Šumava meteoroid - was it a small comet?

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Abstract. Šumava event was one of the brightest bolides detected by the European Network. At the altitudes from 75 to 59 km its light curve shows four major maxima. Low strength appears the evidence of its cometary origin, while spectrum is consistent with a chondritic composition. The velocity of impactor lateral expansion is higher than that caused by simple aerodynamics. We consider some probable models of meteoroid disruption.

Key words: bolides – comets – fragmentation

The interaction of meteoroids with atmosphere allows to estimate parameters of these bodies, their masses, velocities, sometimes composition and structure. Meteoroids have both asteroidal and cometary origin. The last ones permit to learn something about the comet substance, which usually (except a catastrophic event) does not reach the Earth surface.

Detailed observational data on meteoroids are being collected by Bolide Networks. Most of the observed bodies are relatively small, only a certain number of them have diameter probably exceeding 1 m (Ceplecha, 1994).

1. Šumava bolide

We have analysed observational data on Šumava (EN041274) bolide, which was registered by European bolide Network.

This bolide entered the atmosphere with velocity of about 27 $\mathrm{km\,s^{-1}}$ and began to be visible at the altitude of 92 km. Four bright flares were registered on its light curve (up to -21.5^m). The first maximum appeared at the altitude of about 75–76 km, the peak intensity was reached in the third flare at altitude of 67 km (Fig. 1a). The deceleration curve was of bad quality, the last measured velocity was 23.6 km $\mathrm{s^{-1}}$ (at the altitude of about 61 km). The bolide disappeared at the altitude of 58 km.

Assuming classical theory of meteoritics the initial mass of the meteoroid was estimated as 5000 kg (Borovička and Spurný, 1996). A disruption is needed

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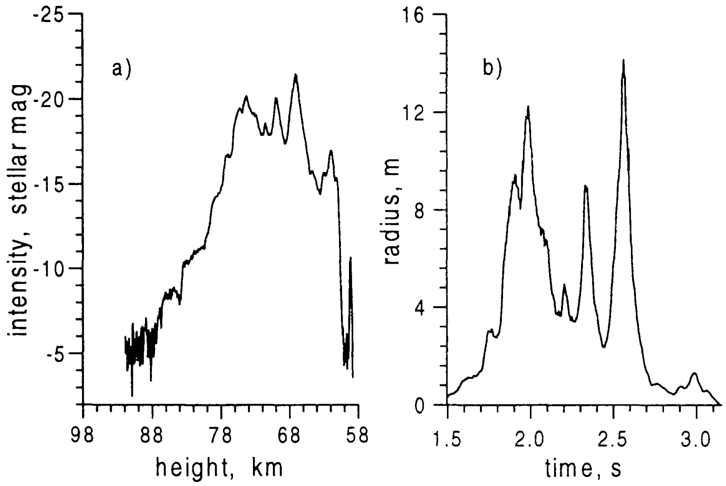

Figure 1. The light curve (a) and radiative radius (b) of Šumava meteoroid

to explain light curve and deceleration. No fragmentation in the sense of visible fragments was noticeable but the image of luminous trajectory on photographs was produced by a source of considerable length, possibly a string of fragments. The flares on the light curve are associated with breakups, fragmentation pressure is about 0.25–1.4 bars. The extreme fragility of Šumava appears an evidence of its cometary origin.

