The Tunguska Event

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18.1 Introduction

In the early morning of 30th June 1908, a powerful explosion over the basin of the Podkamennaya Tunguska River (Central Siberia), devastated 2 150 ± 50 km^2 of Siberian taiga. Eighty millions trees were flattened, a great number of trees and bushes were burnt in a large part of the explosion area. Eyewitnesses described the flight of a "fire ball, bright as the sun". Seismic and pressure waves were recorded in many observatories throughout the world. Bright nights were observed over much of Eurasia. These different phenomena, initially considered non-correlated, were subsequently linked together as different aspects of the "Tunguska event" (TE).

Almost one century has elapsed and scientists are still searching for a commonly accepted explanation of this event. Several reviews and books summarize the results acquired by the intensive investigations of the last century, e.g. Kulik (1922, 1939, 1940), Landsberg (1924), Krinov (1949, 1966), Gallant (1995), Trayner (1997), Riccobono (2000), Bronshten (2000), Vasilyev (1998, 2004) and Verma (2005).

Despite great efforts, the TE remains a conundrum.

18.2 The Hypotheses

The most plausible explanation of the event considers the explosion in the atmosphere of a "Tunguska Cosmic Body" (TCB), probably a comet or an asteroid-like meteorite.

18.2.1 Comet or Asteroid?

From his first determination of the basin of the Podkamennaya Tunguska River as the explosion site, Kulik (1922 and 1923) used the term "Tunguska meteorite", for the TCB, and continued searching for an iron body, similar to one found in Arizona (Kulik 1939, 1940; Krinov 1949, 1966). Voznesenskij (1925) hypothesized an equal probability for a stony or an iron body composition. Shapley (1930) was the first to suggest that the Tunguska event was caused by the impact of a comet and Kresák (1978) indicated the comet Encke as the origin of the TCB. Fesenkov (1949), for many years, supported the stony object hypothesis. Later, Fesenkov (1961) worked out a definite model of an impact between a comet and the Earth's atmosphere. From that time onward, the majority of

Russian scientists followed the cometary hypothesis (see for example Grigorian 1998), whereas many western scientists preferred an asteroidal model (e.g. Sekanina 1983, 1998; Chyba et al. 1993).

For many reasons, these two "schools" practically ignored each other until the international workshop Tunguska96, held in Bologna (Italy) from 15th to 17th July 1996 (Di Martino et al. 1998). In the recent past the cometary hypothesis has been favored on the basis that a low-density object was needed to explain the Tunguska catastrophe (Petrov and Stulov 1975; Turco et al. 1982). Subsequently, to account for the concentration of energy release of the explosion, two sub-versions of this hypothesis have been developed, one introducing chemical reactions (Tsymbal and Shnitke 1986), the other nuclear-fusion reactions (D'Alessio and Harms 1989). On the other hand, it has been shown (Grigorian 1976; Grigorian 1979; Passey and Melosh 1980; Levin and Bronshten 1986) that the fragmentation of a normal density object can greatly increase the rate of energy deposition in a small region near the end of the trajectory, thus appearing as an atmospheric explosion. Detailed calculations which include the effect of aerodynamic forces that can fracture the object, and the heating of the bolide due to friction with the atmosphere, have recently been performed, showing that the TE is fully compatible with the catastrophic disruption of a 60–100 m diameter asteroid of the common stony class (Chyba et al. 1993; Hills and Goda 1993). However, due to the uncertainty of such input parameters as the energy and height of the explosion or the inclination angle and the encounter velocity of the impactor, the same calculations do not exclude the possibility that the TCB was a high velocity iron object, nor rule out a carbonaceous asteroid as an explanation of the event. Considering a "plume-forming" atmospheric explosion, Boslough and Crawford (1997) have suggested that the commonly accepted energy-yield is an overestimate and that a 3 megaton event could generate the observed devastation. Many of the phenomena associated with the TE can be related to the formation and collapse of an atmosphere plume, caused either by a comet or by an asteroid. For example, the predicted ejection at altitudes of some hundreds of kilometers of the impactor mass can explain the "bright nights" associated with the TE.

It is difficult to definitely support one or the other hypothesis. Therefore, one way to achieve certainty about the nature and composition of the TCB remains the search for some of its remnants. Numerous radiocarbon analyses of Tunguska wood samples (Nesvetajlo and Kovaliukh 1983), chemical analyses of soil and plants (Kovalevskij et al. 1963; Emeljanov et al. 1963; Kirichenko and Grechushkina 1963; Iljina et al. 1971), bed-by-bed chemical analyses of the peat formed by *Sphagnum fuscum* in 1850–1950 (Vasilyev et al. 1973; Golenetskij et al. 1977a; Golenetskij et al. 1977b; Kolesnikov et al. 1977), isotopic analyses of many different soil, peat and wood samples (Kolesnikov et al. 1979), as well as analyses of the spherules from Tunguska soil samples collected in a radius of several tens of kilometers from the epicenter (Florenskij et al. 1968; Jéhanno et al. 1989; Nazarov et al. 1990) have been completed. Nevertheless, many conclusions of this intensive work are still uncertain, so that further investigations are needed. Although almost every year there is an expedition to Tunguska, so far no typical material has permitted a certain discrimination to be made between an asteroidal or cometary nature of the TCB. Some papers report that hydrogen, carbon and nitrogen isotopic compositions with signatures similar to those of CI and CM carbonaceous chondrites were found in Tunguska peat layers dating from the TE

(Kolesnikov et al. 1999, 2003) and that iridium anomalies were also observed (Hou et al. 1998, 2004). Measurements performed in other laboratories have not confirmed these results (Rocchia et al. 1990; Tositti et al. 2006). Moreover, a concentration of microparticles of inferred cosmic origin was found in tree resins dating from the TE (Longo et al. 1994; Serra et al. 1994). Although these data are compatible with the hypothesis of the impact of a cosmic body, they are by no means conclusive and are not sufficient to prove the nature of the TCB. The same can be said about the lacustrine sediments of Cheko Lake (Sacchetti 2001) studied in the framework of the multidisciplinary investigation as carried out by the Italian scientific expedition Tunguska99 (see *http://www-th.bo.infn.it/tunguska/)* (Amaroli et al. 2000; Pipan et al. 2000; Gasperini et al. 2001; Longo et al. 2001; Longo and Di Martino 2002 and 2003; Longo et al. 2005). This field research has been strengthened by theoretical studies and modeling. In a recent paper (Farinella et al. 2001), a sample of possible TCB orbits has been constructed and a dynamic model was used to compute the most probable source of a TCB placed on each of these orbits. The results of calculations gave a greater probability for a TCB coming from an asteroidal source (83%), than from a cometary source (17%).

18.2.2
"Non-traditional" Hypotheses

Vasilyev (2004) states, "We should not exclude the possibility that the Tunguska phenomenon is a qualitatively new phenomenon for the science, that should be analyzed from non-traditional positions". These "non-traditional" approaches still consider an impact with the atmosphere of "something" coming from external space. Several of them, though published in scientific journals, were found to be technically groundless, e.g. the hypotheses involving near critical fissionable material (Zigel' 1983; Hunt et al. 1960), antimatter meteors (Cowan et al. 1965), and tiny black holes (Jackson and Ryan 1973). Others consider alien spacecrafts (Kazantsev 1946; Baxter and Atkins 1976). Kazantsev was the first who explained the lack of fragments or impact craters in Tunguska by an explosion in the atmosphere. Nevertheless, I think that here we can ignore such extremely "non-traditional" hypotheses.

18.2.3
Alternative Approaches

Recently, some "alternative" approaches were presented to explain the TE. Different from the above-mentioned traditional or non-traditional explanations, these alternative approaches deny an impact of an external body with Earth. They claim that the event was triggered by a terrestrial cause. I mention here two of the more discussed alternative interpretations.

