Earth and Planetary Science
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REVIEW

The Structure of the Tunguska Comet

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Abstract: The collision of the Tunguska cosmic body with the Earth occurred more than a hundred years ago. However, the question of the nature of the cosmic body is still being actively discussed. Here, the author demonstrated that the Tunguska cosmic body was indeed a comet, the nucleus of which had a layered structure separated by gas-tight closed partitions. Thanks to these partitions, comets can penetrate the dense layers of the atmosphere, breaking up and losing layers one by one. Here, the author shows that the Tunguska body could have been decelerated by the atmosphere, in which case the explosion above the epicentre would have been a volumetric explosion of a mixture of dispersed cosmic matter and atmospheric oxygen. The author proposes one of the possible methods for the formation of cometary nuclei with partitions at the early stages of the evolution of a protoplanetary nebula.

Keywords: Tunguska cosmic body; Comet structure; Formation of cometary nuclei

1. Introduction

Cosmic bodies of various sizes constantly penetrate the Earth's atmosphere. The explosion of the Tunguska cosmic body over Siberia on 30 June 1908 was accompanied by the most powerful release of energy in hundreds of years, namely 10 megatons of trinitrotoluene (1 kiloton of TNT = 4.185×10^{12} joules).

The Tunguska cosmic object was initially considered to be a comet. Strong arguments in favor of this version are given in the works of Fesenkov [1], Whipple [2], Kresak [3] and Bronshten [4]. Due to the work of Sekanina [5], refuting the possibility that the Tunguska body was cometary in origin, the asteroid hypothesis currently dominates. Doubts by Sekanina led to the emergence of numerous models [6–8] allowing the disintegration of an asteroid object. There, it was suggested that the Tunguska object was a small asteroid with a diameter of 90–190 m [5]. It is assumed that the asteroid completely disintegrated in the Earth's atmosphere [6–8], as this would explain the absence of meteorites at the epicentre of the explosion. In other words, a stone (asteroid) ~100 m in size, meeting a target

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Received: 12 August 2023; **Received in revised form:** 13 December 2023; **Accepted:** 18 December 2023; **Published:** 28 December 2023

Citation: Gladysheva, O.G., 2023. The Structure of the Tunguska Comet. *Earth and Planetary Science*. 3(1): 1–8. DOI: https://doi.org/10.36956/eps.v3i1.924

DOI: https://doi.org/10.36956/eps.v3i1.924

(whose thickness is equivalent to ~10 meters of water), crumbles into dust. Moreover, the amount of cosmic matter that fell to the surface of the earth in the vicinity of the epicenter of the Tunguska explosion turned out to be less than 10^4 kg [9,10].

The main argument of the asteroid hypothesis, expressed by Sekanina [5], is the inability of the comet to approach the surface of the earth. In his opinion, the extremely fragile material of comets could not have survived under the influence of large aerodynamic pressures.

Nevertheless, there are calculations showing that not only asteroids can affect the Earth's surface. Grigorian [11] analyzed the mechanical and thermodynamic processes accompanying the invasion of a cosmic body and concluded about the cometary nature of the Tunguska fall. Having familiarized himself with the scientific discussion about the nature of the cosmic body, Grigorian [12] came to the conclusion that there are no reasons to reject the hypothesis about the cometary nature of the Tunguska object. Stulov [13] showed that the snow-ice sphere is capable of breaking up at an altitude of 20–37 km. In this case, gas products continue to move and the shock wave will be capable of knocking down a forest. However, according to Stulov, it is impossible to determine the properties of a space object that has invaded the Earth's atmosphere from its influence on the environment [13].

It was hypothesized that the Tunguska cosmic body was an extinct fragment of the nucleus of the Encke Comet [3,14,15]. That is, the parent body of this object was a comet of the Jupiter family. It is possible that the Tunguska cosmic body had no relationship with the Encke Comet. According to Jopek et al. [16], at least a dozen comets moved in orbits close to the orbit of the Tunguska object. However, Sekanina [17] concludes that their study based on combining atmospheric and interplanetary dynamic considerations led to an asteroidal origin for the Tunguska cosmic body.