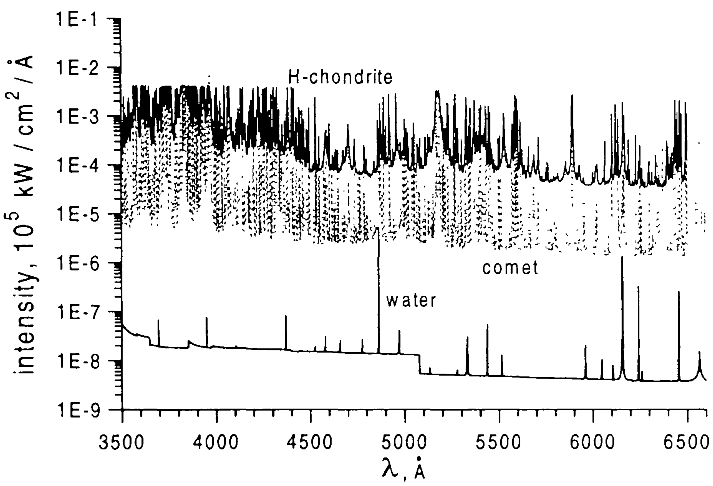

Figure 2. The model spectra of radiation emitted by meteoric vapour at the bolide head at the altitude of about 70 km for 3 m in radius body

At the end and at the beginning of luminous trajectory also the spectra were recorded. The spectra are consistent with the chondritic composition.

We have modelled radiation of vapour from meteoroid with different composition. The spectra of H-chondrite, comet (with composition similar to Halley comet) and icy body in the observational passband are given on Fig. 2.

Due to high contents of dust and presence of metallic atoms in comet substance the difference in the comet and H-chondrite spectra is not so large. Similar lines are present in both spectra. If the continuum radiation was not registered it was difficult to distinguish the comet from the H-chondrite vapour radiation. That is the case of Šumava. Thus, the observed spectra cannot be a proof of chondritic composition.

Another situation arises, if the meteoroid is composed from pure ice. In that case meteor vapour radiation in the observational passband is substantially smaller. If the dust/ice ratio varies in a wide range in cometary meteoroids, the luminous efficiency of the formed vapour will vary substantially.

2. Problem of Šumava fragmentation

A radiative radius, i.e. the effective radius of a body or of a cloud of fragments and vapour, causing the same luminosity as observed, was estimated. The luminous and ablation coefficients were taken from the results of ablating piston model (Golub' *et al.*, 1996). The radiative radius of the bolide increases in all flares and the velocity of lateral expansion in the first flare appears to be 50–60 $\mathrm{m\,s^{-1}}$ (Fig. 1b). The value is larger than lateral velocity u which could be caused by simple aerodynamic loading, i.e. about 10 $\mathrm{m\,s^{-1}}$ ($u \sim v\sqrt{\rho_a/\rho_b}$, where v is body velocity, ρ_a, ρ_b are the atmosphere and body densities). Attempts to reproduce the first flare with this velocity were unsuccessful. Aerodynamic loading alone cannot explain the great rate of meteoroid expansion and great effective radius of the falling body.

Borovička and Spurný (1996) supposed that the first flash resulted from a sudden 400 kg mass loss due to fragmentation. The word 'sudden' implies a time interval of about 0.1 s or a distance along trajectory of about 2–3 km. Their description gives reconstruction of the bolide radiation.

However, a simple destruction (loss of strength) itself could not give a great energy release and a radiation flash. It was clearly demonstrated in the simulations of SL-9 comet fragment deceleration and ablation (Nemtchinov *et al.*, 1997; Shuvalov *et al.*, 1997). Above 1 bar level altitude the evaporation rate is very high. The great mass of vapour could not be decelerated by the rare atmospheric gas and tended to couple around the fragment. The vapour moves surrounding the falling body increasing 2–3 times an effective meteoroid size and does not cause bright flare. Similar is valid for Šumava meteoroid.

Thus the real fragmentation (which leads to high energy flashes) should involve not only destruction itself but the mechanism of expansion which is necessary to diminish the density (and to be decelerated). One of the probable mechanism may be a volumetric evaporation (possibly not completed) of some part of the falling body, resulting in explosion-type expansion. We modelled that case in a frame of 2D numerical approach. At an altitude of 76 km the meteoroid is considered to consist of an opaque core with density 100 $\mathrm{kg\,m^{-3}}$