The first is a tectonic interpretation (e.g. Ol'khovatov 2002), which considers the coupling between tectonic and atmospheric processes in a "very rare combination of favorable geophysical factors." Another recent work that should be mentioned is the "kimberlite interpretation" (Kundt 2001), which considers the TE as caused by the tectonic outburst of some 10 megaton of natural gas. For the volcanic (outflow) interpretation, Kundt presents the estimates of the involved mass and kinetic energy of the vented natural gas, of its outflow timescale, supersonic and subsonic ranges, and buoyant escape towards the exosphere.

The main idea of this latter work is contradicted by at least two facts. The first and more obvious point against the hypothesis of an explosion from the ground is that the eyewitness testimonies describe the trajectory of a *bolide crossing the sky* (see Sect. 18.3.2). Among these testimonies, the earliest, given a few days after the event by educated people, have a high trustworthiness. On that basis, the first Kulik expedition (1921–1922) gathered sufficient information to conclude, that "the meteorite fall in the neighborhood of the Ogniya river, a left tributary of the Vanavara river, which is a right tributary of the Podkamennaya Tunguska (Hatanga) river" (Kulik 1922, 1923, 1927; Landsberg 1924). The first expedition could not go farther than Kansk, about 600 km from the Tunguska explosion site. Five years later, Kulik discovered the site about 50 km from the mentioned tributary of the Vanavara River.

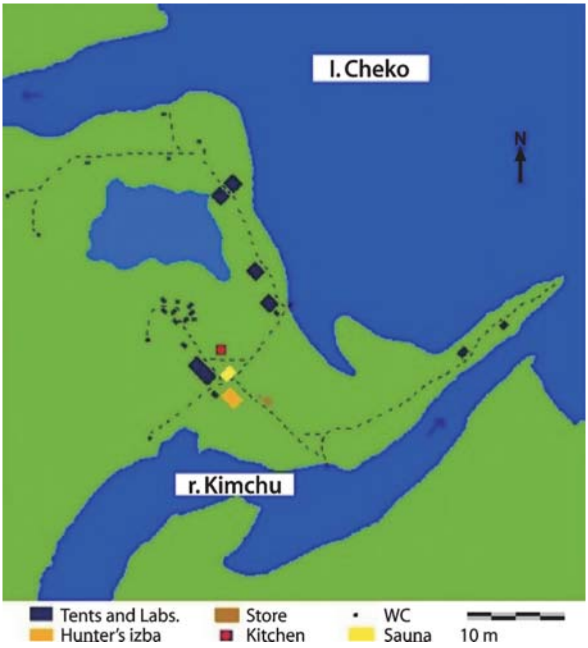
A second objection comes from the absence of debris clearly referred to the explosion in the epicenter area. If we assume that the anomalous optical phenomena observed after the TE, were due to particles released in the atmosphere by the explosion, we should find an increasing concentration of those particles (with grain-size progressively decreasing) toward the explosion epicenter. As also pointed out by Kundt, we do not observe a carpet of dust in the vicinity of the epicenter as we should observe for the explosion of a meteorite, but also (and more markedly) for the explosion of a diatreme or any volcanic emission. How could an explosion "from below" disperse dust in the atmosphere to an extent comparable to that of the Krakatau without leaving significant traces close to the epicenter? It seems more probable that an explosion "from above" could explain this occurrence.

Moreover, geological maps of the region (Sapronov 1986) and our own observations during the Tunguska99 expedition do not report the presence of mantle rocks, such as peridotites or eclogites, which are usually associated with kimberlites. Though the area is centerd on the roots of the lower Triassic Kulikovsky paleovolcanic complex (see Fig. 18.1), which extends over an area 25 × 20 km wide, displaying numerous, various sized craters, it is presently a tectonically stable cratonic region, as testified by the low intraplate seismicity. The map from the USGS catalog, which reports significant worldwide earthquakes during historical times, confirms this stability.

Finally, the "radonic storm" registered at our base camp (see Fig. 18.2) during the Tunguska99 expedition (Longo et al. 2000; Cecchini et al. 2003) has nothing to do with a "kimberlite" phenomenon, as suggested by Kundt. Indeed, we registered an intensity enhancement of gamma radiation during a thunderstorm (see Fig. 18.3) due to radon daughters, as observed in other parts of the world, where no "kimberlite interpretation" is possible. Though we cannot accept the main ideas of Kundt, the outflow theory can help us to understand some aspects of the TE. It is plausible, and even probable, that gas releases took place from the permafrost dissolution (caused by the impact of the TCB and not by a kimberlite outflow). For example, part of the multiple explosions heard for more than half an hour by many earlier trustworthy witnesses (Kulik 1922, 1927; Obruchev 1925; Voznesenskij 1925) might probably be due to a rapid release of gas (methane) from the permafrost layer as a consequence of the thermal burst related to

Fig. 18.1. Satellite view of the Kulikovsky paleovolcanic complex (*1* – lake Cheko, *2* – river Kimchu, *3* – Northern swamp, *4* – Southern swamp, *5* – river Khusma)

Fig. 18.2.
The base camp of the Tunguska99 expedition on the shore of the lake Cheko (drawing by Andrey Chernikov)



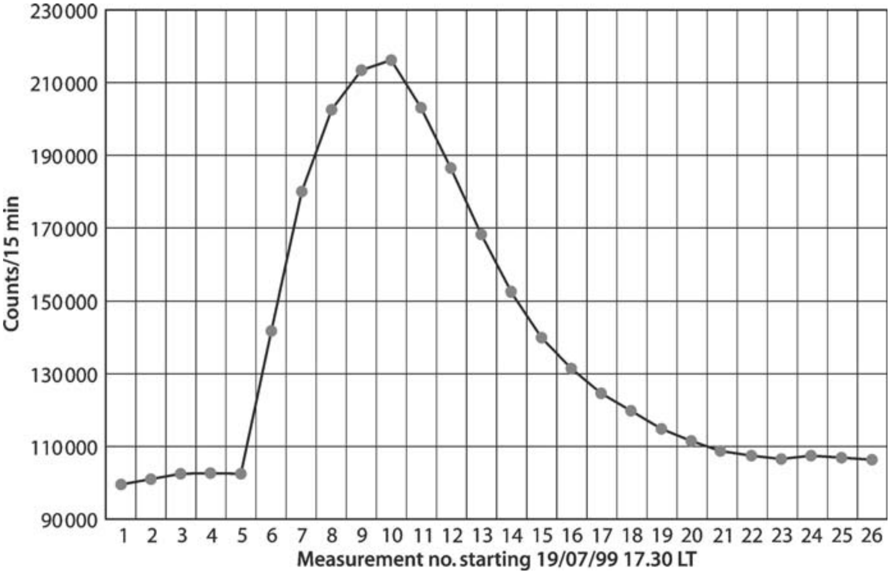


Fig. 18.3. Gamma-ray (25 keV – 3 MeV) intensity enhancement registered at the base camp of the lake Cheko during the thunderstorm of July 19, 1999. Note the steep rise of counting rate, while it is raining. It corresponds to gammas emitted by radon daughters

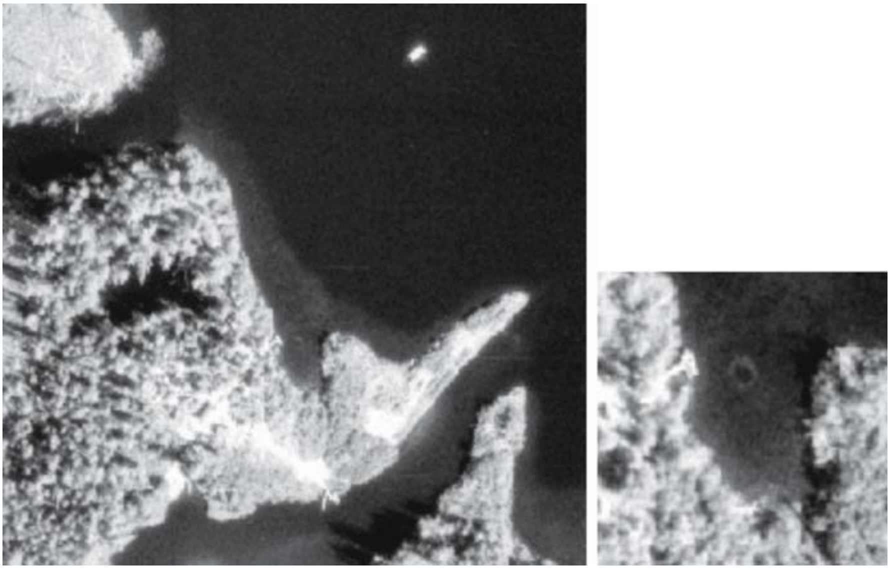


Fig. 18.4. Aerial view of the camp of the Tunguska99 expedition (23 July 1999). Near the shore, a hole with a few meters diameter resulting from a gas outflow can be seen on the lake bottom

the main event. Indeed, in July 1999, we observed a small "crater" originated "from below" on the Cheko Lake bottom (see Fig. 18.4). It could be due to methane emission from decaying organic matter in the *surface* layer of some tens of meters. Obviously, this does not contradict the known *tectonic stability* of the region.

