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Water in the trail of the Chelyabinsk bolide

O.G. Gladysheva
Ioffe Physical-Technical Institute of RAS, St.Petersburg, Russa, (Olga.Gladysheva@mail.ioffe.ru / Fax: +7(812)2971017)

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.

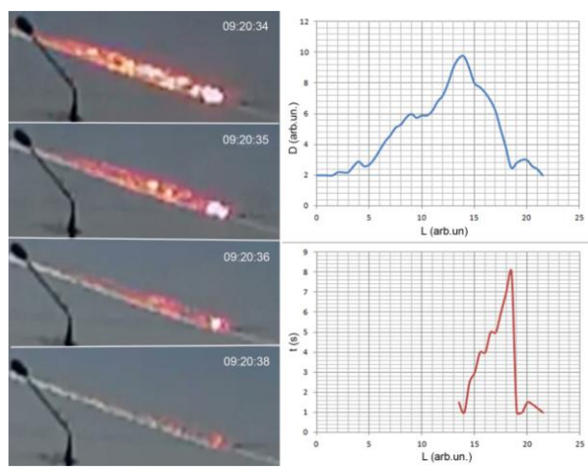

Figure 1: The residual glow of the trail after the flight (video from Kamensk-Uralsky [8]). The time on the images corresponds to the time of recording. The upper right panel: the change of the vertical diameter of the glow zone of the bolide along the flight trajectory. The lower right panel: the duration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

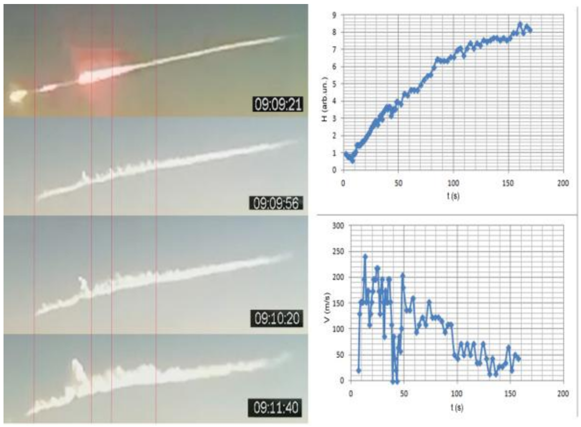

Figure 2: Inflated "bubbles" above the "hot spots" (according to video material [9]). The time on the images corresponds to the time of recording. The upper right panel: vertical displacement of the main cloud from the initial point on the trajectory. The lower right panel: the speed of ascent of the 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.

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Did a Comet Deliver the Chelyabinsk Meteorite?

O.G. Gladysheva
Ioffe Physical-Technical Institute of RAS, St.Petersburg, Russa, (Olga.Gladysheva@mail.ioffe.ru / Fax: +7(812)2971017)

Abstract

An explosion of a celestial body occurred on the fifteenth of February, 2013, near Chelyabinsk (Russia). The explosive energy was determined as ~500 kt of TNT, on the basis of which the mass of the bolide was estimated at ~10^7 kg, and its diameter at ~19 m [1]. Fragments of the meteorite, such as LL5/S4-WO type ordinary chondrite [2] with a total mass only of ~$2 \cdot 10^3$ kg, fell to the earth's surface [3]. Here, we will demonstrate that the deficit of the celestial body's mass can be explained by the arrival of the Chelyabinsk chondrite on Earth by a significantly more massive but fragile ice-bearing celestial body.