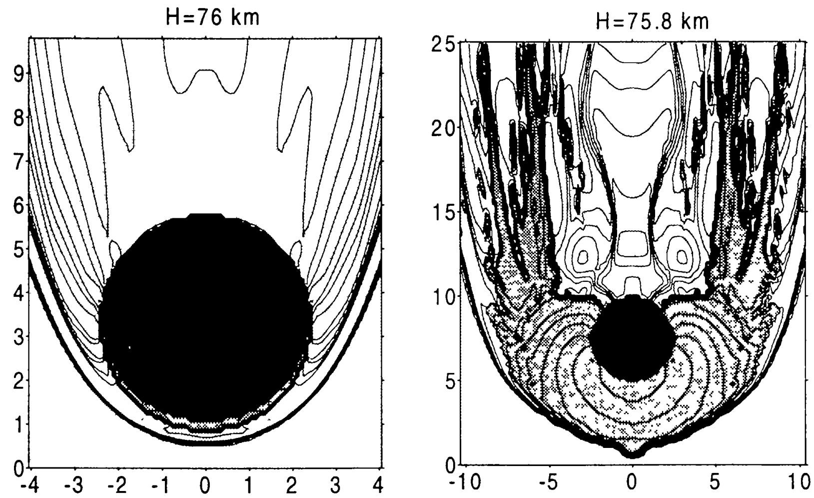

Figure 3. Initial data for the problem of meteoroid deceleration with volume evaporation and result of 2D simulation. Density contours are presented. Grey shading marks twophase mixture absorbing radiation from the shock, dark shading corresponds to the substance not exposed to radiation because of the screening effect. H is the altitude, all distances are measured in meters.

and semitransparent fragile envelope with a thickness of 3–4 cm and the same initial density (Fig. 3). In some sense this envelope is an analogue of destructed layer in the model (Borovička and Spurný, 1996). Assuming the core radius 2.3 m this corresponds to total mass 5000 kg and envelope mass of 400 kg. We considered that half of incoming hydrodynamical flux is converted into shocked air radiation, half of air radiation flux is absorbed by the destructed layer, and the energy is released uniformly across the mass.

The results of 2D simulations show that volumetric evaporation of the falling body and resulting expansion of formed mixture may explain the Šumava flashes and total disintegration at an altitude 60 km. The heating due to volume energy release allows vapour cloud to expand with very high velocity. A cloud of vapour is acting as a gaseous meteoroid with an increasing cross-section. However, the volumetric evaporation was induced artificially into the model and it is not clear if such evaporation can occure in a real meteoroid. For materials of known composition and structure it seems not possible.

3. Probable model of meteoroid disruption

We propose a hypothesis for Šumava-like meteoroid fragmentation during the enter into atmosphere. According to model Dressler (1991) a comet is a low-density ($100\,\mathrm{kg\,m^{-3}}$), dirty snow ball covered by an insulating layer (crust) with depleted amount of volatiles and thickness of about 1–4 cm. The lowest value of strength was estimated as about 5×10^3 dyn cm^{-3}. The aerodynamical loading is higher by an order of magnitude of this limit at altitude of about 80 km. Under the action of aerodynamic forces the porous body is compacted and its shape will be similar to a flattened disk.

The disk will fragment into small pieces (their size is comparable with disk thickness). We may treat these fragments as dust in the vapour. Due to decreased size they will evaporate much more rapidly than the parent meteoroid. Due to aerodynamic loading or (and) partial evaporation of the volatiles at 80 km altitude fragments or (and) small volumes of the vapour move in the lateral direction. A cloud of vapour and fragments is acting as a gaseous meteoroid with an increasing cross-section. The initial velocity of expansion is probably higher than that caused by simple aerodynamic loading as it was shown for volumetric evaporation in previous section.

The common shock wave comprising the fragments and vapour is being formed. The dense cloud of vapour will screen the remaining large fragments. But as soon as the vapour cloud will be dispersed they will appear again and the process will be repeated (a new flash will follow).

This model needs further elaboration, improvement and verification by detailed numerical simulations.