18.3
Known Data

18.3.1
Objective Data

Three main kinds of objective data on the Tunguska explosion are available: seismic and barometric registrations, recorded immediately after the event, information on the bright nights, observed in Eurasia in July 1908, and data on forest devastation, systematically collected 50–70 years later and recently integrated with the data of the 1938 and 1999 aerial photographic surveys.

Seismic and Barometric Registrations

Seismic records from Irkutsk, Tashkent, and Tiflis were published together, two years after the event (Levitskij 1910), those from Jena, three years later. However, the first paper that connected to the TE the origin of these seismic waves was published only in 1925 (Voznesenskij 1925). Similarly, the barograms recorded in 1908 in a great number of observatories throughout the world, were associated with the TE some twenty years later (Whipple 1930; Astapovich 1933). From the analysis of the available seismograms and barograms, the time that the seismic and aerial waves started was calculated. The main results obtained are listed in Sect. 18.4.

Bright Nights Observed

In 1908, the attention of astronomers and geophysicists in Europe and Asia was drawn to some unusual phenomena, such as bright nights, noctilucent clouds, brilliant colorful sunsets and other observations. It is difficult to conclude that some of these phenomena are really "anomalous". For example, in June-July, the appearance of noctilucent clouds reaches its maximum and it is difficult to distinguish between "usual" and "unusual" noctilucent clouds. Therefore, I shall consider here only the bright nights phenomenon.

Bright nights ("at midnight, it was possible to read the newspaper without artificial lights"; see Figs. 18.5 and 18.6) were described in many papers (e.g., De Roy 1908; Shenrock 1908; Süring 1908; Svyatskij 1908). At that time, many explanations for the bright-nights phenomenon were proposed. Up to 1921, meager information about a great 1908 bolide was published only in some local Siberian newspapers. Nobody considered a link between these phenomena, although on 4 July 1908, the Danish astronomer Torwald Kohl wrote: "It would be advisable to learn whether in recent times some great meteorite has been seen in Denmark or elsewhere" (Kohl 1908). It was only in 1922, after his first recognition in Siberia that Kulik wrote about a probable link between the bright nights in Eurasia and the explosion in Central Siberia (Kulik 1922). From that time onward, such phenomena have been considered as two parts of the Tunguska event.

The phenomenon and its correlation to the TE, was thoroughly studied in the 1960s (Zotkin 1961; Vasilyev et al. 1965). The 4 March 1960 issue of *Science* published a letter from the Committee on Meteorites of the Academy of Science of the USSR addressed to foreign scientists and asking them to send all the information available on the optical phenomena of 1908 (Fesenkov and Krinov 1960).

Zotkin (1961) studied the bright nights, observed in 114 points of the globe. He distinguished observations following the 30 June from those preceding that date. He considers the latter poorly reliable and of "local character", whereas the events observed from the 30 June did not have a "local" character and were observed in more than a hundred points of Europe and Asia.

Vasilyev (1965) considered a more complete data set and referred to 86 communications and articles dated to 1908. He lists 14 cases of bright nights from 21 to 29 June 1908 and 159 cases from 30 June up to 3 July (in subsequent papers, he indicates about twenty other cases from 4 to 28 July). He considers *all* these cases related to the Tunguska event and this is not easy to explain.

It seems to me that Zotkin's approach is more acceptable. Only the bright nights following the 30 June should be related to the Tunguska event. This is confirmed by the *global* character of the phenomenon and by *polarization* measurements. The "global" character of the phenomenon, observed in the nights beginning on 30 June and 1 July 1908 are illustrated in Fig. 18.5 (Vasilyev and Fast 1976). As can be seen, the bright nights were observed on an area of about 12 million km^2, from the longitude 6.5° W (Armagh, Ireland; see Fig. 18.6) up to 92.9° E (Krasnoyarsk) and from the latitude 41° N (Tashkent) up to 60° N (Petersburg). If the bright nights are due to dust in the atmosphere, the light reflected should be polarized. Busch (1908a,b) measured the daylight polarization in Arnsberg (Germany). His results indicate an absence of the effect in the first half of 1908 up to 28 June, a strong effect the 1 July that gradually disappears up to 25 July. The conclusions of Zotkin were that it is difficult to accept that dust particles could reach Great Britain from Tunguska in 22 hours. Therefore, they were ice particles from the comet tail and the comet nucleus exploded in Tunguska. Bronshten (1991) hypothesized that the particles were transported from Tunguska by gravitational forces. In Boslough and Crawford model (1997), the mass of the impactor, as well as water from the humid lower atmosphere, are ejected above the top of the atmosphere and within 15 minutes can extend more than 2000 km from the impact site.

Data on Forest Devastation

The data on forest devastation are a second kind of objective information source about the event. The main part of these data refers to the tree fall and the direction of flattened trees. From these data we can obtain information on the coordinates of the wave propagation centers (often called "epicenter(s)") and on the final TCB trajectory.

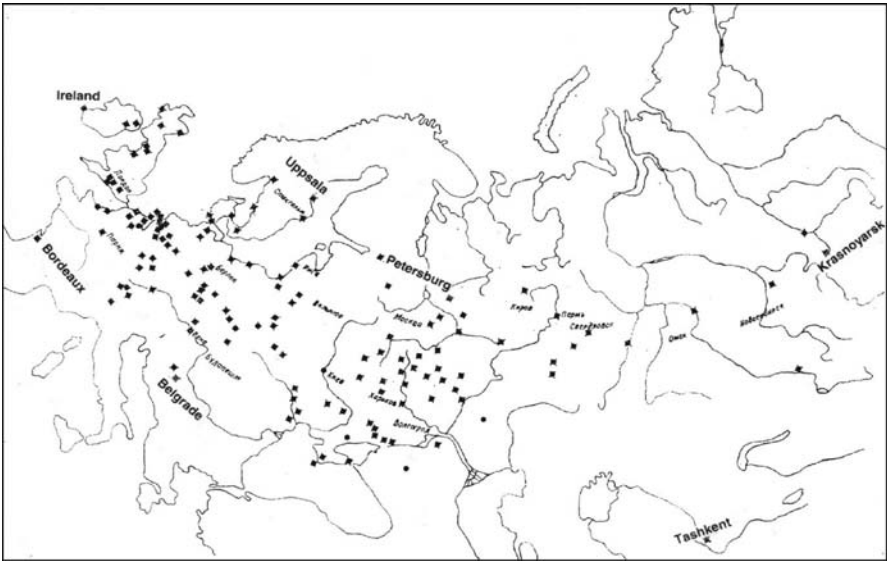


Fig. 18.5. Stations where anomalous bright nights were observed the 30 June/1 July 1908

