A&A manuscript no.
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07 (07.13.1; 07.13.2)

ASTRONOMY
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A solution for the Tunguska event

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Received 1 September 1998; accepted 10 December 1998

Abstract. This letter presents a new solution for the Tunguska event of June 30th, 1908. The solution has been obtained starting from seismic data, is in fair agreement with the observational evidence, and supports the asteroidal hypothesis for the origin of the Tunguska cosmic body. It is based on an improved model of the hypersonic flow around a small asteroid in the Earth's atmosphere.

Key words: meteors, meteoroids – minor planets

1. Introduction

On June 30th, 1908, something exploded over Tunguska, in central Siberia. Over the last ninety years this catastrophic event has inspired a plethora of scientific investigations. Despite many interesting findings, there are still substantial open questions and inconsistencies among the theories and the available data (for a review see Vasilyev 1998).

Among many different effects, the Tunguska explosion produced shock waves, which were recorded by seismographs at several sites. Ben–Menahem (1975) made a detailed analysis of these seismic records and derived an explosive energy of 12.5 ± 2.5 Mton. He also concluded that the data on the energy source are consistent with an airburst at a height of about 8.5 km.

In a previous letter (1998), we have shown that seismic data can be used to characterize the very bright 1993 Lugo bolide, obtaining a good match between the derived solution and the observations. Here the same methodology is applied to analyze the Tunguska event, using Ben–Menahem's analysis as a starting point.

2. Current models

Several different models have been developed in order to fit all the available data on the Tunguska event (e.g. Chyba et al. 1993, Grigorian 1998, Hills & Goda 1993, Lyne et al. 1996). All these models have contributed significantly to a general improvement in our understanding of the atmospheric disruption of meteoroids. They usually assume that the fragmentation process starts when the aerodynamic pressure is equal to the mechanical strength S of the cosmic body. Relating air density to airburst height, this allows one to derive the meteoroid speed (V):

$$V = \sqrt{\frac{S}{\rho_{\rm sl}} \exp\left[\frac{h}{H}\right]}, \tag{1}$$

where $\rho_{\rm sl}$ is the atmospheric density at sea level, h is the height of first fragmentation and H is the atmospheric scale height (about 8 km). From Ben–Menahem's analysis we infer that there was a single fragmentation event; there is no evidence of multiple explosions, as it should occur during multiple fragmentation events (Ben–Menahem 1975). Thus Eq. (1) can be used to derive V, provided one assumes that the first fragmentation coincided with the airburst occurred at $h = 8.5$ km.

For different types of cosmic body, corresponding to different assumed values for S (taken from Hills & Goda, 1993), we obtain the results listed in Table 1.

Table 1. Speed of the Tunguska cosmic body vs. strength according to Eq. (1)

Body type	S [Pa]	V [km/s]
Comet	$1 \cdot 10^6$	1.5
Carbonaceous chondrite	$1 \cdot 10^7$	4.7
Stone	$5 \cdot 10^7$	10.6
Iron	$2 \cdot 10^8$	21.2

Now, since before exploding large meteoroids undergo a limited mass loss during their atmospheric path, the pre–explosion speed must be close to the (geocentric) orbital speed, and thus must be greater than the Earth's escape velocity (11.2 km/s). Therefore, according to the results derived from Eq. (1), the most plausible solution would be that of an iron body. However, the iron body hypothesis is not consistent with the recent on–site recovery of microremnants from a stony object (Longo et al. 1994, Serra et al. 1994).

Actually, taking into account the uncertainty in the value of S and the different measurement errors (both of which are difficult to quantify), the stony object solution could not be entirely ruled out using this argument (typical geocentric speeds for near–Earth asteroids are ≈ 15 km/s). However, it is known that the interaction of large meteoroids (or small asteroids) with the Earth's atmosphere is characterized by a great variety of behaviors, and any quantitative theory should take into account a large number of variables: size, shape, rotation, composition, internal structure, orbital speed, flight path angle. Thus for the time being each bolide must be seen as a case study, which can provide useful insights for a future comprehensive theory. As a further consequence, Eq. (1) cannot be trusted to provide quantitatively reliable results in every case.

For instance, we know that sometimes meteoroids explode at dynamic pressures much lower than their mechanical strength (Ceplecha 1995). In the case of the Lugo bolide, an interesting possibility is that this behavior may have been related to a porous structure of the meteoroid (Foschini 1998). However, Tab. 1 shows that in the case of Tunguska we have the opposite problem, and that we should assume an anomalously high mechanical strength. Therefore, I will look into another direction for a possible solution of the conundrum.

