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Chelyabink meteorite entry model and damage on the surface

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Abstract

In this paper we model an atmospheric entry of the Chelyabinsk meteorite to show that this event represents a typical behaviour of a large chondritic body in the Earth's atmosphere: it was fragmented, ablated, and decelerated to a free-fall velocity. Atmospheric shock waves reached the surface, caused on overpressure of up to 1500 Pa, and damaged on an area of about 50 km*100 km.

1. Introduction

On the early morning of February 15, 2013, thousands of people observed a bright flash in the sky over the city of Chelyabinsk in the Urals region of Russia. The flash was followed by a powerful sonic boom which destroyed windows across the area of ~ 5000 km^2 injuring more than 1500 people, mainly by broken glass. Numerous video recordings of the event have allowed us to reconstruct the body's trajectory and fragmentation history with a high degree of accuracy. The entry angle was unusually low, approximately 17° to horizon; an observed trajectory length in the atmosphere exceeded 250 km; a few flashes occurred between altitudes of 40-20 km [1]. The total mass and energy of meteorite were estimated based on its infrasound signal [2], the energy of the brightest flash [3], and ground effects (this paper). Its pre-atmospheric size was probably around 15-20 m with the total energy of 300 (100-500) ktons (1 kton is equal to $4.2 \cdot 10^{12}$ J). However, only a small fraction of the mass was found near Chelyabinsk — mainly just tiny pieces with the largest fragment weighting 1.8 kg. The meteorite is an ordinary L5 chondrite, the most common meteorite type on Earth. Similar events may occur relatively often, about every 10-100 years.

1.1 The model and initial conditions

The simplest way to model a meteorite entry is a usage of the so-called point-mass approximation [4] complemented by a simple equation describing fragmentation, e.g., the pancake model [4] or the SF model [5]. Initial conditions for the SF model were taken from observations (an entry angle and a velocity); an initial size, strength and ablation coefficient varied to match observed light flashes. To describe an interaction of shock waves with the surface we used the 3D hydrocode SOVA [6] complemented by the equation of state for air. The results of the SF model were used as initial conditions for the 3D model.

2. Results

2.1 Atmospheric entry

One of numerous calculated trajectories is shown in Fig.1. Although an energy release curve has a single maximum (instead of three observed flashes), all energy is released between 35-25 km, where the real flashes occurred. A dashed line shows an unrealistic trajectory without fragmentation. In this case the meteoroid reaches the surface with a velocity of ~6 km/s and creates a 300-m-diameter crater.

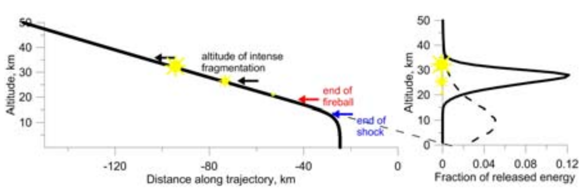

Fig.1: A trajectory of the largest fragment (left) and the total energy release in the atmosphere (right). Yellow stars show observed flashes. A dashed line corresponds to an unrealistic trajectory without fragmentation.

2.2 Shock waves and damage

Atmospheric entry models do not provide any information on shock waves generated in the atmosphere. The simplest (and the quickest) way is to model an ariburst in the atmosphere assuming that the total meteoroid energy is released instantaneously at a certain altitude. Propagation of shock waves and their interaction with the surface is shown in Fig.2. Maximum overpressure on the surface increases with increasing energy and a decreasing altitude of the “airburst”. For a fixed energy, the total affected area (maximum overpressure exceeds 500 Pa, some windows are broken) increases with an increasing altitude.

Table 1: Radius of damaged area [km]

Airburst altitude	200 kton	400 kton
10 km	34	50
20 km	52	64
30 km	>60	>80

The real entry requires 3D modeling. Calculated energy release (Fig.1) or the observed flashes may be used as initial conditions. A damaged zone is not circular in this case, although its size is approximately the same as in 2D models.

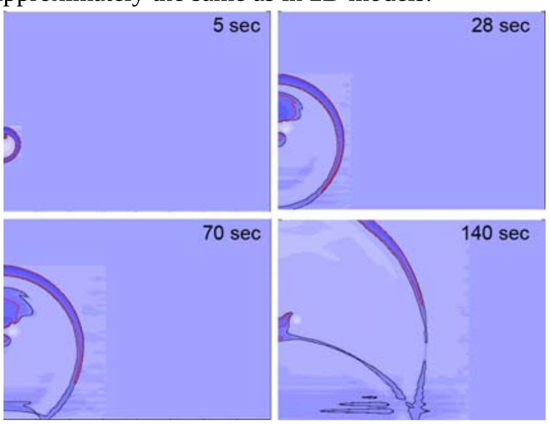

Fig. 2: Shock waves after a 200 kton airburst at an altitude of 20 km. The ratio of shock pressure to standard atmospheric pressure at a given altitude is shown. A red line corresponds to the ratio of 1.02, a black one – of 1.

3. Summary and Conclusions

The Chelyabinsk meteoroid demonstrated a typical behavior of a chondritic cosmic body in the atmosphere. Simple quasi-analytical models produce reasonable results except of the total recovered mass. Interpolation of the SF model into 2D and 3D allows to estimate ground effects.

Small cosmic bodies are still difficult to observe; their interaction with the atmosphere may vary in a wide range due to their different properties (size and strength being the most important). However, we can minimize the risk of impact-related injuries by teaching a few basic facts about meteorites and their interaction with the atmosphere. If you see a bright flash in the sky, do not panic, stay away from the windows, find a secure spot to hide for a few minutes and time the interval between the flash and the sonic boom.

References

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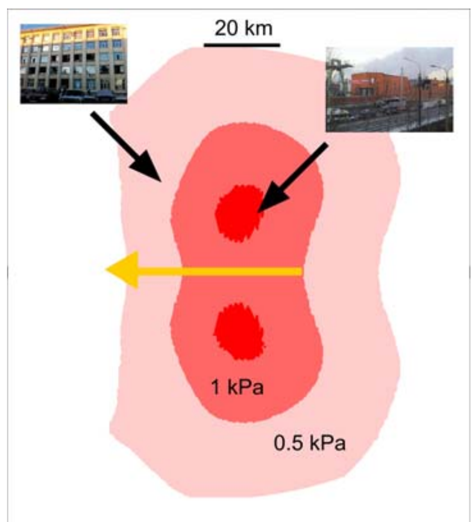

Fig.3: Damaged area. A long yellow arrow represents a projection of the brightest part of the Chelyabinsk meteoroid trajectory to the surface.