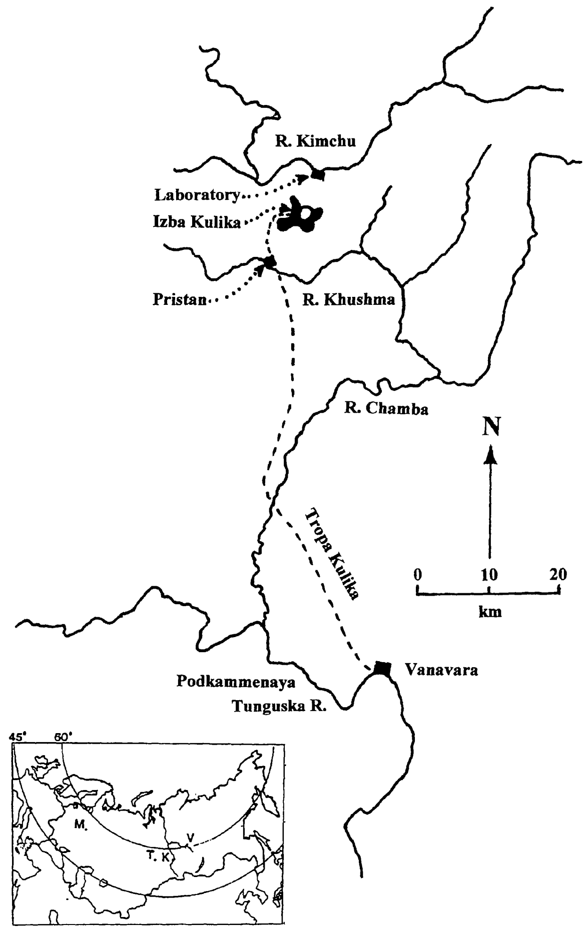

Figure 1. The situation of the epicentre with respect to Vanavara and the relevant rivers. *Inset:* location of the epicentre within Russia. M=Moscow, T=Tomsk, K=Krasnojarsk, V=Vanavara.

Geologically, the general area is covered with upper Paleozoic or lower Mesozoic basalts[6] of the order of 200 million years old. The epicentre is in the crater of a long-

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Figure 2. Aerial view of the epicentre. The northwestern swamp is in the foreground, Mount Stoikovitch behind it on the right. Seen roughly from the northwest. [CT92/2/67] (All photographs by the author, with identification numbers in square brackets.)

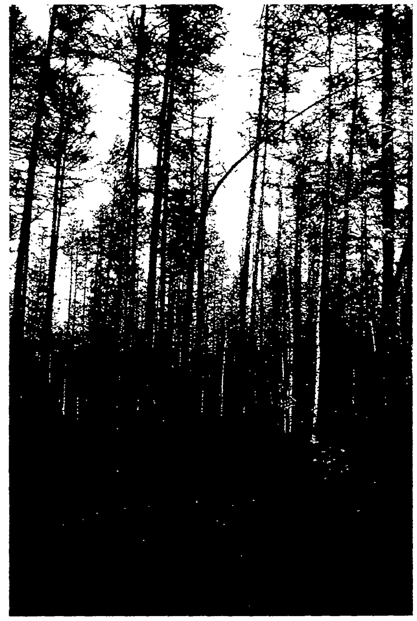

Figure 3. Typical taiga – mixed woodland with a herb layer underneath. [CT94/3/254]

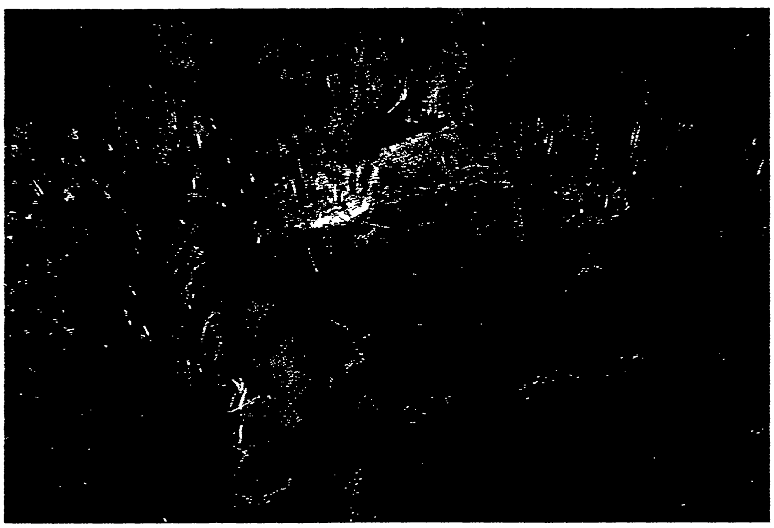

Figure 4. Part of the swamp, looking almost straight downwards. Occasional patches of open water (black) are visible amongst the green vegetation. [CT92/2/63]

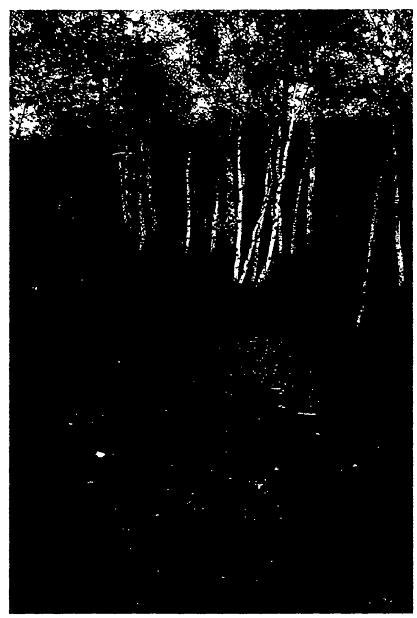

Figure 5. Peat mounds growing out of the northwestern swamp. Small shrubs grow over the mound; the white patches on the ground are lichen. [CT94/3/287]

extinct volcano. Mount Stoikovitch, the central hill, is the frozen magma pipe. The swamp surrounds this and is surrounded in turn by the old crater wall including Mount Farrington. These volcanic structures are all weathered almost beyond recognition.

The main research area is bounded by the River Kimchu on the north and by the River Khushma on the south (Figure 7). Both are small, typically of the order of 10 metres across and shallow enough to wade in many places. The swamp drains into both of them. There is a lake, Ozero Cheko (Swan Lake) on the Kimchu.

Expeditions over the years have built log cabins in three locations. Best known is the Izba Kulika, the Kulik Hut, at the foot of Mount Stoikovitch next to the swamp (Figure 8). On the banks of the Khushma is the Pristan, the Landing Stage, where earlier expeditions arrived by boat. On the Kimchu is the hut known as the Laboratory, built about 1980.[9]

The summit of Mount Farrington is the normal cartographic reference point. Its northern summit bears a wooden pylon visible from much of the epicentre. Its southern summit, about 100m away, is the astro-radio point whose position was measured in 1929 using astronomy and radio time signals.[7] A GPS reading taken in 1994 located the southern summit at 60° 55′ 01″ N, 101° 56′ 55″ E.[8] The epicentre in the sense of the point under the explosion is 3km to the southwest and has not been located to a better accuracy than a few hundred metres.

