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On the nature of the Tunguska meteorite

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Abstract. The complete lack of stony splinters over vast territory (15 000 km^2) surrounding the epicenter of the Tunguska catastrophe implies that the Tunguska body is unlikely to be an asteroid, as assumed by several researchers. We review the arguments that make this hypothesis unlikely.

Key words: comets: general – meteors, meteoroids – minor planets, asteroids – solar system: general

1. Introduction

In a recent publication, Foschini (1999) invoked new arguments in support of the asteroidal nature of the Tunguska meteorite. Assuming that the explosion of the Tunguska body occurred when the dynamic pressure of the atmospheric aerial flow became equal to the mechanical strength S of the body

$$\rho\nu^2 = S \tag{1}$$

or

$$\rho\nu^2 = \frac{\gamma}{\gamma - 1} S \tag{2}$$

where ν is the velocity and γ is specific-heat ratio C_p/C_ν. From Eq. (2), assuming S=10^6 Pa for comets and S=5·10^7 Pa for stony bodies, Foschini obtained velocities of respectively 2.3 and 16.5 km s^{-1} for these two bodies. On the basis of a comparison he concluded that the impact was more likely to be due to an asteroid than to a comet, because the former velocity is too low for producing an explosion.

2. The shortcomings of the asteroidal hypothesis

We argue in the following that the complete lack of stony fragments over the area affected by the shock waves generated either by the meteorite itself or by its explosion is in itself sufficient to reject the hypothesis that the Tunguska body is an asteroid, as claimed by Sekanina (1983), Chyba et al. (1993), Foschini (1999) and others.

To answer possible objection that these fragments might have been poorly sought, we recall the report by the leader of most research expeditions to the site of catastrophe, Prof. N.V. Vasil'ev (1984). In order to test Anfinogenov's model that assumed a possibility for the fall of stony fragments to the surface of the Earth, a variety of techniques have been applied: magneto-, inducto-, fluoro- and metallometry, visual searches, electric logging, schlich testing, etc. (Vasil'ev 1986). No stony fragments were found in this extensive and punctilious search.

The formation of rock fragments of different sizes after explosions of very high energy (chemical or nuclear) was reliably established by Sadovskii et al. (1982) from an analysis of many powerful explosions. In the Tunguska case, stony fragments could separate from the main body before the explosion.

In an attempt to reconcile the asteroidal hypothesis with the complete lack of stony fragments, Svettsov et al. (1995) put forward the hypothesis that all stony fragments vaporised during the explosion under the action of intense radiation from the fireball.

To test this assumption, we can calculate the flux of radiative energy incident on a stony fragment situated, say, at 100 m from the source of radiation. The total energy of the explosion, according to different estimates, ranges 10^{23} erg (Korobeinikov et al. 1983) to 4·10^{23} erg (Ben-Menachem 1975). Unfortunately, the fraction of the energy which is converted into radiation is not precisely known either, and ranges from 1 to 20% (Korobeinikov et al. 1983). For this reason, we calculate the radiative flux in the following way.

According to the first estimate by Zhuravlev (1967), then improved by Tsynbal and Shnitke (1988) and based on testimonies of the eye witnesses located at Vanavara, who felt an instantaneous burn without painful aftereffects in this place located at a distance of 65 km from the epicenter, the impulse of radiation at Vanavara is estimated to be 0.4 J/cm^2 = 4 ·10^6 erg/cm^2. Scaling up the energy from the distance of 65 km to 100 m and taking into account absorption in the atmosphere, which should reduce the radiative flux of Vanavara by a factor of about 10, we find the value of the flux through a surface perpendicular to the beam at 100 m from the source to be 1.6·10^{12} erg/cm^2. Multiplying this quantity by the surface area of a sphere of radius 100 m (1.25·10^9 cm^2) yields for the total energy converted into radiation value 2·10^{22} erg. Thus, if the total energy of explosion is E=10^{23} erg, its fraction transformed into radiation should be 20% (the upper limit of Korobeinikov's estimate). If, however, the total energy is E=4·10^{23} erg, this fraction is only 5%, which is also quite plausible. Then, we can adopt the above cited estimation of 2·10^{22} erg as the total energy converted into radiation.

Now let us check our estimate using another effect, i.e., the radiative burn of trees. According to Zhuravlev (1967), the distance from the point of explosion to the western boundary of the burn region 9.5 km, that is, 6.8 times shorter than the distance to Vanvara. Tsynbal and Shnitke (1988) have indicated that the atmosphere is most transparent for radiation with wavelengths 3.70–3.75 μ. Only 15–18% of the initial flow could pass through the layer of 65 km. That means that on the distance of 10 km from the epicenter the infrared radiative flow will be of order of 16 J/cm^2 (1.6·10^8 erg/cm^2), which is sufficient to damage the foliage of trees.