This paper discusses the arguments in favor of the cometary nature of the Tunguska cosmic body.

2. Problems of the Asteroid Hypothesis

The asteroid hypothesis contradicts the general picture of meteorite falls. The study of meteorites allowed Krinov [18] and Levin with Bronshten [19] to work out the following rule: If the initial mass of an asteroid reaches 10^5–10^6 kg, then during interaction with the Earth's atmosphere, it will break up into fragments that fall to the Earth's surface. This rule is confirmed by numerous observations. Among them are the Sikhote-Alin meteorite [20], the Chelyabinsk meteorite [21] and the crater-forming Carancas chondritic meteorite (mass ~ 10^4 kg) [22]. The minimum mass of the Tunguska object was 10^8 kg, but no meteorites were found at the epicentre. Nevertheless, fragments of the Tunguska cosmic body did reach the Earth's surface.

The study of peat deposits at a distance of < 15 km from the epicentre of the explosion makes it possible to assert that fragments of carbonaceous matter (depleted in ^{14}C) fell out as spots onto the Earth's surface [23,24]. These fragments were a solid or rather viscous substance, since they were deposited on the surface of porous peat [25]. Anomalies of iridium [26], rare-earth elements and platinum group elements were found in the peat layers that were at the surface in 1908, in addition to the anomalous content of carbon and hydrogen (deuterium) [24]. The study of the ^{13}C isotope content in layers of peat deposits near the epicentre [24,27] showed that heavy carbon was a part of the cellulose molecules. The peat layer in which the isotope shifts were found grew over the course of at least 13 years [27]. It can therefore be concluded that during these years the carbon-containing substance of the Tunguska body decomposed and was assimilated by growing moss. As a result of the peat deposit studies, a conclusion was made in favour of the Tunguska body being cometary in nature [25,26,28–30].

In particular, Kolesnikov and colleagues [28–30] explained the small amount of cosmic matter that fell in the vicinity of the epicenter by the chemical composition of the cometary body. On average, it is believed that in comets water, organic matter and mineral components are found in equal proportions [31]. In the Tunguska event, the proportion of mineral components in the cometary body turned out to be significantly less than the proportion of water and organic material. In addition, after a volumetric explosion of dispersed fragments of the comet and discharge processes above the epicenter, a large mass of surface air together with the cosmic matter was carried to a height of more than 70 km [32]. Thus, the cometary nature of the object can explain the results of studying the epicenter.

3. Comet Nucleus Structure

Without a doubt, if we consider a cometary body as a highly porous substance whose internal space was formed under conditions of cosmic vacuum, it will break apart into components as atmospheric pressure increases. The fragile comet material is also unable to withstand large aerodynamic pressures. The cometary nucleus model proposed here circumvents both of these problems. The uniqueness of this model is that the layers of the comet are separated by gas-tight partitions (shells) (Figure 1) [33].

It is known that comets have a porous structure and consist of individual micron-sized granules. These granules are formed during the cooling of a protoplanetary cloud. Each comet granule is a dust particle surrounded by ice and organic impurities [34–36]. Observations of interactions between cometary fragments and the atmosphere have shown that these granules are weakly bound to each other [37,38].

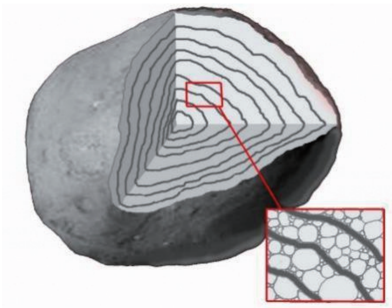

Figure 1. The structure of the comet's nucleus. It consists of layers with granules, separated by closed gas-tight partitions.