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Siberia is a land of strong seasonal contrasts. In July and August, when expeditions are usually conducted, the climate is warm or hot and the days long. The area is one of unspoilt beauty and the visitor realises why Russian researchers often refer to the Tunguska Catastrophe. The sense of another Eden, unsullied by mortgages and road-works, is marred only by occasional forest fires and ravenous mosquitoes. In winter the temperature falls to perhaps –40° to –50°C, making it all the more remarkable that Kulik spent a winter there.[9]

The event

The event took place on the morning of 1908 June 30 (by the Gregorian calendar, though Russia used the old-style one until the Revolution). A bolide came from the southeast and travelled at least 1000km through the atmosphere.[9,10,11] It glowed, having a brightness broadly similar to the Sun's, and left a dust trail behind it. Being supersonic, it radiated a shock wave which was heard as a boom. It was seen and heard in this way over an area 1500km across. It passed near to a small trading post called Vanavara and exploded about 70km away above the taiga. One estimate of the time of the explosion is 07h14m28s local time, 00h14m28s UT[12] (though with what accuracy is unclear). A more recent analysis gives 00h13m35s ±5s UT.[13] Both are based on analyses of seismic records and propagation velocities. Estimates of the explosion height range generally from 5km to 10km, with the more careful estimates being 6.5 km,[44] 7.5km[14] and 8.5km.[15] It generated a pillar of fire and a cloud of smoke estimated as rising to tens of kilometres.[16,17] About 25km from the explosion two nomads, Akulina and Ivan Potapovitch Petrov, were knocked unconscious for a while.[18] 70km away in Vanavara the shock waves were loud, damaged houses slightly and knocked people over. The heat flash at that distance was painful.[19] No-one is known to have been killed as a direct result. For general reviews on the event see references 2, 4, 10, 20 and 21.

Few of the requirements of good fireball recording were fulfilled. Most of Siberia is sparsely populated; few if any of the observers understood the nature of meteors and noted relevant details. The people in the vicinity of the explosion were not, apparently, interviewed with a view to obtaining meteor data until 1924, sixteen years later;[22] many of their accounts are suspect. About 650 people who were up to 1000km from the epicentre have been interviewed over the years.[23] Some of these interviews were as recent as 1974, however, and the accuracy of the memories is debatable.[24] The poor quality of this evidence creates serious problems for any attempt to calculate the trajectory; this must be borne in mind when considering conclusions about the Tunguska Cosmic Body.

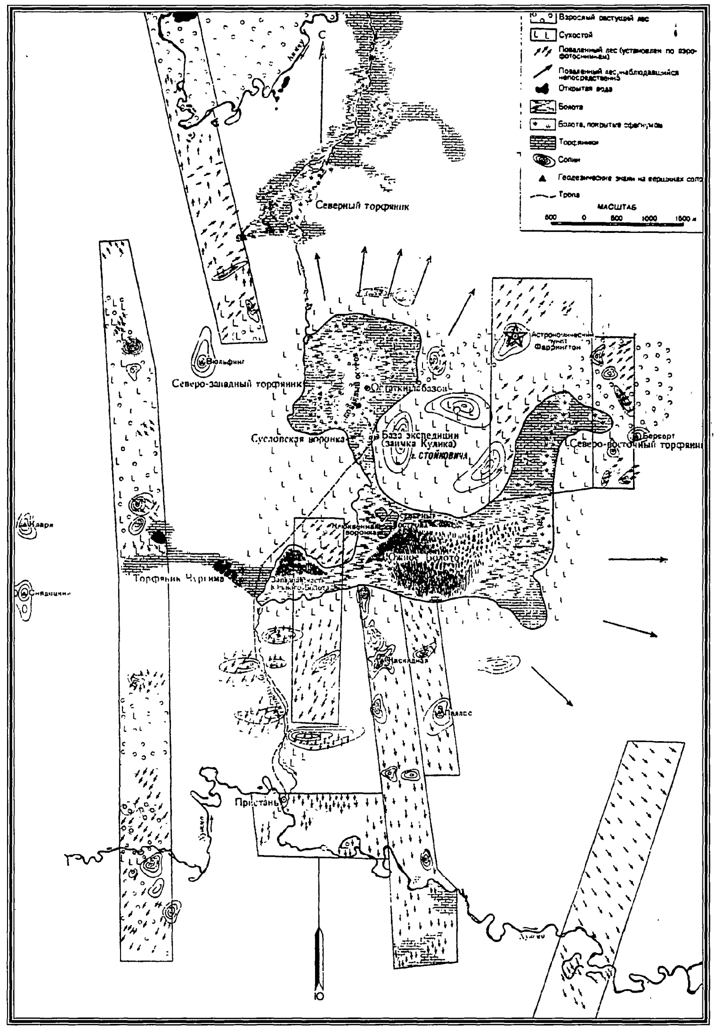

Figure 6. Detailed map of the epicentre. (The trapezia are boundaries of a tree-fall survey.) *Provenance unknown.*

Effects of the bolide

These can conveniently be divided into three categories: distant, local and physical remains.

Outside the epicentre

The shock wave from the explosion hit the ground in the epicentre and generated seismic waves much as an earthquake would have done; it amounted to Richter 5.0.[12] These waves were recorded by many distant stations.[25,26] Later analysis of these records also gave the accurate timing of the explosion and an estimate of the explosion energy.[12]

The explosion also generated several cycles of very low frequency sound termed Air Pressure Waves. These ranged from about 3mHz (5 minute cycles) to about 30mHz (30 second cycles) plus indistinct higher-frequency components.[25] They were recorded by microbarographs at six stations in England. Though not understood at the time, they were later found to come from the Tunguska explosion and confirmed the timing and location.[25,26,27] Abroad, the station

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Figure 7. River Khushma, looking downstream from the Pristan in the morning. [CT94/3/102]

at Potsdam recorded them twice, first the waves by the direct route and second those which travelled the other way round the world via the epicentre's antipodes.[26]

Much of Europe had no real darkness on the night following the event (June 30/July 1): the sky was covered with high, light cloud.[28] There are records of people reading newspapers and photographing their local cathedral at midnight without artificial light.[25,29] The sky was described variously as snow-white, pink, red, golden, orange-yellow and green; presumably some of these were normal sunset colours. Geographically, the effect appears to have stretched south to a line from Bordeaux to Tashkent,[30] and north at least to Aberdeen and Stockholm;[26] to the west it did not reach America and probably not far into the Atlantic[30] (Figure 9). These effects were repeated on the next two nights; from one report, the second night (July 1/2) was the brightest.[31] There is also one such report from June 29/30, i.e. within a few hours before or after the impact.[32] Astronomers reported abandoning attempts at observation.[33] In the day, unusual cloud of a mother-of-pearl appearance[26] and haloes round the Sun[28,29] were reported. Further away, in the United States, regular recordings of atmospheric transparency showed a marked deterioration which started two weeks later and lasted a month.[34] All these effects were presumably caused by dust associated with the bolide. The light nights may have been caused by the dust reflecting sunlight; calculations[30] suggest this is possible. There has been speculation as to whether the dust would have been within the atmosphere or above it. The particle density in the latter case seems too small, but this is uncertain.[35,36,11] The time for dust to remain in the atmosphere would depend on particle size. Both possibilities imply dust travelling with the bolide on a virtually parallel path. Atmospheric dust would have travelled by this route and then hit the atmosphere over Europe; it arrived too soon for wind to have blown it from Tunguska.[26]