During the interaction of large (>10 cm) meteorites with the earth's atmosphere, 1–25% of the original body mass is usually retained [4], whereas the Chelyabinsk bolide retained only ≤0.02% of its initial mass. It is assumed that all other matter evaporated. During the course of several days, the Suomi satellite registered the aerosol trail of the Chelyabinsk body [5].
It is natural to suppose that after ablation and explosive fragmentation, fragments of deep inner layers should fall to Earth. However, this proved not to be the case. Tracking [6] and isotope [7, 8] research showed that a significant portion of the Chelyabinsk meteorite fragments belonged to the surface layers of a celestial body before its entry into the earth's atmosphere. It is widely known that while a meteorite is in outer space, it is bombarded by currents of charged energetic particles, i.e. galactic (GCR) and solar (SCR) cosmic rays. Cosmic rays may form tracks (particle traces) in minerals of target, as well as cascades of secondary particles, terminating in the formation of radioactive or stable isotopes at different depths from the surface.
The study of 450 phosphate and olivine microcrystals of the Chelyabinsk meteorite showed that ~5% of the examined matter was directly exposed to SCR radiation, and in several granules a track density gradient was discovered from the surface to deep within the microcrystal. It is determined that the source of the appearance of such a gradient can be only the direct bombardment of the crystal by SCR iron nuclei with energy of 1-100 MeV [6].
Interacting with the surface of the meteorite, protons and helium GCR nuclei form isotopes, some radioactive, which are allocated to a specific location by depth in the body of the meteorite. A measurement of the composition of radionuclides ^{22}Na, ^{26}Al, ^{54}Mn and ^{60}Co in 12 fragments of the Chelyabinsk meteorite, and a comparison of the results with model calculations of the formation of these isotopes in meteorites according to depth, showed that 4 fragments of the meteorite were located in a layer 30 cm deep, 3 fragments at a depth of 70-90 cm, two more at a depth of <180 cm and the remaining 3 fragments at a depth of ≤250 cm from the surface of the meteorite [7]. Analysis of the composition of the cosmogenous isotopes ^{10}Be, ^{26}Al and ^{3}He in 10 samples of the Chelyabinsk meteorite and comparison of the results with the model calculations led to the conclusion that the radius of the Chelyabinsk meteorite was 3-4 meters [8].
In addition, the Fe^{3+} ion was discovered in the meteorite, indicating that conditions were more oxidised than those characteristic of the Chelyabinsk meteorite matter [9]. One of the possible reasons for the formation of Fe^{3+}-containing oxides and hydroxides would be the meteorite's introduction to a humid or even aquatic environment. Fe^{3+} hydroxides were found around troilite granules in so-called "rusty halo" zones, where water could penetrate from surface layers through microfractures. The authors arrived at the conclusion that the Fe^{3+} hydroxides could also form during the meteorite's collision with an object containing ice. And the most important, that the Chinese meteorological satellite Feng-Yun 2D registered water as ice debris in the bolide trail [10].
Study of the destruction process of the Chelyabinsk body led to the conclusion that a large part of the object was not durable (~1 MPa), while the durability of a stone meteorite >15 MPa corresponded to only <1% of the initial mass [11]. We can assume that a celestial body with a durability of ~1 MPa delivered the durable stone Chelyabinsk meteorite to Earth,

having become “tied” to it during a space incident, traces of which were found in the form of shock melting of the meteorite matter [2, 6].
The dispersion ellipse of the Chelyabinsk meteorite matter is close to the classic representation of the destruction of meteorites, though it shows a certain displacement relative to the flight trajectory, likely linked to wind transfer (fig.). According to the location of small pieces of the meteorite, it may be concluded (fig.) that the Chelyabinsk bodye began to disintegrate into fragments at altitudes of 30–35 km under dynamic pressure of <5 MPa, which would not so much disturb a durable meteorite. However, a series of explosions occurred at these heights, registered by sound data [11]. As a result of these explosions, the fragments that reached earth may have been knocked out of the surface layers of the meteorite. The location of the meteorite in the zone of explosions explains the trajectory deviation of the largest fragment by 1.3^{o} from the initial flight direction [11] and crust melting on all, even small fragments of the meteorite [3, 7].