Now we return to considering the fragmenst. The above estimate for the radiative flux should be halved to take into account the fast rotation of the fragment and halved again in view of the oblique incidence of rays and shadowing by the irregularities of its surface. Furthermore, we should consider the fast motion of the fragment away from the point of explosion at a velocity of about 2 km s^{-1}, or 11% of the velocity of the main body, according to Hills and Goda (1993). This additionally reduces the radiative flux by a factor of more than 1.5 (Bronshten 1999). Finally, during the evaporation, a dense layer of vapour forms around the fragment. As a result, the radiative flux becomes 15 to 100 times smaller (Bronshten 1983). The combination of all these effects reduces the flux by more than two orders of magnitude, to about 10^{11} erg/cm^2. Since the specific energy of evaporation of stony bodies is 8·10^{10} erg/g, we find that only a fraction of a gram will be evaporated, from each square centimeter of the fragment's surface during 0.1 sec.

Let us consider another evaporation mechanism, namely the interaction of fragments with the atmosphere during their fall from the point of separation of the ground. Calculations of the mass losses deceleration of fragments ejected vertically downward from a height of 8 km, based on the physical theory of meteors (Bronshten 1983) showed that, for initial masses ranging from 12 to 30 kg, about 17–21% of the initial mass could reach the ground as 5 kg remnants. However, the deceleration of different fragments will be completed at different heights depending on their masses: at 5 km for 30 kg, at 3.5 km for 100 kg, and at the ground level for 1t. A 12 t fragment will reach the ground at a fraction of its cosmical velocity, i.e., 3.2 km s^{-1}.

Thus, we see that neither the radiation from the fireball nor the interaction with the air flow after the explosion can evaporate stony fragments of the hypothetical body of asteroidal nature. Therefore, this body could not be stony. Only the icy nucleus of a comet could explode without leaving large fragments.

3. Discussion

From the above estimate, we conclude that the asteroidal hypothesis cannot be valid. However, the question arises of why various studies by highly qualified scientists yield results that favour this hypothesis. As it turns out, the authors of these studies either did not take into account all relevant effects (as for example, Svettsov), or either used a crude theory (Chyba et al. 1993), or assumed erroneous values for the parameters (Foschini 1999).

As an example, let us consider the parameters used by Foschini. For comets, he assumes S=10^6 Pa as for glacier ice. However, cometary nuclei, as determined from observations of the disruption of some comets under the action of solar tides, have S=2·10^4–4·10^5 Pa (e.g., Öpik 1966).

Another parameter, γ, was assumed by Foschini to be 1.7 following Kadono and Fujiwara (1996). But the gas behind the shock front that precedes a meteorite (having a velocity of 11–72 km s^{-1}) as well as in the compressed layer is highly ionized. Therefore, γ should be much lower in such conditions. This parameter can be calculated according to the relation (Zeldovich and Raiser 1967)

$$\gamma = \frac{\rho^* + 1}{\rho^* - 1}$$

where ρ^* is the compression in the shock lyer (ratio between the densities behind and ahead of the front). It can be found from the expression $\rho^* = 4 + 3Q/\epsilon$, where Q is the specific energy of ionization and ϵ is the specific kinetic energy of particles in the compressed layer. We obtain $\gamma = 1.67$ only in the case Q = 0; if, however, Q is not equal to zero, then γ should be lower.

Accurate calculations for a wide range of pressures and temperatures consistent with meteoric conditions show that under such conditions, γ = 1.15 (Bronshten 1965). Then the multiplier in Foschini's Eq. (2) becomes equal to 7.67 instead of 2.43.

However, the main problem in Foschini's derivation is the assumption that the explosion of the Tunguska body took place after the condition given by Eq. (2) came to be satisfied. Actually, the disruption of such a body begins much earlier, at a height of about 100 km. The body' becomes flattened perpendicular to the trajectory and subsequently acquires a form of a medusa, with edges bended backward. A shock wave passes through the body, breaking down its material into numerous debris. Initially thay fly together, embraced by a common aerial shock wave (the detached shock wave surrounding the body should be distinguished from the internal shock wave in the body). Later these debris separate from one another and fly independently.

A detailed theory of this fragmentation process was developed by Grigoryan (1979) and independently, by Hills and Goda (1993). Grigoryan's theory was improved by Bronshten (1985), who supplemented the mechanical breakdown with the process of evaporation of the body and its debris. The flight of the Tunguska meteorite accompanied by its fragmentation in conformity with Grigoryan's theory was calculated by Levin and Bronshten (1986). Also, Bronshten (1995) showed that the theories developed by Grigoryan's and Hill's and Goda's theories are equivalent theories are equivalent. The theory proposed by Chyba et al. (1993) is only a rough approximation which leads to incorrect estimates for the height of the complete disruption of icy and stony bodies, as discussed by Bronshten and Zotkin (1995).

4. Conclusion

The complete lack of stony fragments over a vast territory surrounding the epicenter of the Tunguska catastrophe implies that the asteroidal nature of the Tunguska meteorite is unlikely. The experimental and theoretical evidence points out the fact that, even upon very strong explosions, differently sized hard fragments should be formed and should survive. Neither radiation from the exploding fireball nor the interaction of the fragments with the air during their fall to the Earth can vaporize them completely.

The Tunguska body could only be of cometary nature. It seems probable that it was genetically related to the Encke comet, in accordance with the hypotheses of Zotkin (1966) and Kresak (1978).

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