Were the bolide a comet, the dust might have been tail material,[37,26] though this cannot be confirmed without pre-impact observations of any such comet. The TCB was coming from the general direction of the Sun, so the tail would have preceded the body and might plausibly have spread its dust over Eurasia west of the impact site, as observed.[26] However, there might be too little dust to cause the effect.[11] If the body were an asteroid it might well have carried a dusty regolith.[38] This would have been held to the asteroid by very weak gravity and might have become detached and followed a nearly parallel path. It is frustrating that one astronomer reports abandoning spectroscopic work due to the light.[33] Although sky spectra were described as characteristic of reflected or scattered sunlight, it would have been interesting to have re-examined them in the light

Figure 8. The Izba Kulika (Kulik Hut). Chopping wood in front is Gennadij Andreev of Tomsk State University, who does much of the organisation of expeditions nowadays. [CT92/2/121]

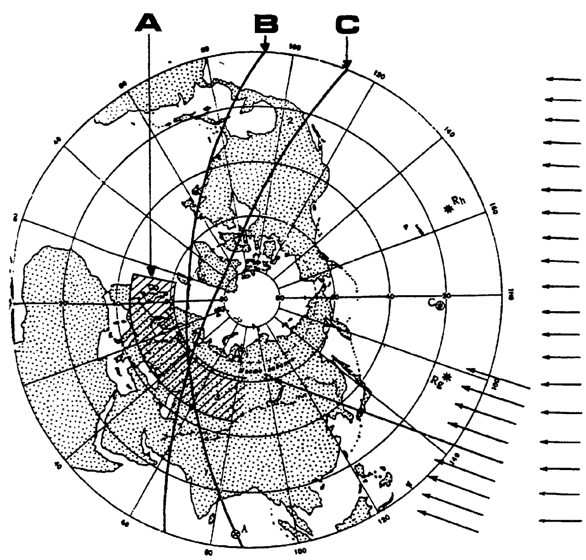

Figure 9. Area of anomalous twilight presumably caused by the Tunguska meteorite. A: Approximate area (crosshatched) where light nights were seen. B: The terminator at the time of the impact. C: Boundary of the hemisphere visible from the direction from which the TCB came. From reference 67, Figure 4.

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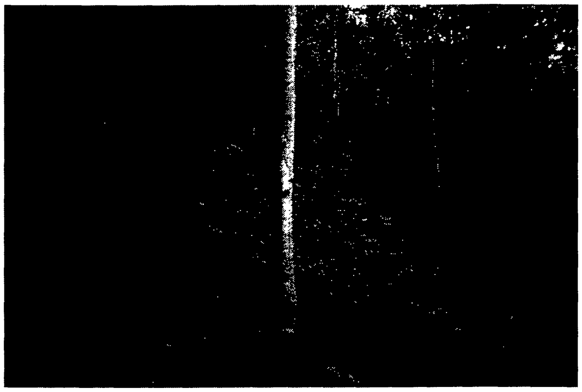

Figure 10. A tree which was felled in 1908, above Churgym Canyon and about 2km from the exact epicentre. [CT94/3/129]

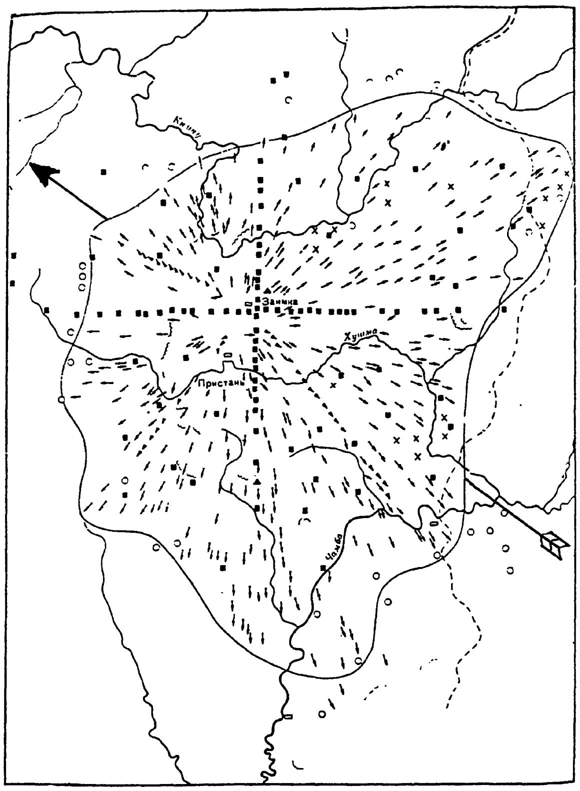

Figure 11. Tree-fall map of the epicentre. The outer boundary of the main area of felled trees is shown as a butterfly-shaped line. Arrows show the fall directions of trees. A plausible trajectory with an azimuth of 125° is shown. Adapted from reference 42, Figure 4.

of current knowledge of cometary and asteroidal spectra. It is unclear whether any full record of the spectrum was kept, though there was no sign of the glow being auroral in nature.[29,33]

There is a possibility that the Tunguska body may have generated aurorae in the Antarctic about seven hours before the impact. This would be explicable were it a comet whose ion tail preceded it towards the Earth.[39]

The event may have caused perturbations in the Earth's magnetic field. Irkutsk Observatory, about 900km south of the epicentre, registered changes starting three minutes after the explosion and lasting 4–5 hours. They were different from normal magnetic storms of solar origin but similar to ones caused by nuclear explosions.[20,40]

Inside the epicentre

The bolide exploded above the taiga; the presumed mechanism is described below. The first effect of the explosion on the ground was a large pulse of visible and infrared radiation which set fire to the forest. This was followed some tens of seconds later by the blast from the explosion; recent work[41] suggests that this would probably blow the fire out. It is currently unclear how long the fire actually lasted; it also appears to have occurred in isolated patches.[9]