The study of the trees that survived the event near the epicentre of the Tunguska explosion made it possible to identify particles ranging from 0.5 to 10.0 μm in size from the resin of the branches [39,40]. Particles that had a high degree of probability of belonging to the Tunguska body were identified using tree rings. It has been noted that these particles were both rounded, i.e. subjected to heating and melting, and had torn or ragged edges, and among the latter, there were both metallic [40] and non-metallic [39] particles. Only granules of comet matter can pierce the thin bark of branches and deliver non-molten dust particles inside. Micron-sized particles with ragged edges could separate from the asteroid during its disintegration at an altitude of about 7 km, but it is unlikely that they would be able to reach the level of tree branches unchanged and not change as they pierce bark.

The comet body in addition to the individual granules contains large structures that also consist of granules (Figure 1). Probably, the Tunguska cosmic body consisted of structures of different sizes. They will be released in the process of disintegration of the comet, and could fall down under the influence of gravity and explode. Ice granule will be ejected from these structures during explosions. Several dozen explosions took place at different heights above the epicenter [32].

The OSIRIS cameras onboard the Rosetta spacecraft made it possible to obtain hundreds of images of the 67P/Churyumov-Gerasimenko comet surface with unprecedented spatial resolution [41,42]. They showed the presence of both large, isolated boulders (> 10 m) and numerous medium-sized boulders from < 1 m to 10 m on the comet's surface. According to our calculations[43], eyewitnesses could hear explosions from precisely this size of objects during the Tunguska event. Nearby sounds of explosions similar to thunder (in a cloudless sky) were heard by local residents across a territory of ~5×10^5 km^2 during the Tunguska event [43]. We showed [43] that along with the main cosmic body that exploded above the epicentre, a whole swarm of smaller objects entered the Earth's atmosphere.

Space missions of recent decades have shown that the nuclei of the 9P/Tempel 1, 19P/Borrelly and 81P/Wild 2 comets have a layered internal structure [44]. It has been suggested that Jupiter family comets developed a stratified structure during the formation of the comet nuclei. We propose that the layers in the structure of comets are separated by hermetic (gas-tight) partitions [33]. The existence of partitions between layers is a necessary condition. The porous structure of a cometary body, formed in the vacuum of space, cannot exist at atmospheric pressure in the absence of closed gas-tight partitions. The internal pressure of a comet is significantly lower than that of the atmosphere, so when the outer shell of a comet is damaged, it will split into its original components due to the shock wave caused by the pressure drop [33].

4. Explosive Fragmentation of Comets

The explosive fragmentation of a cometary body in flight can be caused by several reasons. Calculations and space research experience have shown that the thin shells of some aircraft can explode due to intense electrification when moving through the air [45]. The same can happen with the closed shells of a cometary structure. Furthermore, when heat enters a cometary object, water and volatiles will sublimate in the surface layers, which also leads to the expansion and rupture of the shells. Thirdly, and as mentioned earlier, when the outer shell is damaged, the shock wave (due to the pressure drop) leads to the destruction of the outer layer of the comet and the release of matter [33].

Explosions of the 17P/Holmes comet confirm the significant role of sublimation in the destruction of comets. The Holmes comet accumulated solar energy under a gas-tight shell for several months before the explosion [46]. The rupture of the shell led to the ejection of the surface layer of the comet and a significant increase in its brightness. The repeatability of the Holmes comet explosions does not contradict the existence of partitions between the layers and assumes that the properties of the outer shells of comets and partitions are identical.

There are two sketches of the Tunguska body [47,48], based on which one can imagine what the object looked like in flight (Figure 2). The first image (Figure 2a on the left) [48] is actually a generalization of eyewitness accounts. According to their stories [49], the object had a matte head and a transparent tail with sparks. Between the head and tail was an isthmus, the object was like a rye sheaf. This description of the Tunguska body in flight is the most popular [49]. The second sketch (Figure 2b on the left) was made by student Naumenko [47], who was exiled to Siberia for participating in the revolutionary movement. He had an understanding of astronomical observations. At first glance, the drawings have little in common. However, if we imagine a cometary object ~100 meters in size, which sheds shells one after another (Figure 2c), then everything falls into place. The ejected substance forms the head of the flying object, and large comet fragments with sparks burn out in the tail. As a result, the visible object is ~10 km long. A model of the object (Figure 2b on the right) is shown at the same angle as the cosmic body was observed by Naumenko in Kezhma at 214 km from the epicenter.