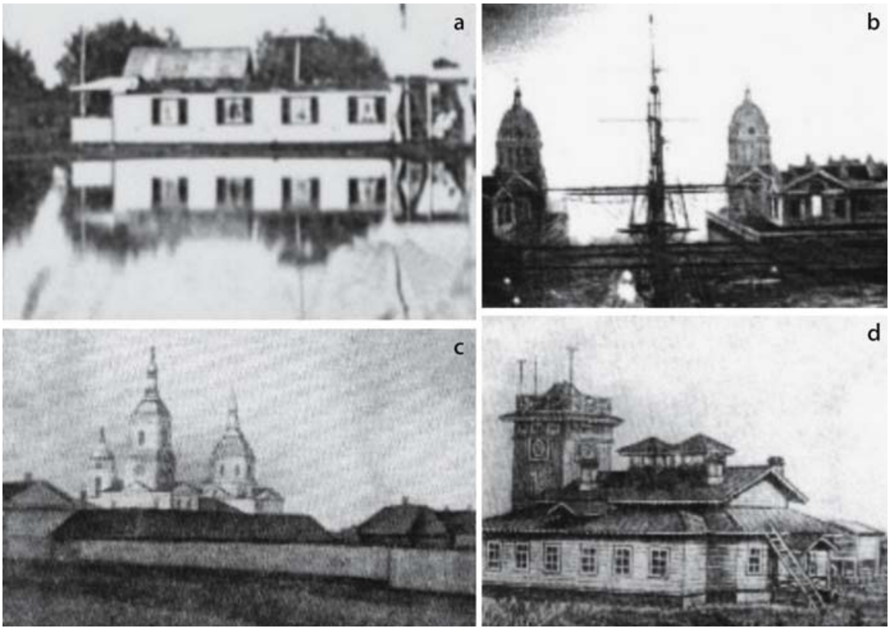


Fig. 18.6. Photos taken during the bright night of 30 June 1908 in (**a**) Armagh, (**b**) Greenwich, and (**c**) Tambov. **d** The Irkutsk observatory at the beginning of the 20th century

Though Kulik discovered the radial orientation of fallen trees as early as 1927, systematic measurements of fallen tree azimuths were started only during the two great post-war expeditions organized by the Academy of Sciences in 1958 and 1961 (Florenskij et al. 1960; Florenskij 1963), and during the Tomsk 1959–1960 expeditions. Under the direction of Fast, with the help of Boyarkina, this work was continued for two decades during ten different expeditions from 1961 up to 1979. A total of 122 people, mainly from Tomsk University, participated in these on site measurements. The data collected have been published in a catalog in two parts: the first one contains the data obtained by six expeditions (1958–1965), which include the whole set of single-tree azimuths and the azimuths averaged on trial areas equal to 2500 m^2 or 5000 m^2, chosen throughout the whole devastated forest (Fast et al. 1967). In the second part, the data collected by the six subsequent expeditions (1968–1976) were given (Fast et al. 1983).

The data on forest devastation also give information on the energy emitted and on the height of the explosion. Indeed, these data include, not only fallen tree directions, but also the distances that different kinds of trees were thrown, the pressure necessary to do this, information on forest fires and charred trees, data on traumas observed in the wood of surviving trees and so on (e.g. Florenskij 1963; Vorobjev et al. 1967; Longo and Serra 1995; Longo 1996, 2005).

In order to correct, update and enlarge the fallen tree distribution data, we performed a new aero-photographic survey during the Tunguska99 expedition (Longo and Di Martino 2002, 2003) (see map on Fig. 18.7). This survey was needed to obtain a new unified catalog, which includes: (*1*) corrected Fast data (Fast et al. 1967, 1983), (*2*) data from Kulik's 1938 aerial photosurvey never previously analyzed, (*3*) never published data collected in 1967 by the Anfinogenov group in the central region of the site. These three datasets have been checked and completed with our on-site measurements carried out in July 1999 and 2002 to obtain the coordinates of different reference points in the same area. These data allowed us to recognize ground elements on the aerial pictures and to connect them to the regional topographic net.

Unfortunately, a map containing all the data from Fast's catalogs (Fast et al. 1967, Fast et al. 1983) has never been published. In the last 40 years, the map of fallen tree azimuths used for comparison with theoretical models (e.g. Korobeinikov et al. 1990; Boslough and Crawford 1997) was the one constructed by A. Boyarkina, V. Fast and co-workers (Florenskij 1963; Boyarkina et al. 1964). This map contains only the data on the azimuths measured in 1958–1961. The new unified catalog and the new map (Longo et al. 2005) have been constructed using a number of tree azimuths and trial areas several times larger than those considered in Fast's analyses. Moreover, we have introduced a reliability degree for each trial area averaged azimuth. The reliability degree has been assigned on the basis of the percentage of singletree azimuths that lay in a sector of 15° centered on the averaged azimuth. A good agreement between the new map and the horizontal aerodynamic pressure calculated on the basis of Korobeinikov et al. (1990) model has been obtained.

No Impact Craters or Meteorite Fragments

Data on forest devastation and records of the atmospheric and seismic waves have made it possible to deduce the main characteristics of the Tunguska explosion, i.e. its

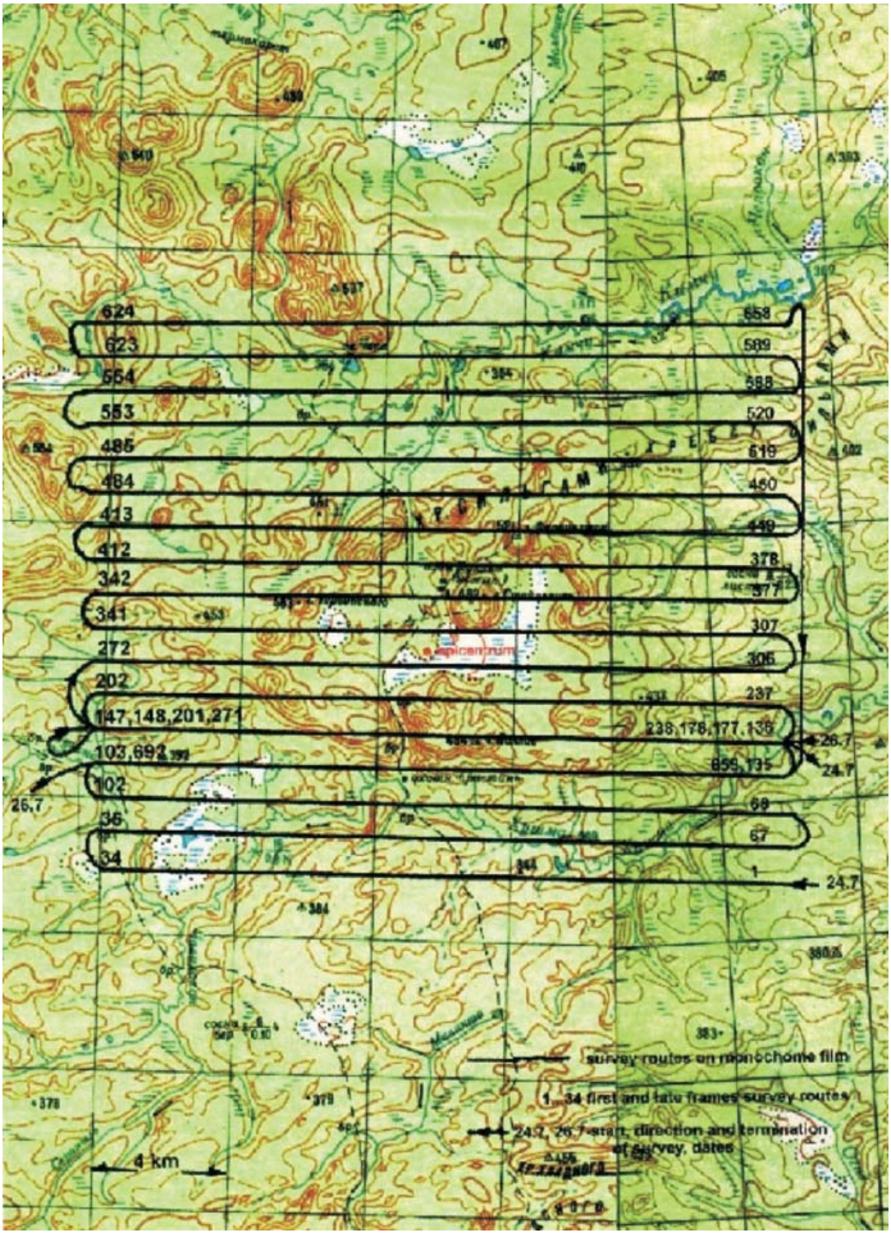


Fig. 18.7. Flight routes of the 1999 aero-photosurvey

exact time, $00^h 14^m 28^s$ UT (Ben-Menahem 1975), the coordinates of the point usually called epicenter, 60° 53' 09" N, 101° 53' 40" E (Fast 1967), the energy release, equivalent to 10–15 million tons of TNT (Megaton) that corresponds to about one thousand times the Hiroshima bomb energy, and height of the explosion (5–10 km), though the values for the last two parameters are estimated with great uncertainty. However, neither macroscopic fragments of the cosmic body, nor a typical signature of an impact, like a crater, have ever been found in an area of 15 000 km^2, so that the nature and composition of the TCB and the dynamic of the event have not yet been clarified.