The blast flattened most of the trees in the area, generally laying them down with their crowns pointing away from the epicentre (Figure 10).The details have proved useful in testing theories of the bolide trajectory and the explosion. Much experimental and theoretical research has been conducted into 'the pattern of the throwing-out of the trees', as Russian papers normally call it. A survey of the directions of fall, conducted in 1961,[42] shows three major departures from a simple circular pattern (Figure 11). Firstly, many trees in the centre were left standing but stripped of most of their branches: 'telegraph-pole trees' (Figure 12). Being underneath the explosion, they were pushed downwards rather than sideways. Secondly, the outer boundary of the tree fall is not circular but a butterfly shape, approximately symmetrical about the bolide's trajectory. Thirdly, trees in the 'wings' of the butterfly did not fall radially outwards from the epicentre. Their fall directions, if projected backwards, cross the bolide's ground track slightly 'uprange' of the epicentre. All these effects can be explained by models which assume that the trees were propelled both by the blast from the explosion and by the shock wave from the bolide's prior supersonic passage (Figure 13). The point explosion had the main effect but the sonic boom modified the tree fall in the south-eastern area. Both a physical[43] and a mathematical model[44] have generated reasonable simulations of the reality when working from plausible speeds and angles of the trajectory (Figure

Figure 12. A telegraph-pole tree in the exact epicentre. [CT92/2/151]

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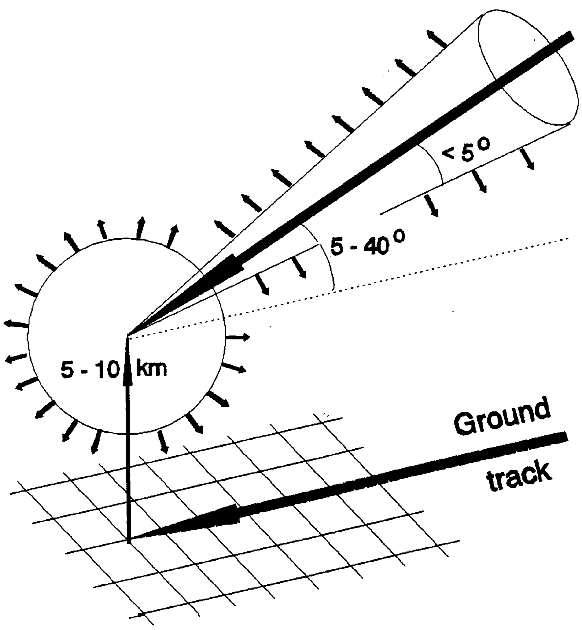

Figure 13. The shock waves comprising two components. The hypersonic bolide radiated a conical ballistic wave (of which the internal angle, here exaggerated, was so small that it was approximately a cylindrical wave). The explosion generated a shock wave, presumably spherically symmetrical.

14). There are other minor deviations from the pattern, some due to hillsides protecting trees but others without apparent cause.[45] The outer limit of the fall area is generally between 15 and 35km from the centre (Figure 11). 2150±50km^2 of trees were felled.[46]

The forest regrew faster than is normal after forest fires.[20] Suggestions that the heat of the bolide turned atmospheric nitrogen into nitric oxide, which acted as fertiliser,[34] proved unfounded.[47] The effect was previously ascribed to radioactivity measured in the area, but these measurements are now thought to be mistaken.[47] Nor can increased illumination from the lack of tree cover explain the observations. It may be that trace elements from the bolide stimulated growth;[20] Europium is one element suggested.[48]

Forest fires are a natural part of the ecology of the taiga, so it should not be assumed that any burnt tree in the epicentre was damaged in 1908. The Russians have conducted much research into the burn patterns on these trees. Not all the trees engulfed in the fire died, though many survivors show scars from the tissue repair which followed. In more lightly burnt trees, a cross-section will show thicker, brown annual growth rings in the region of the 1908 ring, often only in the direction of the epicentre[49] (Figure 15). In these cases thermal radiation was presumably the major heat source, any forest fire damage being minor. Some pines had branches stripped off and smaller new ones have grown out at right-angles to the original branch, i.e. tangentially to the trunk (Figure 16).

The shape of the swamp may have been affected by the explosion, though no scientific visit was made to the site until 1927, nineteen years after the event. Il'ya Potapovitch Petrov lived in Vanavara and accompanied Kulik to the epicentre in 1930. When he saw the Southern Swamp he declared that the swamp level was lower than before, leaving the peat islands higher, though in one place he said that solid peat had been replaced by swamp.[5] Whether his memory is to be trusted is debatable. There are also several reports of streams bursting forth from the ground and fissures appearing,[18] though few if any of these have been confirmed.

There may have been genetic changes in the flora and fauna of the area. These have been studied in pines and in insects which migrate very slowly. The area of these mutations correlates well with the trajectory as deduced by other means. Forest fires and heat from the explosion do not seem to explain the effect. Causes under consideration are ionizing radiation from the bolide and electromagnetic pulse[20,50]

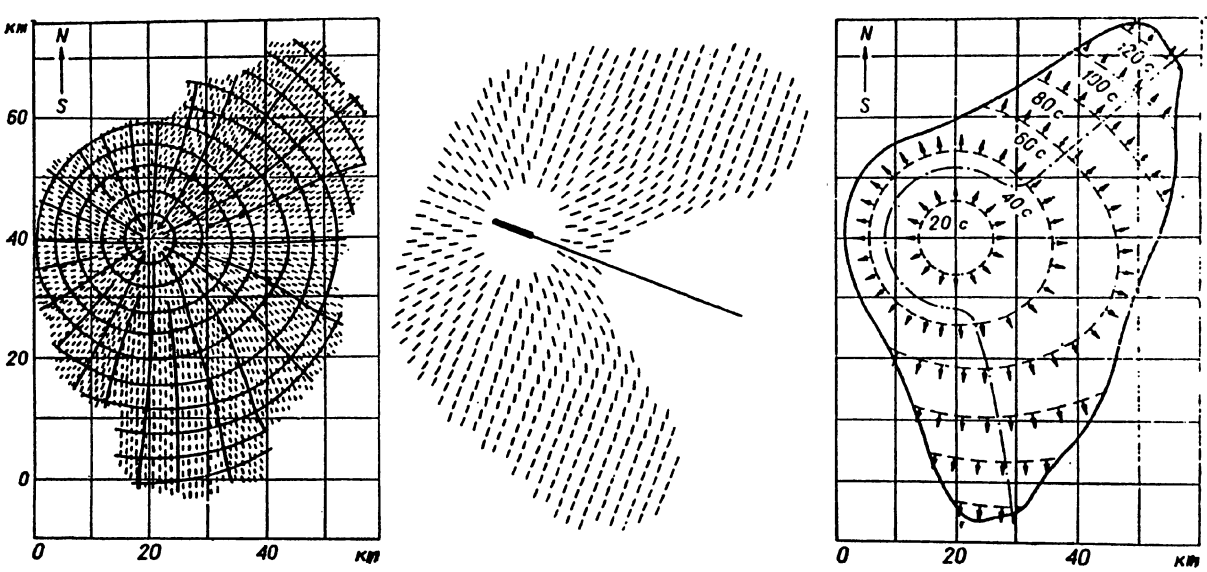

Figure 14. Tree-fall patterns: comparison of models with reality. *Left:* as measured in the epicentre. *Center:* as modelled physically.[43] *Right:* as modelled mathematically.[44] From reference 14.