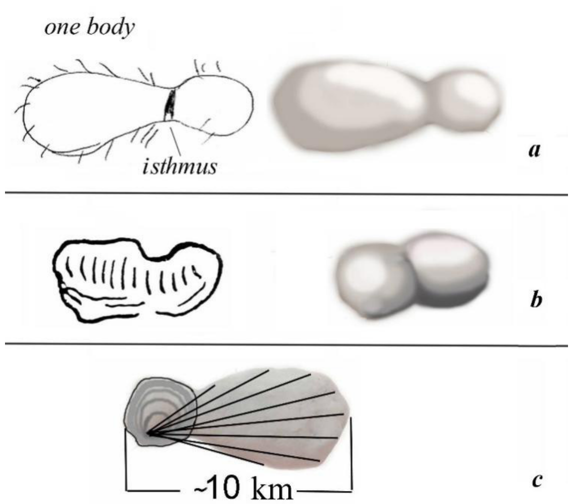

Figure 2. Tunguska's body in flight. (a) drawing of the object (left) [48] and its schematic reconstruction (right); (b) drawing by Naumenko [47] (left) and its schematic reconstruction (right); (c) appearance of the whole luminous phenomenon produced by the atmospheric entry of the Tunguska cosmic body.

According to observations from eyewitnesses, it has been determined [49] that the visible head of the Tunguska body had a size of ~2 km. It is natural to assume that the object itself was an order of magnitude smaller (~100 meters). From this, we can conclude that the substance of the surface layer was ejected from the object in an explosive manner. Ejected granules formed the object's head, while large fragments burned in the form of sparks in the tail. Eyewitnesses noted that the object's flight near the epicentre was accompanied by sounds similar to frequent rifle shots or machine gun fire [33]. This also is consistent with the explosive ejection of matter during the successive release of layers.

5. Another Argument against the Asteroid Hypothesis

The Tunguska space body was able to slow down in flight. The main evidence of the Tunguska event is the forest trees knocked over by shock waves in the vicinity of the epicentre. Research on the fallen forest trees was carried out through numerous expeditions. As a result, a map was drawn up showing the positions of the fallen trees. The effect of the shock wave from the flying body was determined by the deviation of the position of the trees in a radial direction. The Tunguska body moved with an azimuth of ~300° (evaluated starting from the south through the west) with the trajectory having a small angle of inclination from the horizon (about 20°) [18,25]. When an object moves at high speed along such a trajectory, the trees fall perpendicular to the trajectory on both sides [50]. No such fall pattern for the trees was found. Having studied the interaction of the shock wave of the explosion and the wave generated by the flying body, Zolotov [50] showed that the shock wave from the flying cosmic body was much weaker than the shock wave of the explosion. This suggests that during the flight, the spatial object lost speed as it moved. According to calculations [50], near the epicentre, the object moved at a speed of less than 3 km·s^{-1}. The deceleration of the object can be explained by the fact that the explosive release of matter significantly increases the size of the frontal surface of the body. According to our calculations [25], if we consider the effective radius of the object to be 2–5 times greater than the real one (~500 m), then the cometary body was able to slow down significantly.

An explosion of an asteroid in the Earth's atmosphere is only possible due to a release of kinetic energy. It is generally accepted that at a speed of less than 5 km·s^{-1}, an explosion of a body occurring due to a release of kinetic energy is impossible [51]. This once again speaks in favour of the cometary hypothesis for the Tunguska object. Comets become electrified and heated when they move in the dense layers of the atmosphere, meaning that fragmentation will continue even at a low speed. This means that the object most likely approached the epicentre surrounded by a cloud of fragments. The final destruction of the object near the Earth's surface and the detonation of the gas-air mixture could have occurred due to discharge processes between the electrically charged body and the conductive Earth. The result of this detonation was a volumetric explosion [32].