3. Hypersonic flow

When a large meteoroid enters the Earth's atmosphere, it has a speed in the range $12 \div 72$ km/s, hence it moves at *hypersonic* speed (that is, with Mach number greater than about 5). Since here we are interested in the dynamics of a meteoroid large enough to reach the lower atmosphere, the fluid can be treated as a continuum. Thus, we can use current knowledge about hypersonic aerodynamics in order to understand meteoroid airbursts. For thorough presentations of this theory, the reader is referred to the books of Shapiro (1954), Landau & Lifshitz (1987), and Holman (1989).

It is important to note that for large Mach numbers the linearized equations for the speed potential are not valid, so we cannot use laws holding for supersonic speeds. In hypersonic flow, Mach waves and oblique shock waves are emitted at small angles with the direction of the flow, of the order of the ratio between body thickness and length, and thus tend to follow the surface of the body. Under these conditions, the atmospheric path of a large meteoroid can be seen as a long cylinder, generating pressure waves that can detected as infrasonic sound (Cumming 1989, ReVelle 1976).

The small angle of Mach and oblique shock waves gives also rise to the concept of hypersonic boundary layer near the surface. In front of the meteoroid there is a bow shock, that envelopes the body. The shock is stronger on the symmetry axis, because at this point it is normal to the stream. Then, we find a zone where molecular dissociation is the main process and even closer to the body surface, we find the boundary layer, where viscous effects are dominant. As the air flows toward the rear of the meteoroid, it is reattracted to the axis, just like in a Prandtl–Meyer expansion. As a consequence, there is a rotation of the stream in the sense opposite to that of the motion (rectification); this creates an oblique shock wave, which is called wake shock. Since the pressure rise across the bow shock is huge when compared to the pressure decrease across the Prandtl–Meyer expansion, one can assume, as a reasonable approximation, that there is a vacuum in the rear of the meteoroid. For illustrative images of a hypersonic flow, we refer to Chapter 19, Volume 2, of Shapiro (1954).

The fluid temperature increases in the boundary layer, because the speed must decrease to zero at the meteoroid surface; moreover there are heating effects due to viscous dissipation. There are also regions (like in the Prandtl–Meyer expansion) in which the presence of vacuum or near–vacuum strongly reduces heat transfer, and this contributes to the increasing body temperature. If the generation of heat increases so quickly that the loss of heat may be inadequate to achieve an equilibrium state, we may have a thermal explosion. This explosion generates pressure waves that can be detected on the ground by seismographs. Note that after the Tunguska event no meteorite was recovered, so the argument the meteorites are usually cold immediately after landing does not rule out this kind of thermal explosion in this case.

Current models of the Tunguska event consider, as a reference, the stagnation pressure only (e.g. Hills & Goda 1993), although, for the reasons outlined above, a realistic physical description should account for heat transfer and generation processes as well. A similar conclusion on the need for a coupled radiation–hydrodynamical model has been recently reached by Borovička et al. (1998a, 1998b), following a detailed analysis of theories and observations for the Benešov bolide.

4. The importance of the stagnation temperature

Let us now consider the heating due to the conversion of kinetic energy of the flow into thermal energy, when the gas is brought to rest (in the boundary layer). This process can be described in terms of a steady flow energy in an adiabatic process:

$$h_0 - h_\infty = \frac{V_\infty^2}{2}\,, \tag{2}$$

where h_0 and h_∞ are the stagnation and free stream enthalpy of the fluid, respectively, and V_∞ is the free stream speed. Note that the choice of the reference frame is not important here: if we consider a frame centered on the body, the fluid will move, and *vice versa*; therefore V_∞ can be interpreted as the body's speed with respect to the atmosphere. We can rewrite Eq. (2) in terms of temperature:

$$T_0 - T_\infty = \frac{V_\infty^2}{2c_\mathrm{p}} \tag{3}$$

where c_p is the specific heat at constant pressure. During the atmospheric path, as the Mach number is large, the meteoroid's speed is close to the maximum value corresponding to the stagnation temperature. Changes in the stream properties are mainly due to changes in the stagnation temperature T_0, which is a direct measure of the amount of heat transfer.

This argument stresses the importance of the stagnation temperature in hypersonic flow, since it is related to the maximum speed of the stream, which in turn is close to the speed of the cosmic body. According to Shapiro (1954), the relationship between stagnation temperature and maximum speed of the stream can be expressed in the following way:

$$V_\mathrm{max} = \sqrt{\frac{2\gamma}{\gamma - 1} R T_0}\,, \tag{4}$$

where γ is the ratio of specific heats. By means of the equation of state for the air, V_max can be expressed as a function of the stagnation pressure and density:

$$V_\mathrm{max} = \sqrt{\frac{2\gamma}{\gamma - 1}\frac{p_0}{\rho_0}}\,. \tag{5}$$