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(see the comments on magnetic perturbations above). In terms of Darwinian evolution these effects would constitute an additional source of original mutation, which would then presumably be subject to recombination and natural selection in the normal way. There is a possibility that a man born in the area in 1908 acquired genetic anomalies.[20,50]

There are other possible effects described in the Russian literature though with only passing references in English-language works, such as thermo-luminescent changes of the rocks and magnetic anomalies in the soil and rock, increasing towards the epicentre.[50,20]

Physical remains

No macroscopic physical remains of the bolide have been found, so there was a meteor but no meteorite, though the term Tunguska Meteorite has become traditional, especially in the Russian literature.

A number of sub-millimetre spherules, ranging down to a few micrometres across, have been found in the soil and peat of the epicentre. The task of distinguishing meteoritic particles from soil and wind-blown industrial dust is daunting. Much of the initial collection was performed magnetically[51] which would, of course, lose purely stony material from an asteroid or comet. More recent work has isolated the 1908 layer in the peat.[52] Of the material collected in the field, laboratory analysis of element ratios[52,53,54] rejected most as definitely or possibly terrestrial. More was probably derived from the continual influx of fine meteoritic dust which drifts down through the atmosphere. A small remainder convincingly originated from the Tunguska bolide. The element compositions which were found match no known meteorites[55,56] but are plausible for cometary material.[52] Elements showing significant enhancements include bromine, lead, iron, rubidium, nickel and iridium.[52,56]

The discovery of such material has also been reported in 1908-layer ice samples from the South Pole,[53,57] suggesting that the explosion lofted material into the stratosphere whence it descended on much of the Earth. Other workers have failed to get the same results with other Antarctic samples; it has also been sought but not found in Greenland ice.[47]

Calculations suggest that the TCB would have generated up to 30 million tonnes of nitric oxide (NO) during its atmospheric passage,[34] which would have had radical ecological effects. When rained out, for instance, it would have acted as fertiliser and maybe caused the fast forest re-growth. Other workers regard the quantity as exaggerated[14] and the nitrate-rich layer which would be expected in Greenland ice has not been found.[47]

Pine trees in the epicentre have yielded further samples of meteoritic material. A team from Bologna University has taken samples from trees which survived the explosion and are growing today. Where a dead branch emerges from a pine tree it is surrounded with resin; this holds any dust which drifts down onto it. Such branches were identified; the point which was on the outside of the tree in 1908 was located by counting annual growth rings. Typical meteoritic elements showed concentrations at this point.[58]

Possible evidence for meteoritic material exists in the

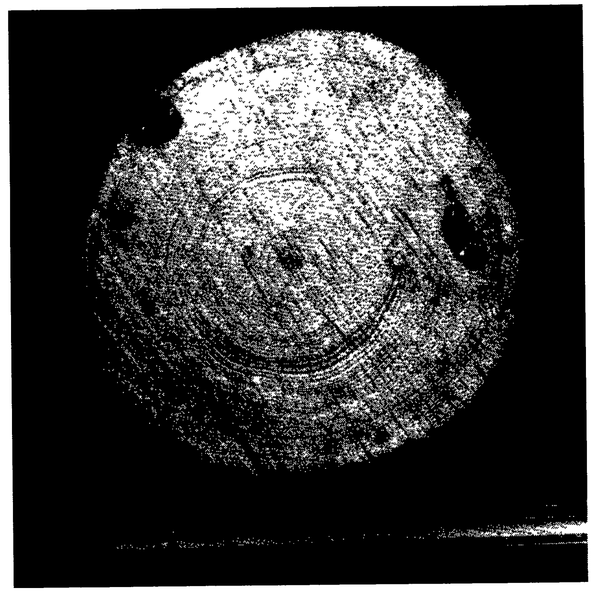

Figure 15. Cross-section of a tree cut in 1992. The growth rings following 1908 are thicker and darker in the direction of the explosion towards the bottom of the photograph. (The darker oval patches are merely exuded resin.)

Figure 16. Branches growing from a tree which survived 1908. The original branches were removed by the shock; new ones have grown tangentially to the trunk, at right angles to the original branches. This tree is at the Pristan, about 5km from the exact epicentre. [CT94/3/306]

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Figure 17. A small crater in Churgym Canyon. The notebook on the left is 20cm long. [CT94/3/136]

form of three small craters (Figure 17) found in Churgym Canyon in the epicentre by Gennadij Andreev of Tomsk State University in 1991.[9] The possibility has been voiced that these are hypervelocity impact craters formed by meteoritic material expelled by the explosion. There are, however, non-meteoritic explanations. One of the craters showed a marked deterioration between 1992 and 1994; in the opinion of the author it is unlikely to be 85 years old. Other workers, shown 1994 photographs, share this view.[59] The second crater can be ruled out, as a back-projection of any projectile's trajectory hits the canyon wall.[8] The third crater has not been examined by the present author. The matter is not yet settled but opinion seems to be moving away from a meteoritic origin.

It is an open question whether any macroscopic fragments await discovery. The swamp could hide many sizeable specimens, though one would have expected others to have rained down upon solid ground. The present author estimates dry land to constitute about 70% of the most explored centre of the area and researchers to have spent over 100 person-years in the epicentre. Probably everyone visiting the site has kept their eyes on the ground from time to time hoping to find something. It is arguable that fist-sized meteorites would have been found unless they are absent or extremely rare. However, recent work[41] estimates that the body would have disintegrated into typically centimetre-sized fragments. These might have been overlooked if people were looking for larger objects, especially if the fragments were stones rather than irons or stony-irons. Finally, it is entirely possible that the energy involved in the explosion vapourised the entire body and that only a fine dust of re-solidified droplets rained down. Most of these would have since been washed into the soil by rain or carried into the rivers by melting snow.

Misleading information

As with many topics of general interest, a certain amount of misinformation circulates about the Tunguska event.

In 1927 Kulik[19] described holes with widths ranging from about a metre to tens of metres and depths of up to tens of metres. The description is unclear but they were probably in the peat islands[60] (Figure 5). He thought these 'meteorite holes' would contain meteoritic fragments, though they turned out to be normal features of peat bogs, possibly caused by ice expansion in winter.[61] Kulik was not an ecologist and spent much time excavating them.

In recent years, a local hunter found a crater 150km southeast of the epicentre, where a detached fragment of the bolide might conceivably have landed. Unfortunately, when investigated this turned out to be of terrestrial origin.[9]

The reader will occasionally encounter reports of enhanced radioactivity in the area. Subsequent, more careful work has found no such enhancement beyond that due to fall-out from nuclear tests during the Cold War.[30,62]

There are many other minor problems of accuracy such as a translation of Kulik's original paper giving the longitude 30° in error, inaccurate distances from Vanavara and the use of old obscure Russian units of length.[63] Finally, it is not always realised that at least two Whipples have written about Tunguska. Francis John Welsh Whipple (1876–1943) worked on the air pressure waves; Fred Lawrence Whipple (born 1906), best known for his work on comets, has researched other aspects.