18.3.2
Eyewitnesses Testimonies

There is a great number of eyewitness testimonies. The more complete collection of these testimonies is provided by Vasilyev et al. (1981). It contains direct observations of the Tunguska explosion from 386 different points and a list of the geographical coordinates of these points. To these observations, the authors have added news published in newspapers, reports and communications from many official employees for a total of 708 testimonies. It is easy to find contradictions in this material collected for more than 60 years by very different people. Sometime these contradictions are more apparent than real. As an example I can remember the contradiction recently removed by Fast VG[1] and Fast NP (2005). As is well known, two centuries before the TE, the czar Peter I introduced a reform in the Orthodox Church. Entire villages of people that did not recognize the reform were sent to Siberia. Therefore many Siberian regions and villages in 1908 were populated by people following the "old faith". For them, the daily timetable was regulated starting from the morning prayers at "*obied*", i.e. 8 o'clock in the morning. When asked about the explosion time, they answered that the explosion took place some time before the *obied*, which really corresponds to the seismic wave registrations after 7 o'clock local time. For the secular people that collected the testimonies, the word *obied* means lunch, i.e. about 12–14 o'clock. Therefore, they completed the forms by noting that the eyewitness stated that the explosion took place at noon, or even in the afternoon. These testimonies were considered not trustworthy due to the clear contradiction with instrumental registrations. A thorough statistical analysis performed by the Fasts (2005) has shown that the distribution of "midday eyewitnesses" correctly reproduces the distribution of the population following the "old faith".

To use them properly, it is important to take into account the different trustworthiness of the testimonies. I think that we can distinguish the following groups of testimonies in decreasing order of trustworthiness:

1. The testimonies collected *in the days immediately following the Tunguska explosion* by the director of the Irkutsk magnetic and meteorological observatory Voznesenskij (1925). Unfortunately, Voznesenskij published them only 17 years later due to an excess of scientific prudence. Immediately after the registration of the earthquake N° 1536, in the morning of 30 June 1908, Voznesenskij sent to all his correspondents a request to report what they or other people had observed on that morning. In his paper he gives a table with the results received from 61 correspondents and a map

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[1] It was the last contribution to the Tunguska studies given by the great researcher Vilgem Genrikovich Fast (1936–2005).

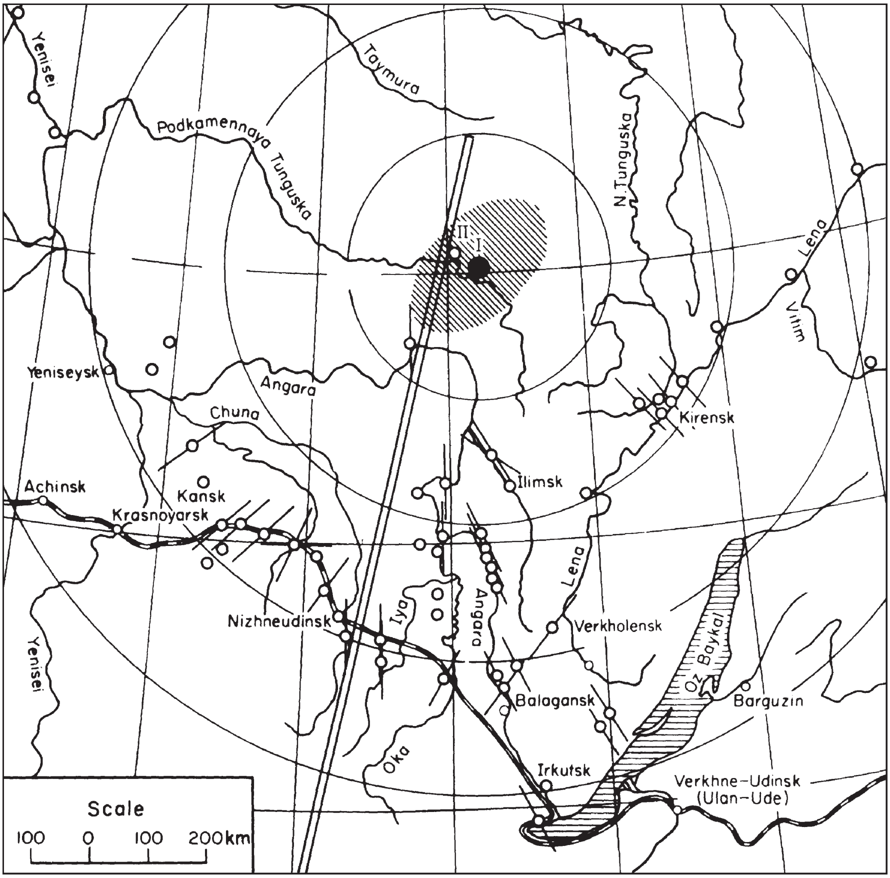


Fig. 18.8. A map with the dislocation of the correspondents that sent in July 1908 their reports to the Irkutsk Observatory. The map was published by Voznesenskij (1925) and reproduced by Krinov (1949, 1966)

showing their location on a very great territory (Fig. 18.8). Moreover, he refers to many individual testimonies from "cultured" people (chief of town post office, employees of meteorological observatories, agronomist and so on).

2. The testimonies collected before, during and immediately after (up to 1933) the expeditions of Kulik. They were collected mainly by Obruchev (1925), Suslov (1927) and Kulik (1922, 1923, 1927). I have mentioned in Sect. 18.2.3 that this primary information was sufficient to understand in 1922 that research had to be directed to the north of the Podkamennaya Tunguska River, in the neighborhood of the Vanavara River.
3. In the period from about 1933 up to 1958 practically no new eyewitness was questioned and, finally, in the 1960s, a massive material with hundreds of new testimonies from old people was collected in many regions. A thorough examination of these records can still be useful as Fasts's work shows.

No doubt that the more valuable testimonies are those written immediately after the fall by the correspondents of the Irkutsk observatory. They are not influenced by Voznesenskij who asks only about observations related to the *earthquake N° 1536*, without any reference to a flying body. Many of these reports are written before the publication in local newspapers of the first information on the event. These genuine reports, synthesized by Voznesenskij in 1925, are now stored in the Archives of the Meteorite Committee of the Russian Academy of Sciences hereafter referred as "Archive RAS". In the following paragraph, I give in brackets the page of the document N° 57 of Archive RAS in which these testimonies are gathered.

To describe what seen in the morning of 30 June 1908, no one of these reports testify something different from a flying object. Many reports are written after questioning a great number of persons. For example, the director of the meteorological station of Maritui states that his report is written after the interrogation of about 500 persons on a great territory around his station (19). I quote here some descriptions of the correspondents:

> "a large group of local inhabitants noticed a ball of fire in the north west coming down obliquely" (3); "the workmen saw a fiery block flying, it seemed, from south east to north west" (4); "in the north west a pillar of fire appeared about 8 meters in diameter … it was accurately established that a meteorite of very large dimensions had fallen" (5); "the local peasants told me that they saw some sort of fiery ball flying in the north" (6); "a loud noise was heard … probably from a passing meteor (aerolith)" (9); "some of local inhabitants had seen an elongated body narrowing towards one end, about one meter in length, torn as it were from the Sun…this body flew across the sky and fell in the north east" (16); "the fall of an aerolith was observed … a fiery streamer was seen" (26); "a ball of fire appeared in the sky and moved from south east to north west. As the ball approached the ground … it had the appearance of two pillars of fire" (36).