4. Plumes formed by Šumava – like event

Cometary-like meteoroids are also interesting from the viewpoint of possible ejection of oxygen molecules to high altitude. Recently Boslough and Gladstone (1997) have suggested that 'black holes' in the Earth ultraviolet airglow observed by Polar satellite (Frank *et al.*, 1986) may be explained by O_2 ejection from below 80 km due to plume formation. The mass of the stone impactors in the air-ejection model may be as low as about 1–10 tons.

Our numerical simulations (Shuvalov, 1999) have shown that development of Kelvin-Helmholtz instabilities at the wake boundaries prevents a creation of ballistic plumes for small stony impactors. This results in a drastical decrease in the height of debris rising. Cometary meteoroids penetrate less deeply than the stony ones and create wider entry columns. To determine a height of rising for the Šumava debris cloud the energy release along the trajectory was assumed to be proportional to the observed light intensity. Thus it is substantially nonuniform and enhances the action of instabilities. Hydrodynamic simulations have shown that due to intense turbulence caused by disintegration of the meteoroid at altitudes of about 65–78 km the ejected air and debris reach only the altitudes of about 140 km and could not cause a hole due to extraction of molecular oxygen above the maximum of atomic oxygen atmospheric glowing. So the air ejection hypothesis of black hole formation seems inapplicable to

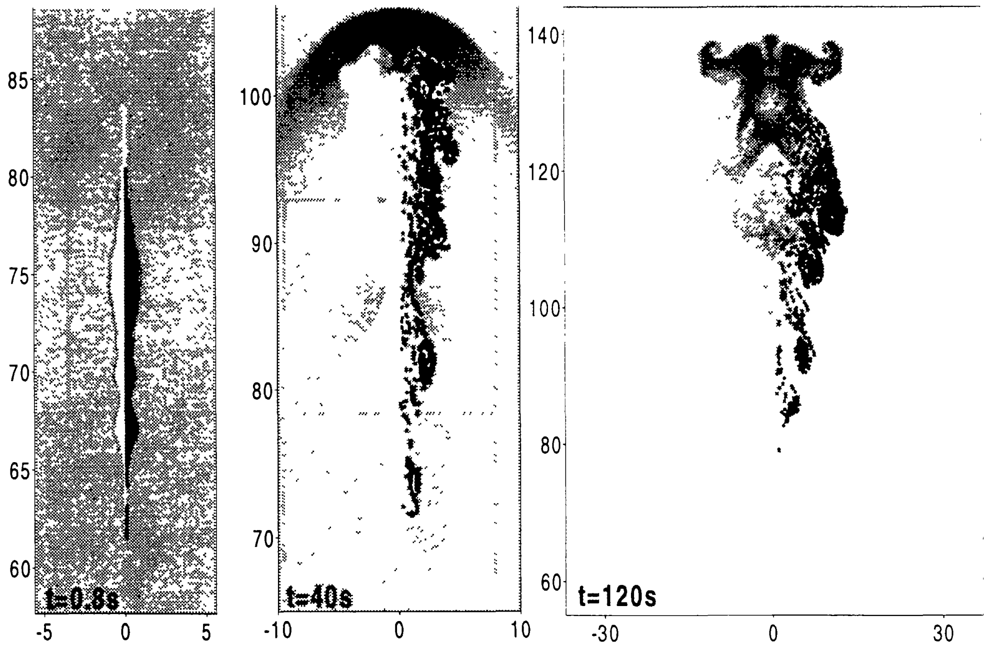

Figure 4. An evolution of Šumava debris cloud. The intensity of shading is proportional to the gas density. Black dots correspond to the marker particles initially disposed within the wake.

'normal' (Šumava – like) small comets. To eject air and to avoid bright flashes such meteoroids should be even less dense and more fragile than Šumava.

It seems that our attempts to explain the behaviour of Šumava bolide and further simulations may allow to learn more about structure and properties of the comet substance.

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Section 2

Dynamical Origin and Evolution of Near-Earth Objects