The explosion

For many years the explosion of an asteroid or even a comet in the atmosphere seemed implausible. Mechanisms are now well established, however, by which such explosions may take place. The idea of Progressive Breaking[14,64] has recently been made quantitative.[41,65] As a body plunges into the atmosphere air resistance decelerates it by retarding the leading surface. The front decelerates the rest of the body by building up internal pressure. As the object moves deeper into the atmosphere, the air density and the body's internal forces increase. At a certain point these stresses may exceed the breaking strength of the material and the bolide fractures into a number of pieces. These spread sideways, increasing the cross-sectional area of the fragmented body and thus its deceleration. In one version of the theory[14] these fragments are weaker than the original and they themselves shatter very soon afterwards. In another version,[41] the increased air resistance increases the rate of fragmentation. In either case, the rate of deceleration and shattering builds up quickly. The kinetic energy of the body is $1/2mv^2$, where m is the body's mass and v its velocity. Assuming the body to have originally had a heliocentric orbit, v would be at least 11km/s (less atmospheric deceleration prior to breaking). These quantities dictate high energies and thus high temperatures when dissipated in a relatively small volume of atmosphere. Whatever the details of the deceleration and fragmentation mechanism, this large energy release in a small space and time will amount to an explosion.

It will give some idea of scale to consider a bolide at the bottom of the likely range of masses at the explosion, namely 100,000 tonnes. If travelling at the lowest velocity, and even if (for illustration) only 1% of its kinetic energy were dissipated in the explosion, this would amount to nearly 10^{16} Joules, over two gigawatt-hours. Expended in a few seconds, this energy will have been released mainly as heat of the bolide, radiant energy (principally infrared and visible) and acoustic energy. Various estimates of the explosion energy have been made,[34,11,44,66] mainly in the range

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10^{16}J to 10^{17}J. The blast was equivalent to an explosion of 12.5 megatonnes TNT.[12]

The bolide: quantities

Size estimates for the Tunguska event are difficult owing to the paucity of quantitative records; tabulated estimates[34,11] show a wide range. In reading the literature on the subject, it should be noted that most theoretical papers merely quote another paper's quantities, rarely justifying the selection. A commonly encountered value may not be good but merely popular. Indeed, many papers simply choose the most common value for meteors in general, for instance 45° for the altitude of the trajectory.[17] The quantities below, except where giving the full ranges of values, are generally derived from observational work.

Trajectory

The broad outlines of the geocentric trajectory are clear from eye-witness accounts: the TCB came generally from east or south of east, not on a high trajectory. Although these reports are of limited value, they do seem to constrain the azimuth to between 70° and 130° east of north. They also imply an elevation of at least 15° above the horizon;[24] few estimates exceed 45°. Other methods of calculating the trajectory include (1) the line of symmetry in the tree-fall pattern, (2) trajectories that make simulations match other details of the tree-fall pattern and (3) mapping the burns on the trees. These all have their part to play, though they can tell slightly different stories.

Azimuth

This is given as the compass bearing of the direction from which the bolide appeared. Estimates range at least from 104°[69] to 127°; other doubtful estimates lie outside this range. Probably the most commonly given estimate is about 115°,[67] although this worker now estimates 126°±12°.[23] Another, perhaps more careful analysis gives 123°±4°[68] with the comment that, with the uncertainties of these observations, it is 'impossible to choose a unique radiant'.

Altitude

Here we use the angle α above the horizontal at which the bolide flew, although some papers use the zenith distance, $90°-\alpha$. With the imprecision of this figure, it is normally taken as having the same value throughout the atmospheric trajectory. Estimates have been made at least in the range 11° to 60°,[11,69] though the extremes are contentious. Recent analysis of eye-witness accounts gives figures of 20°[23] or 17°±4°[68]; modelling of the flight of the bolide tends to suggest 30° to 40°.[43,44,65] No better consensus seems to have emerged than the range 15° to 40°.

Speed

The velocity of the body will have changed in a complicated way under the influence of the Earth's gravity and air resistance. The outline is reasonably clear, however. As it approached the Earth the TCB will have been accelerated by gravity; as it encountered the top of the atmosphere its geocentric speed will have been between approximately 11km/s and 73km/s, assuming it originally to have been in orbit round the Sun. (There is no reason to suppose it to have originated outside the Solar System.) Were it to have originated in a geocentric orbit, this is reduced to about 8km/s. As it passed through the atmosphere prior to the explosion, the acceleration due to gravity will have been minor compared with the deceleration due to air resistance. After the explosion its pre-atmospheric speed will have been essentially lost: any remaining particles will have fallen at their terminal velocities, although with a slight sideways velocity spreading the area upon which they fell. Any remaining fraction of the pre-explosion velocity may also have carried them 'downrange'.

Two speeds are often estimated: the pre-atmospheric speed and the speed immediately prior to the explosion. For the former, analysis of the tree-fall pattern and simulation of the behaviour of the body and its shock waves constrain this to 22–30km/s.[14] Figures for the pre-explosion velocity range at least as widely as 7km/s and 50km/s.[69] One of the few values based on observations is 7.5km/s, which conforms to the seismic records.[12]

Location of the epicentre

The point under the explosion has not been found to a better accuracy than a few hundred metres. This is not surprising considering that one is locating a point under a large explosion more than 5km overhead. The boundary of the fallen trees suggests an approximate centre and the burn marks on surviving trees also point towards the centre. Perhaps most work has been done on the directions in which the trees were felled; by and large these point away from the exact epicentre (Figure 11). The point under the explosion as determined from these tree-fall directions is termed the Epifast, after Prof. W. G. Fast, a mathematician of Tomsk State University who has made many detailed statistical analyses of these data. The best estimate of the location is 60° 53′ 09″ ± 6″ N, 101° 53′ 40″ ± 13″ E.[46] (6″ of latitude and 13″ of longitude at 60°N are both equal to about 185 metres on the ground.)

Explosion energy

This can be estimated with reasonable accuracy from the seismic and air-pressure wave records. Much detailed work has gone into this[12,44,46] and it is one of the better constrained of Tunguska quantities. Estimates are generally in the range 10^{16} to 10^{17}J. Many papers have an annoying habit of giving it in (mega)tonnes TNT blast-power equivalent, rarely specifying the conversion assumed; 1Mtonne of TNT is equivalent to about 4.2×10^{15}J.[70] Some papers also give the energy of the ballistic wave due to the hypersonic passage through the atmosphere, often as energy per metre. One mathematical model estimates[44] that, over the last 20km of the trajectory where trees were felled, this was three times the explosion energy. Being spread over a long trajectory, however, it made the lesser contribution to the tree-fall pattern.