The testimony of page 16 was written the 30 June 1908 (the day of the event), that of page 6 – the 1 July 1908 (the day after the event), the others – from a few days up to six weeks after the event. Many correspondents could not understand what they have seen or heard. For example, in the letter referred to on page 6, the correspondent wrote to the Irkutsk observatory: "I have the honor to ask submissively the observatory to communicate and clarify what this means and could it be dangerous for human life".

These testimonies, and many others, contradict the "alternative" approaches (see Sect. 18.2.3) that deny the impact of an external body with Earth.

18.4
Parameters Deduced

18.4.1
Explosion Time

Studying the available seismic data, a first determination of the explosion time as 0^h 17^m 12^s UT was obtained by Voznesenskij (1925). This value was used up to the 1960s. The explosion time deduced from the barograms of 6 British meteorological stations, was equal to 0^h 15^m UT (Whipple 1930). The independent analysis of the barograms from 13 Siberian stations, gave an explosion time equal to 0^h 16^m 36^s UT (Astapovich 1933). These two sets of data were subsequently analyzed more carefully taking into account the exact distances and the properties of seismic and atmospheric waves. Pasechnik (1971) obtained a first result ($0^h\ 14^m\ 23^s$ UT), based solely on Jena and Irkutsk's seismic data. Two additional and more complete analyses were independently performed by Ben-Menahem (1975) and Pasechnik (1976). They found practically the same value for the time the seismic and aerial waves started (see Table 18.1, updated from Farinella et al. 2001).

Pasechnik (1976) calculated that the time of the explosion in the atmosphere was 7–30 seconds earlier depending on the height and energy of the explosion; this interval was subsequently reduced to 2–20 seconds (Pasechnik 1986). In the 1986 paper, however, Pasechnik revised his previous results obtaining a value equal to $0^h\ 13^m\ 35^s \pm 5^s$ UT. The commonly accepted explosion time is the time given by Ben-Menahem for the instant the seismic waves started, i.e. $0^h\ 14^m\ 28^s$ UT.

18.4.2
Coordinates of the Epicenter

The first contact point between the Earth surface and the shock wave from the airburst is commonly called "epicenter," though this term is not proper. From the data collected during the first three expeditions, Fast (1963) obtained the epicenter coordinates 60° 53' 42" N, and 101° 53' 30" E. These values are very close to the final ones 60° 53' 09" ± 06" N, 101° 53' 40" ± 13" E, calculated by Fast (1967) analyzing the whole set of data from the first part of the catalog (Fast et al. 1967). At about the same time, Zolotov (1969) performed an independent mathematical analysis of the same data and obtained the second values quoted in Table 18.1. The coordinates of Fast's epicenter with the uncertainties quoted, corresponding to about 200 m on the ground, were subsequently confirmed in all Fast's papers.

Examining the direction of fallen trees seen on the aerial photographic survey performed in 1938, Kulik suggested (1939, 1940) the presence of 2–4 secondary centers of wave propagation. This hypothesis was not confirmed, although neither was it definitely ruled out, by Fast's analyses and by seismic data investigation (Pasechnik 1971, 1976, 1986). Some hints of its likelihood were given by Serra et al. (1994) and Goldine (1998). This hypothesis is compatible with the recent reanalysis of the direction of fallen trees made on the basis of Fast's data integrated by those obtained from the 1938 and 1999 aerial photosurveys (Longo et al. 2005). The high trustworthiness of earlier eyewitnesses is also in favor of the multicenter hypothesis (Voznesenskij 1925, Archive RAS).

18.4.3
Trajectory Parameters, Height of the Explosion and Energy Emitted

The final TCB trajectory can be defined by its azimuth (α), here given from North to East starting from the meridian, the trajectory inclination (h) over the horizon and the height (H) of the explosion. These parameters can be estimated from the data on forest devastation, seismic records and eyewitness' testimonies.

The height of the explosion is closely related to the value of the energy emitted, usually estimated to be equal to about 10–15 MT (Hunt 1960; Ben-Menahem 1975), although some authors consider the energy value to be higher, up to 30–50 megaton

Table 18.1. Parameters deduced for the Tunguska explosion. In the last column, the sources used to find the given values are indicated: *SM:* seismic measurements; *BM:* barographic measurements; *FT:* fallen tree directions; *FD:* forest devastation data; *EW:* eyewitnesses

Source	Parameter	Remarks
	Time of the explosion (UT)	
Ben-Menahem (1975)	$0^h 14^m 28^s$	SM
Pasechnik (1976)	$0^h 14^m 30^s$	SM, BM
Pasechnik (1986)	$0^h 13^m 35^s$	SM
	Geographic coordinates of the epicentre	
Fast (1967)	60°53'09'' N, 101°53'40'' E	FT
Zolotov (1969)	60°53'11'' N, 101°55'11'' E	FT
	Height of the explosion, H (km)	
Fast (1963)	10.5	FD
Ben-Menahem (1975)	8.5	SM
Bronshten and Boyarkina (1975)	7.5	FD
Korotkov and Kozin (2000)	6 – 10	FD
	Trajectory azimuth, α (deg)	
Krinov (1949)	137	EW
Fast (1967)	115	FT
Zolotov (1969)	114	FT
Fast et al. (1976)	99	FT
Yavnel' (1988)	114 – 138	EW
Andreev (1990)	123	EW
Zotkin and Chigorin (1991)	126	EW
Koval' (2000)	127	FT, FD
Bronshten (2000)	122	EW
Bronshten (2000)	103	FT, FD
Longo et al. (2005) (single body)	110	FT
Longo et al. (2005) (multiple bodies)	135	FT
	Trajectory inclination, h (deg)	
Krinov (1949)	17	EW
Sekanina (1983)	< 5	EW
Zigel (1983)	5 – 14	EW
Yavnel' (1988)	8 – 32	EW
Andreev (1990)	17	EW
Zotkin and Chigorin (1991)	20	EW
Koval' (2000)	15	FT, FD
Bronshten (2000)	15	EW, FT
Longo et al. (2005) (single body)	30	FT
Longo et al. (2005) (multiple bodies)	30 – 50	FT

(Pasechnik 1971, 1976, 1986). In agreement with the first energy range, which seems to have more solid grounds, the height of the explosion was found equal to 6–14 km. A height of 10.5 ± 3.5 km was obtained by Fast (1963) from data on forest devastation. Using more complete data on forest devastation, Bronshten and Boyarkina (1975) subsequently obtained a height equal to 7.5 ± 2.5 km. From seismic data, Ben-Menahem deduced an explosion height of 8.5 km. Data on the forest devastation examined, taking into account the wind velocity gradient during the TCB flight (Korotkov and Kozin 2000), gave an explosion height in the range 6–10 km.

A close inspection of seismograms of Irkutsk station, made by Ben-Menahem (1975), showed that the ratio between East-West and North-South components is about 8 : 1, even though the response of the two seismometers is the same. Since the Irkutsk station is South of the epicenter, Ben-Menahem (1975) inferred that this was due to the ballistic wave and therefore the azimuth should be between 90° and 180°, mostly eastward. However, it is not possible to obtain more stringent constraints on the azimuth from seismic data.

It is not clear how Voznesenskij (1925) determined the direction of the bolide's flight given in Fig. 18.8. Using only the eyewitness data collected in 1908, Yavnel' (1988) obtained $\alpha = 114° - 138°$ and $h = 8° - 32°$. A critical analysis of the eyewitness reports written in 1908 together with those collected in the nineteen-twenties, made by Krinov (1949) gave an azimuth $\alpha = 137°$ with $h = 17°$.