In order to obtain a condition for the meteoroid breakup, the stagnation pressure p_0 must be set equal to the mechanical strength S of the body. As for the stagnation density, we have $(\rho_0 - \rho_\mathrm{air})/\rho_\mathrm{air} \approx 1$ (Landau & Lifshitz 1987), where ρ_air is the undisturbed air density at the airburst height. Finally, by expressing ρ_air as a function of atmospheric height h and ρ_sl, like in Eq. (1), we obtain a new equation to estimate V_max, which is close to the speed of the cosmic body at breakup V:

$$V \approx V_\mathrm{max} = \sqrt{\frac{\gamma}{\gamma - 1}\frac{S}{\rho_\mathrm{sl}} \exp\left[\frac{h}{H}\right]}\,. \tag{6}$$

For γ we can use a value of about 1.7, resulting from experimental studies on plasma developed in hypervelocity impacts (Kadono & Fujiwara 1996). Comparing Eq. (6) to Eq. (1), we see an additional factor of about 1.6. This comes from the fact that Eq. (6) derives from Eq. (4), according to which the stagnation temperature depends on speed when a body is travelling at hypersonic velocity. Eq. (6) shows that the airburst occurs thanks to the combined thermal and mechanical effects acting on the meteoroid. In other words, thermodynamic processes decrease the effective pressure crushing the body in a significant way, so the same body can reach a lower altitude, or for a given airburst altitude a lower strength is required.

5. A new analysis of the Tunguska event

By means of Eq. (6) we can replace Table 1 with a new table for the breakup speeds of different types of cosmic body (see Tab. 2). Note that now the inferred speed for an iron body would be too high, and stony bodies provide the most plausible solution. This is consistent with the results of a detailed analysis of several hundreds meteors carried out by Ceplecha & McCrosky (1976) and Ceplecha (1994), who found that a height around 10 km is fairly typical for stony objects.

Table 2. Speed of the Tunguska cosmic body vs. strength according to Eq. (6)

Body Type	S [Pa]	V [km/s]
Comet	$1 \cdot 10^6$	2.3
Carbonaceous Chondrite	$1 \cdot 10^7$	7.4
Stone	$5 \cdot 10^7$	16.5
Iron	$2 \cdot 10^8$	33.0

We can now calculate other data for the Tunguska event solving the equations of motion and the luminosity equation, according to the procedure described in Foschini (1998). The results are summarized in Table 3. The following assumptions have been made: (i) the luminous efficiency τ is 5%; (ii) the diameter of the object is calculated assuming a spherical shape and a density of 3500 kg/m^3, typical for a stony object.

Table 3. Summary on the properties of the Tunguska Cosmic Body

Apparition time (UT)[a]	1908 06 30 00:14:28
Latitude of airburst[a]	60°55′ N
Longitude of airburst[a]	101°57′ E
Airburst height[a]	8.5 km
Explosion Energy[a]	12.5 Mton
Mass	$4 \cdot 10^8$ kg
Diameter	60 m
Abs. Visual Magnitude	−29.4
Velocity	16.5 km/s
Inclination[b]	3°
Path azimuth[a,c]	115°

[a] From Ben–Menahem (1975).
[b] Over the horizon.
[c] Clockwise from North.

Comparing these results to previous ones and to the available data (for a review see Vasilyev 1998), we note a generally good agreement, except for the trajectory inclination over the horizon. The value obtained here is about 3°, while Vasilyev reported that the most likely inclination angle was about 15°. However, he also noted the possibility of a good aerodynamic shape of the Tunguska cosmic body, that may have decreased the inclination angle. Moreover, we have neglected the lift effects, following Chyba et al. (1993).

Among the authors quoted by Vasilyev, only Sekanina derived an angle lower than 5°. Interestingly, it was just Sekanina (1998) who strongly favoured the conclusion of an asteroidal origin for the Tunguska cosmic body. The results obtained here provide additional support for Sekanina's conclusion.

6. Conclusions

In this paper, we have outlined a new analysis of the the Tunguska event, starting from seismic data obtained by Ben–Menahem (1975) and improving the relationship between body speed, mechanical strength and airburst height. The main conclusion is that the Tunguska cosmic body was probably a stony asteroid, with a diameter of about 60 m.

We have also summarized the properties of the hypersonic flow around a small asteroid in the Earth's atmosphere. We have shown that the stagnation temperature is a direct measure of the body speed. This introduces a multiplicative factor of $\sqrt{\gamma/(\gamma-1)}$ in the Eq. (1), which is instrumental to derive a reasonable solution for the Tunguska event. Eq. (6) is consistent with the idea that the meteoroid's fragmentation is due to the coupled action of thermodynamical and mechanical processes.

This kind of analysis can be applied whenever the body is large and compact enough to reach the lower atmosphere. Further investigations are needed for application to other cases. However, the crucial role of the stagnation temperature is probably a general feature of any realistic model of meteoroid flight and breakup.

Acknowledgements. The author is grateful to an anonymous referee for useful comments. A special thank to P. Farinella for constructive review.

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