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Mass

Again, two sets of figures will be found. The mass immediately prior to the explosion has been estimated between 10^5 and 10^6 tonnes.[14,30,65] The pre-atmospheric mass is normally derived from the pre-explosion mass; the calculation depends critically on the initial velocity assumed, making all such estimates particularly uncertain. Values quoted are generally in the range 10^5 tonnes[65] to 10^7 tonnes.[71] The seismic data suggest 5.10^6 tonnes, deriving the mass from the explosion data and then allowing for the estimated atmospheric path.[34]

Size

This is normally estimated from the mass on the basis of some assumption of the density. Densities typically assumed are 8 for iron bodies, 3 for stones and 0.5 for comets,[41] all in tonnes/m$^3 \equiv$ g/cm^3. The value chosen will, naturally, reflect the writer's assumptions on the asteroidal *vs* cometary question. Values for the equivalent radius are generally in the range 38[65] to 95[11] metres before encountering the atmosphere. There is also an outside estimate of 100–300 metres,[72] though this is based on an unrealistically low density of 0.001 tonnes/m^3. There is an estimate of 30 metres radius prior to the explosion.[73]

The bolide: its nature

Many explanations for the Tunguska event have been advanced over the years, ranging from the reasonable to the implausible. Realistically, the straightforward explanations of an asteroid or comet are the most likely. All the most common hypotheses will be considered here.

Here is not the place to describe the nature of asteroids or comets in detail.[74] Asteroids probably comprise mainly stony and/or metallic material of some physical strength, similar to the stone, stony-iron and iron meteorites which probably originate from them.[38] Comets appear to comprise a mixture of volatile ices, organic material, tars derived from them and silicaceous material, probably of little physical strength.[75,76] They may also contain embedded asteroidal material.

Cometary and asteroidal meteors

Small comets and asteroids and fragments of them impact the Earth's atmosphere frequently, generating fireball observations and meteorite finds. Larger bodies are rarer. It has been estimated that a Tunguska-sized body or larger impacts every few centuries;[77] this has been questioned, but the order of magnitude is probably correct. Such impacts are presumably common on geological timescales, merely rare on historical ones.

When assessing cometary and asteroidal theories it must be borne in mind that the parameters of the trajectory, which affect many conclusions critically, are known only with poor accuracy.

One current matter of contention is whether a comet would penetrate as low as 5–10km above the ground before exploding. Two recent papers reject this. One[41] is based on a pre-atmospheric velocity of well over 30km/s and predicts a pre-explosion velocity of 16–18km/s, which are both probably wrong. The other[17] chooses only one altitude and two velocities for comet simulations; other values might give different conclusions. A third paper[65] predicts disintegration heights down to around 10km, possibly allowing a comet to conform to observations. It does assume a comet to be pure ice, however, with greater strength than the other papers. Cosmic ray exposure and perihelion passages give comets sintered surfaces, which may be stronger.[78] Such strengthening might make a comet more plausible. When the nature of the cometary mantle is understood better, it would be interesting to repeat the above work using more appropriate breaking strengths.

Comet

Comets occupy a wide range of heliocentric orbits which could conform to almost any trajectory of the bolide. With the possible exception of some carbonaceous chondrites, no meteorites are thought to derive from comets. Thus no sizeable meteoritic fragments would be expected, excepting possibly any embedded asteroidal material. Comets comprise probably a quarter to a half volatile ices[79] which would presumably vaporise.

Various attempts have been made to identify the comet which, either in its entirety or as a fragment, provided the TCB. Fesenkov described a similarity to Mrkos,[30] though without specifying which of Mrkos' comets he meant. Kulik favoured 7P/Pons-Winnecke,[80] Kresák proposed a fragment of 2P/Encke.[81] This last candidate has been argued for and against over the years,[11,65] including a tie-in with a giant comet postulated to have entered the inner solar system around 20,000 years ago and shed fragments over the millennia.[82]

In favour of the cometary theory, it explains (1) the lack of meteoritic fragments; (2) the distribution of dust causing the light nights;[26] (3) the composition of extra-terrestrial elements found in the epicentre;[52,55,56] (4) the possible Antarctic aurora.[39] Against it, it may fail to explain the deep penetration of the TCB into the atmosphere.

An earlier argument against the cometary theory was that no such comet was seen before the impact. Calculations, however, have shown that it would have been very difficult to observe in the week before impact.[83] It would have been a 26th magnitude object and would have appeared very close to the Sun.

Asteroid

Asteroids occupy a restricted range of heliocentric orbits, generally prograde and clustered near the plane of the ecliptic, though near-earth asteroids have more varied inclinations. The Tunguska body appears to have fulfilled these requirements. It has been suggested, in fact, that certain subtleties of the trajectory argue for an asteroidal rather than a cometary source,[11] though this has been disputed.[65] It must be borne in mind that the origin of near-earth asteroids is

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still uncertain, both cometary and main-belt asteroidal sources being possible. Thus indications that the TCB is asteroidal in orbit do not necessarily prove it asteroidal (i.e. stone and/or iron) in composition.

Recent research on the way that meteoric bodies disintegrate in the atmosphere[41] has led to an estimate that the TCB left fragments of about centimetre size spread 1cm deep across a circle 2km across. This work also favours a weak stony asteroid as the body. It is unclear from the English-language reports of the field work whether such fragments would have been found were they there. It is possible that the fierce freeze-thaw action of the Siberian winters would have reduced such material to individual mineral grains by the time that the first samples were taken.

In favour of the asteroidal theory, it explains (1) possibly, the lack of meteoritic fragments (if they were centimetre-sized and disintegrated through freeze-thaw action); (2) the penetration of the TCB relatively deep into the atmosphere. Probably the main argument against it is that it fails to explain the elements of cometary signature found in the epicentre.

Meteoroid-like body

Another theory is that the body was extremely porous,[72] giving a low density to allow the fierce deceleration which occurred. More recent work explains this by sideways spreading, as described above. The idea has also been questioned on the grounds that no such material is known in the solar system.[14]

It has also been suggested that there may be bodies 'neither cometary nor asteroidal'[84] and that the Tunguska bolide may have been such.[2] More recently this idea has been revived[85] with fragments of an icy moon, a fractionated comet or an asteroid mantle being considered. Certainly our present view of comets and asteroids leaves the distinction far from clear-cut; given our current inability to classify the bolide as cometary or asteroidal, these related possibilities should not be ruled out.

Natural nuclear bomb

This modification of the cometary hypothesis suggests that the air pressure built up in front of the decelerating bolide might have created the temperatures and pressures necessary for thermonuclear fusion. The hydrogen would have come both from cometary ices and the atmosphere. However, calculation shows this contribution to the explosion to be minute, at most 5mJ, even if the mechanism were to work.[86] The suggestion can be ruled out.