Analysing the data on flattened tree directions from the first part of his catalog (Fast et al. 1967), Fast found a trajectory azimuth $\alpha = 115° \pm 2°$ as the symmetry axis of the "butterfly" shaped region (Boyarkina et al. 1964; Fast 1967). The independent mathematical analysis of the same data gave $\alpha = 114° \pm 1°$ (Zolotov 1969). Having made another set of measurements, Fast subsequently suggested a value of $\alpha = 99°$ (Fast et al. 1976). In this second work, the differences between the mean measured azimuths of fallen trees and a strictly radial orientation were taken into account. He gave no error for this new value, but a close examination of Fast's writings suggests that he considered an error of 2°. Koval' subsequently collected complementary data on forest devastation and critically re-examined Fast's work. He obtained a trajectory azimuth $\alpha = 127° \pm 3°$ and an inclination angle $h = 15° \pm 3°$ (Koval' 2000).

From a critical analysis of all the eyewitness testimonies collected in the catalog of Vasilyev et al. (1981), Andreev (1990) deduced $\alpha = 123° \pm 4°$ and an inclination angle $h = 17° \pm 4°$. Zotkin and Chigorin (1991) using the data in the same catalog obtained: $\alpha = 126° \pm 12°$ and $h = 20° \pm 12°$, whereas from partial data, Zigel' (1983) deduced $h = 5° \pm 14°$. A different analysis of the eyewitness data (Bronshten 2000), gave $\alpha = 122° \pm 3°$ and $h = 15°$. In the same book a mean value $\alpha = 103° \pm 4°$ is given obtained from forest devastation data. Sekanina (1983, 1998) studied the TE on the basis of superbolide theories and the analysis of the data available and eyewitness testimonies. He suggested an inclination over the horizon $h < 5°$ and an azimuth $\alpha = 110°$.

From the data on fallen tree directions in our new unified catalog (Longo et al. 2005), we obtain a single-body trajectory azimuth $\alpha = 110° \pm 5°$ and $h = 30°$. The same data are compatible with the hypothesis that the cosmic body was composed by at least two bodies, falling independently but very close one to the other, with a trajectory azimuth ~135° and an inclination of the total combined shock wave axis between 30° and 50°. The first body, with a greater mass, emitted the maximal energy at a height of about

6–8 km. The second, of minor mass, flew a little higher, on the right side and behind the first body, following the azimuth ~135° in the direction of the Lake Cheko. The last azimuth is in agreement with what found by Krinov (1949) and Yavnel' (1988) analyzing earlier eyewitness testimonies.

18.5
Tunguska-like Impacts

The Tunguska event is the only phenomenon of this kind that has occurred in historical time. The consequences of the event can be directly studied in situ. From such a study we can obtain a great amount of information useful to better understand and predict the characteristics of future Tunguska-like impacts, i.e. due to bodies with diameters equal to a few tens of meters. Many different models have been proposed to describe the impact with our planet by bodies having these dimensions. I mention here only some recent models, which imply a greater impact frequency and, therefore, a greater hazard.

18.5.1
Recent Models and Impact Frequency

The frequency of Tunguska-like impacts is highly dependent on the emitted energy, the explosion height and the entry angle.

Most of the published models for Tunguska have assumed that the explosion was essentially from a point source.

Recent models consider that such events are more analogous to explosive line charges, with the bolide's kinetic energy deposited along the entry column.

Plume-forming Impacts

Boslough and Crawford (1997) explain the TE as due to a "plume-forming" atmospheric explosion, i.e. as associated with the ejection and collapse of a high plume. I report here a brief description of the three overlapping phases of the plume formation, as summarized by Stokes et al. (2003):

1. *Entry phase.* When a bolide penetrates a planet atmosphere, it encounters gases at high speed that both slow it down and heat it up. A "bow shock" develops in front of the bolide where atmospheric gases are compressed and heated. Some of this energy is radiated to the bolide, causing ablation (i.e., melting and vaporization that remove material of the bolide's surface) and deformation. The rest of the energy is deposited along the long column created by the bolide's passage; much of the bolide's kinetic energy is lost in this manner. In some cases, aerodynamic stresses may overcome the bolide's tensile strengths and cause it to catastrophically disrupt within seconds of entering the atmosphere. Airblast shock waves produced by this sequence of events may reflect off the surface causing great devastation.
2. *Fireball phase.* The events taking place during the entry phase produce a hot mixture of bolide material and atmospheric gas called a fireball that is ballistically shot upward by the impact. Since it is incandescent, it radiates energy away in visible and

near infrared wavelengths. Buoyant forces cause the fireball to rise because it is less dense than the surrounding atmosphere.

The fireball's energy expands most easily along the low-density high sound speed entry column that was created by the bolide' passage.

3. *Plume phase.* The expanding fireball (and associated debris) rushes back out the entry column, ultimately reaching altitudes of many hundreds kilometers above the top of the atmosphere. After ~10 minutes of cooling and contracting at these heights, however, the plume splashes back onto the upper atmosphere, releasing additional energy as it collapses and impacts.

Boslough and Crawford (1997) re-examined the phenomena associated with the TE in the context of their model. They found that a 3 megaton plume-forming event could generate the seismic waves that were actually observed, whereas Ben-Menahem (1975) considering the waves generated by a point explosion has obtained the generally accepted value of about 12.5 megaton. Boslough and Crawford (1997) obtained a qualitative agreement between the calculated wind speed at different distances and the treefall shown on the map (Boyarkina et al. 1964) used for almost 40 years. This agreement would be improved using our new unified catalog and the corresponding map (Longo et al. 2005). The most convincing aspect of the plume-forming model is that it not only account for forest devastation and seismic and pressure waves but, for the first time, it gives a simple and reasonable explanation of the magnetic field disturbance and of the "bright nights" associated with the Tunguska event. The resulting plume, 100 seconds after the impact, is given in Fig. 18.9. As shown, a mixture of dust, water and tropospheric air is ejected above the top of the atmosphere. It is this material, transported westward rapidly enough, that caused the bright nights within 12 hours at distances up to 6000 km.

Shuvalov (1999) developed a similar plume-forming model. Firstly, he considered a volumetric absorption in the projectile of the radiation emitted by shock compressed atmospheric gas. Subsequently, Shuvalov and Artem'eva (2002) improved the model considering a surface absorption of the radiation. They elaborated a 2D numerical model with radiation and ablation for the impact of Tunguska-like bodies and obtained results similar to those of Boslough and Crawford (1997) for the plume formation and the ejection in the upper atmosphere of hot vapor and air.

All the authors of plume-forming simulations consider their calculations as preliminary and underline the necessity of developing a totally self-consistent 3D numerical model using realistic topography and including simultaneously radiation and ablation, disruption of the bolide, formation and evolution of a fireball and of a plume.

Foschini Hypersonic Flow

Let me mention two other representations of impacts that consider the bolide energy deposited along an entry column. Foschini (1999, 2001) developed a model studying the hypersonic flow around a small asteroid entering the Earth's atmosphere. This model is compatible with fragmentation data from superbolides. Foschini considers a bow shock in the front of the cosmic body that envelops the body. As the air flows toward the rear of the body, it is re-attracted to the axis. Therefore, there is a rotation of the

