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Water in the trail of the Chelyabinsk bolide

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Abstract

At ~03:20 UTC on February 15, 2013 a very bright bolide entered Earth's atmosphere. Fragments of the meteorite fell to the earth's surface. Examination of these fragments revealed that several of them were located directly on the surface of the celestial body [1], while the majority lay at a depth of less than 2.5 m from the surface [2, 3]. The stone meteorite's durability, >15 MPa, corresponded to <1% of the initial mass, while the rest of the object possessed a low durability of ~1 MPa [4]. Moreover, Fe^{3+} hydroxyls were discovered in meteorite samples, the formation of which required water [5]. The glow at the head of the bolide trail, lasting ~8 seconds after the flight of the object, and the development of the cloud trail indicate that the celestial body carried water. The Chinese weather satellite Feng-Yun 2D discovered ice debris (water) in the bolide trail [6]. Here, we will demonstrate that the Chelyabinsk chondrite was delivered to the Earth by an ice-bearing celestial body.

The Chelyabinsk bolide left a trail at an altitude from 18 to 70 km, which initially appeared as a jet aircraft contrail, and subsequently "bubbles" began to rise above it, similar to cumulus clouds. The colour of the trail was white with a slight reddish-brown hue, linked, most likely, to the nitrogen oxides that formed due to the ionisation of the air. From several localities, the trail appeared to be glowing, in contrast to the light-absorbing dust screen, for example, from the 1883 eruption of Kraratoa. The white colour of the trail and its transparency suggests, that the trail was predominantly composed of water, which condensed on aerosol particles.

Clouds in the atmosphere form due to the cooling of air, which is why the amount of water in them can be determined by the humidity of this air. At altitudes of 18–70 km, air humidity is very low and, as a result, high-altitude nuclear explosions do not form dense clouds, in contrast to ground tests. For example, during the explosion of the "Orange" nuclear device on the twelfth of August, 1958, at ~42 km over the Pacific Ocean, a grayish-white radioactive cloud appeared and lasted only 3 minutes [7]. This fact leads one to the conclusion that the celestial body itself introduced water into the atmosphere.

After the flight of the Chelyabinsk bolide, during the final stage of its trajectory, there was a residual glow: so-called "hot spots" [4]. The fading of glow in the most noticeable point of the trail lasted ~8 s (fig. 1), after which air masses (inflated "bubbles") rose for ~3 min (fig. 2). It is important to note that the "hot spots" are not related to the zone of maximum light energy release during the bolide's flight. (fig. 1). Their position correlates with the area of the object's fragmentation and reflect the quantity of matter released by the body. Since the position of the hot spots during glow did not change, and the inflated "bubbles" over them were related to energy release during glow, it can be concluded that the occurrence of these spots was linked to the combustion of the matter of the celestial body.

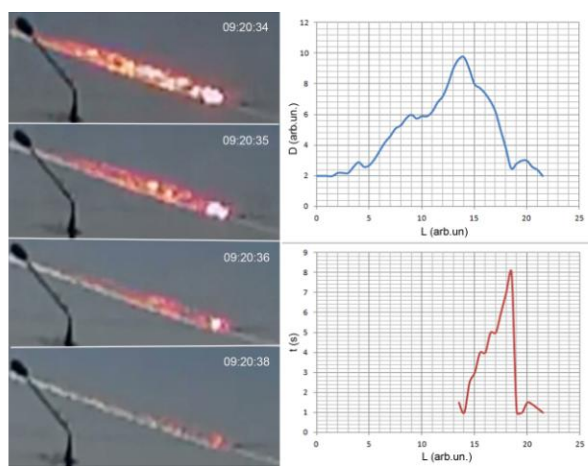

Figure 1: The residual glow of the trail after the flight (video from Kamensk-Uralsky [8]). The time on the images corresponds to the time of recording. The upper right panel: the change of the vertical diameter of the glow zone of the bolide along the flight trajectory. The lower right panel: the duration of the existence of the trajectory's "hot spots".

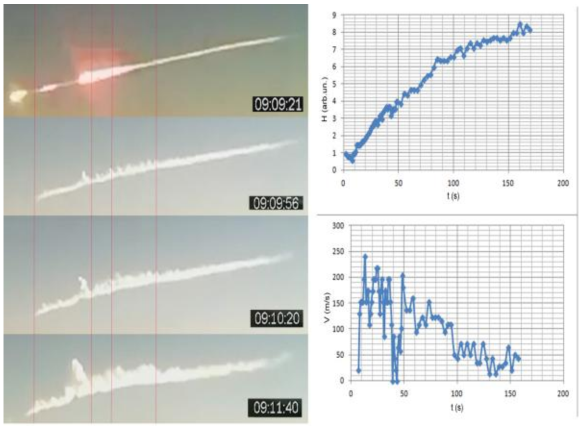

Figure 2: Inflated “bubbles” above the “hot spots” (according to video material [9]). The time on the images corresponds to the time of recording. The upper right panel: vertical displacement of the main cloud from the initial point on the trajectory. The lower right panel: the speed of ascent of the cloud peak averaged from 9 points. Maximum height of the cloud peak’s rise from the initial point on the trajectory taken from 16.8 km.

During the explosive fragmentation of a celestial body in the earth’s atmosphere, carbon and organic matter may ignite, however, the main combustive reaction is the interaction of oxygen in the atmosphere with hydrogen emitted from water. Water molecules released from the moving body into the atmosphere are extremely unstable; they undergo thermal and photochemical dissociation and radiologic decomposition. At temperatures of 4000-5000^o, water splits into hydrogen and oxygen, while at temperatures of 600-1000^o, hydrogen and oxygen unify through explosion. Photochemical dissociation and radiologic decomposition of water occur under the influence of ultraviolet, gamma and X-rays, and also are caused by currents of charged particles and neutrons. This results in the formation of H_2, H_2O_2, and the free radicals H, OH и HO_2. Therefore, during the deceleration of disintegrating fragments flying at cosmic speed, the reaction equilibrium $2H_2O \leftrightarrow 2H_2 + O_2$ is shifted to the formation of hydrogen. A combustion process is initiated, which concludes with the formation of water vapours and the warming of large air masses. As a result, “bubbles” begin to rise.
If the initial width of the trail amounted to ~2 km [4], the maximum altitude of the cloud’s peak over the trajectory exceeded 16 km. The velocity of ascension reached several hundred meters per second (fig. 2). It is important to note that at ~40 seconds (fig. 2) the ascent of the cloud practically ceased, and within 5–10 seconds resumed again. This interval may be explained only by water condensation. The transformation of water vapours to liquid and a crystalline state leads to a decrease in gas density in the cloud and to its warming, resulting in the resumption of the rise of the cloud peak.

Acknowledgements

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