Antimatter

Were the TCB to comprise antimatter, it would react with the normal matter of the atmosphere and might annihilate in an explosion.[87] Objections to this explanation include: (1) The recovery of meteoritic matter from the epicentre; (2) The light nights and sun haloes over Europe; (3) The lack of known large bodies of antimatter; (4) Such a body might have been seen as it interacted with the solar wind before encountering the Earth;[88] (5) Calculations[89] suggest that most of the radiation would be highly penetrating and export much of the energy; it might not be able to create a fireball. All in all, the idea is not regarded as plausible.

Black hole

All known black holes are of stellar size, but it is suggested[90] that smaller ones may have been created in the big bang. Some may still be in existence and one is proposed as the cause of the Tunguska event.[91] The hole is suggested to have had a mass of 10^{17} to 10^{19}kg and a radius of nanometres or less. As it passed through the atmosphere such a body would theoretically generate a shock wave which could have felled the trees. The authors lower the trajectory so that the hole penetrated the ground in the epicentre. They quote a previous paper[43] as saying that a shock wave from such a trajectory could have thrown the trees out in the pattern shown. A careful reading of this paper, in the opinion of the present author, leaves this interpretation uncertain but doubtful.

The black hole would have continued through the Earth; were it to emerge in the Atlantic or the Sahara, both of which have been considered, the 'exit wound' would not have been found.

One objection to this hypothesis is that no such black holes have been observed. As with the antimatter theory, the light nights and the meteoritic material isolated in the epicentre are not explained. At the hole's point of entry into the ground the rock would have shown severe disruption;[92] this has not been found, although it could remain undiscovered under the swamp. The hole's passage through the Earth would have generated enormous seismic activity, which was not observed.[92]

Coronal microtransient

Arches of the Sun's magnetic field rise above the photosphere and carry plasma with them. It has been suggested that these arches might form detached loops of field which would be ejected with the plasma entrained. These might cross the solar system and one of them might have entered the Earth's atmosphere in 1908. At a certain depth in the atmosphere the air pressure overcame the strength of the magnetic field; this released the plasma which then recombined into atoms, releasing its ionisation energy.[93]

There are many problems with this idea, largely because the underlying physics is not given. It is also unclear how such a magnetic structure would cross the Earth's magnetopause intact[9] and why the plasma would not lose its energy by radiation in transit to the Earth.

Alien spacecraft

No review of the Tunguska event is complete without mention of the idea that the explosion was the foundering

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of an alien spaceship. This suggestion has the advantage that it is nearly impossible to disprove. Typical masses and velocities for such craft are unknown, so they may plausibly match any measured figures. If radioactivity is found in the epicentre, this might have been the power pile exploding; if no radioactivity is found, then the craft was not nuclear powered. Unfortunately, as with the fundamentalist alternative to evolution, this lack of falsifiability prevents it from being a scientific hypothesis.

The best known version of this theory[94] contains two useful English translations of Russian material, including Kulik's original paper,[19] though with the longitude 30° in error.[63]

Conclusion

The Tunguska event was caused by a bolide with a final mass of one hundred thousand to one million tonnes exploding in the atmosphere. If it was a comet, it is the best studied instance of such an event to date. The asteroid *vs* comet debate continues, with other possibilities not now highly regarded. In the opinion of the present author, the choice between the main two possibilities is still unsettled. There are plenty of papers confidently demonstrating the TCB to be asteroidal,[11,17,41] with a broadly similar number concluding that it was cometary.[81,82] In assessing the competing claims, one should look not only at what the theories explain well but at what they fail to explain. One should also consider how they fit in with our developing understanding of the nature, dynamics and origin of comets and asteroids. Moreover, many papers address just one aspect such as the atmospheric trajectory or the cosmochemistry. Whilst these are all valuable, the opinion of many Russian workers is that the answer will come through a broad approach including many such lines of research.[95] These researchers intend an ambitious programme of research,[40,50] including chemical and isotopic analysis of soil, trees and peat in and near the epicentre, modelling the flight and explosion of the bolide, modelling the effects of the resulting shock waves, predicting the distribution of TCB material and searching for it, and investigations of the ecological effects, magnetic effects, tree burn patterns, atmospheric anomalies and light nights.

Only tiny quantities of the bolide have been recovered; in the absence of more, much work has taken place on side-effects such as seismic waves, tree felling and light nights. Much depends on the values chosen for parameters such as the mass and trajectory, which are poorly constrained by observation. Other arguments are based on the characteristics of comets and asteroids; our views as to these characteristics are changing. With progress in this field, and in our understanding of how bolides behave in the atmosphere, theoretical analysis of the Tunguska event should mature greatly over the next five to ten years. Similarly, improved knowledge of the chemistry of comets and asteroids will inform analysis of material from the area. Finally, it is even possible that meteoritic fragments, probably small ones, may yet be found in the epicentre.

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Appendix

Kulik

Leonid Alexeivitch Kulik, born on 1883 August 31 (Gregorian calendar), was a mineralogist and leading meteoriticist. Though best known for his work on the Tunguska meteor, he did much to enhance the Russian collection of meteorites and is regarded by some as one of the founders of Soviet meteoritics.

His first attempt to find the Tunguska meteorite was in 1921 but he ran out of time, the Siberian autumn curtailing work. His second expedition in 1927 found the epicentre; he led other expeditions there in 1928, 1929/30, 1937, 1938 and 1939. Expedition reports by Krinov, one of his colleagues, give the impression of a good organiser and leader who was well liked. He had continuing success in obtaining further expedition funds from Akademia Nauk USSR (the Soviet scientific academy). The advent of the Second World War put an end to these expeditions.

He volunteered for service in the War, was wounded and died in captivity, probably in about 1942.[96,4]

Russian research

The vast majority of field work on the Tunguska event has been conducted by Soviet teams, as has much of the theoretical research. Most of this is published in Russian, often in publications virtually unobtainable in the West. A very few are available in English translation. Many important papers appeared in a series of occasional volumes known as *Problems of the Tunguska Meteorite* (*Problema Tungusskogo Meteorita*). Of the field results, only reviews tend to appear in English;[4,30] of the theoretical work, only the better known (e.g. models of the explosion and tree felling[43,44,65]). The reader will have noted that many of the references in the present paper are to a review by Krinov which, whilst informative, is thirty years old. It is axiomatic that researchers should acquaint themselves with the existing literature, often including the basic results. For a westerner working on the Tunguska event this is well-nigh impossible. This has led many Russian workers to regard western research in this field as ill-informed.[95]

The situation is improving slightly. Through the generosity of colleagues in Tomsk State University, the present author has obtained copies of several editions of *Problems of the Tunguska Meteorite* and related publications which have been placed in the library of the Royal Astronomical Society in London; translations of the titles are available from the author. Some Russian journals now provide English translations of the abstracts or at least the titles. Perhaps most important of all, Russians nowadays place more emphasis on publication abroad in English-language journals.

Tomsk State University together with the Tomsk Branch of the Astronomical-Geodesical Society has organised at least one expedition to the epicentre each year since 1958.[9] Since 1990 these have been international,[97] with participants from outside the old Soviet Union. In 1995 a Russian conference on the Tunguska event was combined with a trip to the epicentre.

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