Comets contain on average ~30% organic material and ~30% water [31,52]. These cosmic bodies consist of the primary matter of a protoplanetary nebula and are formed in a reducing (hydrogen-containing) gaseous medium. As a result of the crushing of a cosmic body, substances that are chemically active in the oxygen-containing terrestrial atmosphere are released. The water brought by a cosmic body as a result of interaction with atmospheric molecules and radiation is also decomposed into H_2 and O_2. This is why a cloud of the explosive mixture was formed above the epicentre.

6. Formation of the Comet

Here, we suggest the following process for the formation of this comet. The protoplanetary nebula, rotating around the centre of mass, began to cool from its periphery. With this decrease in temperature, organic components, water vapour and gases began to condense into dust particles, forming the initial granules [34,35]. Gases (CH_4, NH_3, CO_2, H_2S, etc.) condensed on top of the ice. Thus, the ice granules were covered with a layer of organic matter. The organic matter of the granules was exposed to both short-wave radiation, including ultraviolet radiation, and corpuscular streams. Experiments [53–55] have shown that, as a result of all this interaction, organic molecules that were previously volatile at terrestrial temperatures were gradually transformed into high-molecular macromolecules. Studies of porous interplanetary dust particles taken from the stratosphere have shown that individual pellets (primordial dust samples of the solar nebula) have been coated with organic matter [56]. It can be assumed that the substance on the surface of the granules was a kind of glue. The granules stick to each other or are combined in some other way into complex structures (proto-comets).

As the overall mass of the granules increases, the speed of the proto-comet travelling towards the ecliptic, under the influence of gravity, increases. As it moves towards the ecliptic, this object will have collected grains and other similar structures, increasing its mass and speed. We believe that the temperature near the ecliptic plane is higher than at the periphery. We assume that there is a certain distance from the central point of the Solar System at which an object can cross the high-temperature zone and preserve most of its inner composition. During this temporary heating, the surface of the object loses water and volatile components, and a shell of refractory organic materials with dust particles is formed on its surface. Having passed through the heated zone, the proto-comet will again enter the cold zone on the opposite side of the proto-nebula due to inertia. This object will continue to collect grains and fragments along its path in the cold zone. On the one hand, the object will move in a circle around the centre of the Solar System. On the other hand, it will oscillate between the "upper and lower" boundaries of the nebula, passing through the entire thickness of the protoplanetary cloud, and periodically intersecting the ecliptic. It is most likely that the comet formation zone was located near the orbit of Jupiter.

7. Discussion and Conclusions

The opinion that a comet is not capable of penetrating the dense layers of the atmosphere and exploding at an altitude of 7 km is erroneous. It contradicts the results of studies conducted at the epicenter of the explosion. Traces of cometary material were found there and there were absolutely no meteorites.

Conclusion about the insufficient strength of the cometary substance [5], which is not able to withstand large aerodynamic pressures, refers to the comet's speed of more than 30 $km \cdot s^{-1}$. However, it turned out that comets are capable of being slowed down by the atmosphere, and the Tunguska cosmic body moved at a significantly lower speed. According to eyewitnesses, the object was observed in flight for 30 seconds to 1 minute [49]. At normal cometary speeds (more than 20 $km \cdot s^{-1}$), its flight would take a matter of seconds. Our calculations [25], taking into account the sequence of explosions of an object in flight and the release of matter, allow a cometary object with a speed of ≤ 15 $km \cdot s^{-1}$ to reach the epicenter with a speed of less than 3 $km \cdot s^{-1}$.

In addition to the low speed of entry into the atmosphere, the Tunguska object presumably had an orbit that is not typical for comets. Furthermore, a number of works suggest that the Tunguska object was formed as a result of the decay of a giant comet, of ~100 km in diameter [57], that is, the connection of its orbit with comets is not disputed.

Thus, we can conclude that the Tunguska cosmic body was a comet that had an entry speed into the Earth's atmosphere of less than 15 $km \cdot s^{-1}$, that is, it was somehow able to slow down. This question certainly requires further research.

Conflict of Interest

There is no conflict of interest.

Data Availability Statement

All data is publicly available.

Funding

This research received no external funding.

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