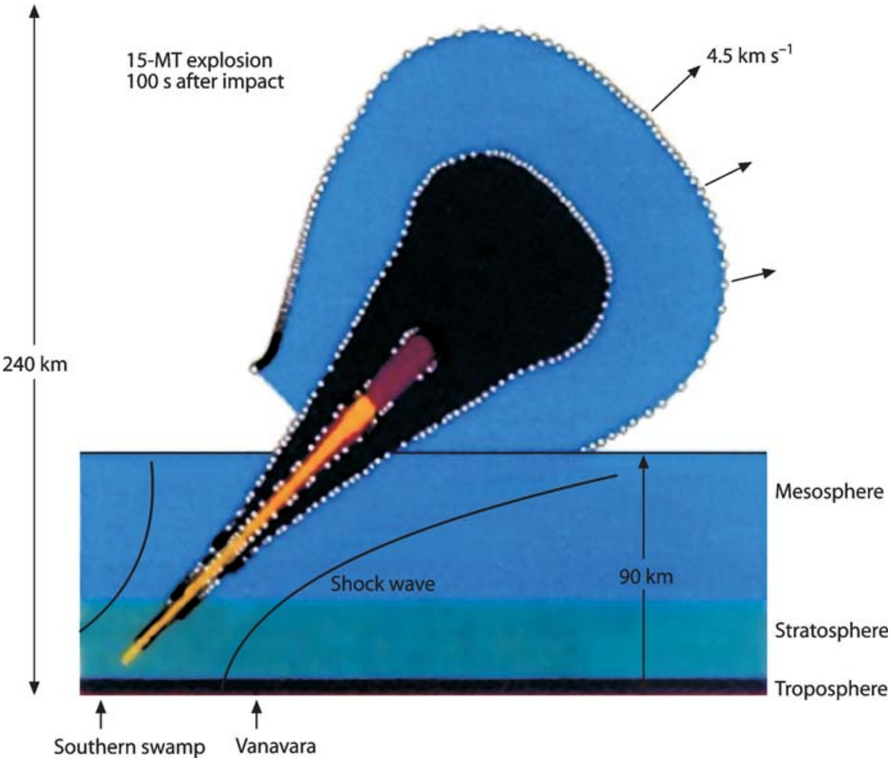


Fig. 18.9. A plume due to a total energy deposition of 15 megaton, 100 seconds after the impact of a stony asteroid (Boslough and Crawford 1977). Material within all but the outermost shell has been ejected from within the troposphere, and contains the mass of the impactor, as well as water from the humid lower atmosphere

stream in the sense opposite to that of the motion and this creates an oblique shock wave (wake shock). Since the pressure rise across the bow shock is huge when compared to the pressure behind the body, it can be assumed that there is a vacuum behind the cosmic body. According to the model, the condition for fragmentation depends on two regimes: steady state, when the Mach number does not change, and unsteady state, when the Mach number undergoes strong changes (Foschini et al. 2001). In the latter case, the distortion of shock waves causes the amplification of turbulent kinetic energy. So, a sudden outburst of pressure that can overcome the mechanical strength of the body, starting the fragmentation process is expected. On the other hand, in the first case – the steady state – the effect of compressibility suppresses the turbulence, and then the viscous heat transfer becomes negligible. The cosmic body is subjected to a combined thermal and mechanical stress.

The key point in fragmentation is how the ablation changes the hypersonic flow. The existence of asteroids with an extremely low density, such as Mathilde (~1300 kg m^{-3}), suggests that such a body could have an increased efficiency in deceleration. A possible process by means internal cavities could increase the deceleration and airburst effi-

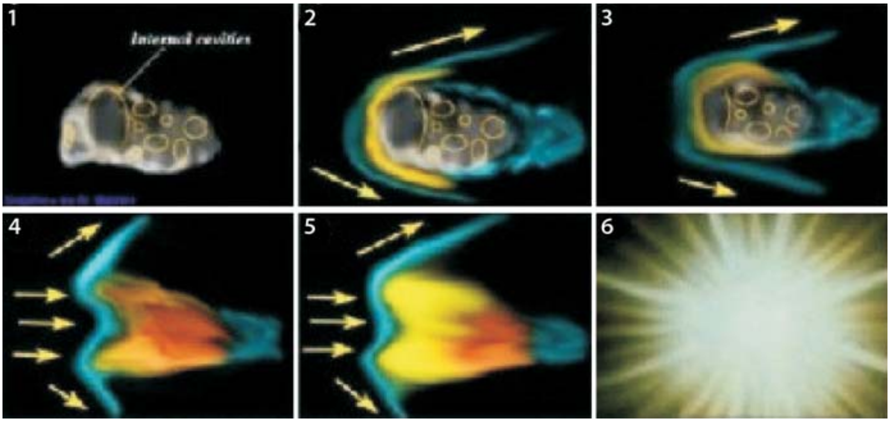
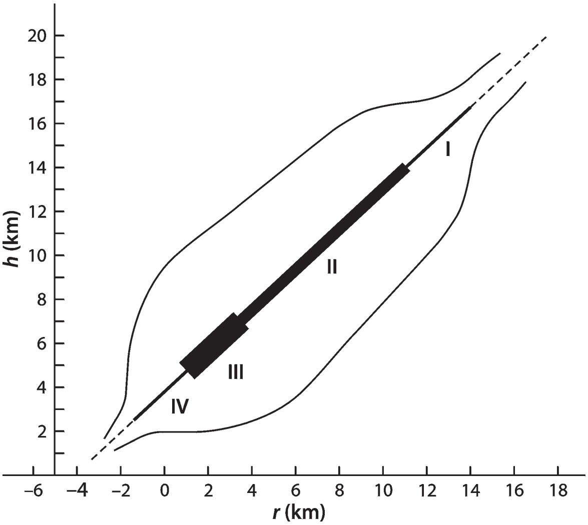


Fig. 18.10. In the Foschini model, as the cosmic body enters the Earth atmosphere, the ablation removes the surface, discovering the internal cavities, which act as something similar to a parachute, thereby increasing the deceleration

Fig. 18.11. The energy emission in the "Anfinogenov spindle". *h* – height from the Earth surface; *r* – distance from Fast epicenter



ciency is shown on Fig. 18.10. Following these lines Farinella et al. (2001) concluded that an object like asteroid Mathilde could explain the TE.

Anfinogenov Spindle

Anfinogenov (1966) and Anfinogenov and Budaeva (1998) proposed a qualitative model of the energy emitted by a "semi-infinite" linear source. The bolide begins disrupting and vaporizing when it enters the stratosphere and releases an increasing energy as it moves down. The energy emission is schematically described by the four cylinders shown in Fig. 18.11. In region I some 20% of mass and energy is lost, about 80% is emitted in regions II and III and less than 1% in region IV. The maximal energy emission is reached at a height of 6–8 km. The resulting shock wave has the form of the so-called "Anfinogenov spindle".

On the basis of the tree fall data and earlier eyewitness testimonies we consider that the TCB was a multiple bolide formed by at least two bodies of similar mass (Longo et al. 2005). They likely entered the atmosphere very close to each other following parallel trajectories with azimuths ~135°. The second body flew slightly higher, behind the first, and was decelerated by the shock wave. The resulting summary shock wave from the different spindles had an inclination angle of it symmetry axis ~45°.

18.5.2
Global and Local Damages

No doubt that a KT impact causes global damages, but the local character of damages from Tunguska-like events is questionable. It depends on the target. For the majority of the Earth's surface, which is water, there would be no damage (the lower limit for tsunami generation is about 10 times the Tunguska energy). Also, most of the land surface is still sparsely populated. The situation is quite different for a Megaton explosion in a large city or a populated region. Apart from the direct damages and casualties, we cannot exclude that some country could interpret that it had suffered a nuclear attack. Even at the time of the real Tunguska explosion, its consequences would have been very different, *if* the cosmic body would have reached the Earth about four hours later. Instead of hitting a non-populated forest at about 60° N, it could have impacted the Russian capital of St. Petersburg at the same latitude. Under these conditions, the Russian participation to World War I and the Russian Revolution would not have been possible. The whole history of humanity in the 20th century would be different. In short, the consequences, even of a "modest" impact are highly dependent on the target.

18.6
Concluding Remark

From the models mentioned in Sect. 18.5, it was deduced that the Tunguska explosive yield has been overestimated by a factor 3–4. This means that the interval between Tunguska-like events can be about three times less than usually expected. The expected frequency for such events, from the present value of about twice in a millennium can approach the century timescale. Therefore, the Tunguska-like impacts may present a more serious hazard than previously estimated. The real Tunguska event is the only phenomenon of this kind that happened during relatively recent time and that can be studied directly. The analyses of the data and samples collected during recent in situ expeditions have made it possible to check some characteristics of the Tunguska event. Many of its aspects are still unclear. Therefore, it is important to further both theoretical and experimental research on this phenomenon. For example, most of the scientists consider that the Tunguska event was due to the impact with the atmosphere of an asteroid or a comet. A clear choice between these two hypotheses has important practical consequences. The knowledge of the nature of the object, which explosion caused the devastation observed, will make it possible to verify and develop the models of the explosion mechanisms and fragmentation of cosmic bodies in the atmosphere. Broadening the study to the known impacts, will allow obtaining better estimates of the impact probability for cosmic bodies with different composition and dimensions.

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