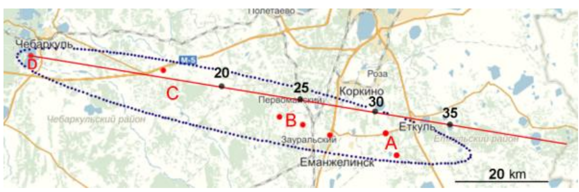

Figure: The impact site of the meteorite.
Note: A straight line: body trajectory. Figures above the line: the height of the trajectory points according to Borovička [11]. Line of points: the dispersion ellipse of meteorite matter. A: location of found fragments in the form of dust or millimeter-long splinters, B: centimeter-long fragments, C: decimeter-long fragments, D: meter-long fragments. Points indicate localities near found meteorite fragments, as well as Chebarkul Lake.

Therefore, the mass deficit of the meteorite, the significant differentiation of the bolide substance in durability and the initial location of the meteorite fragments in the surface layers of the celestial body indicates that the meteorite could form only ~ 1% of the bolide mass. The remaining less durable but more massive part, according to the combustion of matter along the trajectory [12] and the intermittent process of cloud ascent in the trail, contained water. It could be a short-period comet.

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Analysis of meteoroid risk in circumterrestrial space

A. Murtazov
Ryazan State University, Ryazan, Russia (a.murtazov@rsu.edu.ru)

Abstract

A model of the meteoroid-spacecraft collision risk in near Earth space is presented.
The risk from dangerous meteoroids in main meteor showers is calculated. Its level is shown to be close to maximal allowable risk.

1. Introduction

One of the hazards to space technology and humans in near-Earth space is the hazard coming from impacts of micrometeoroids ranging from 1 mm to tens of centimeters in size [1, 2].
Here, streams of meteoroid particles (1 mm to 1 cm) have been and remain difficult to monitor using modern technology. Observable are only meteors they cause.

2. Model of meteoroid risk in near Earth space

Meteoroid risk is the probability (a measure of hazard) that a spacecraft will collide with hazardous meteoroids capable of having a destructive effect on the spacecraft and stop (fully or partly) its operation for a certain number of collisions.
Our physical model of meteoroid risk consists of the following components [3]:
(1) hazardous directions, i.e., distribution of meteor streams and sporadic meteors in space; (2) distribution of meteor streams by seasons of year and by the length of action within these seasons; (3) distribution of meteor streams by velocities and masses; (4) spatial distribution of meteoric particles in the stream itself; (5) effect of the gravitational attraction of meteoric particles by the Earth; (6) effect of shading of meteoroids by the Earth from the observer; (7) orientation of the entire spacecraft as well as its constructive elements relative to the meteoroid arrival direction; (8) time of spacecraft residence on the orbit and time of meteoric stream influence on the spacecraft.

3. Calculating the number of collisions

The expected rate of collision of meteoroids with the spacecraft averaged over the observation interval where t_1 is the moment of start and t_2 is the moment of end of observations, can be taken to be

$$\boldsymbol{N = C\int_{t_1}^{t_2} f(t)dt}. \tag{1}$$

Most often, activity factors (profiles) of meteor showers are analytically (despite their diversity) described by expressions of the form

$$\boldsymbol{F_\lambda = F_0 \cdot e^{-A(\lambda-\lambda_0)^2}}, \tag{2}$$

where F_0 is the density of the meteor stream at the maximum (on the axis of the meteor swarm) at solar longitude λ_0.
The total collision number was calculated as their sum during the shower's maximum activity

$$N = \int_{\lambda_1}^{\lambda_2} F_0 \cdot e^{-A(\lambda-\lambda_0)^2} d\lambda. \tag{3}$$

The current collision number was calculated with regard to the location geometry of a satellite, the Earth, and the shower radiant at that very moment. (Fig. 1) [3, 5].
On the celestial sphere of the spacecraft in a satellite centered coordinate system [3,5] (Fig. 1), the Earth's disc moves along the equator of the spacecraft orbit, and the radiant of a meteor stream describes a small circle, the plane of which is parallel to the equatorial plane of the system. Here, *R*, E, ⊙, ♈, are the directions to the meteor stream radiant, the Earth, the Sun, and the vernal equinox, respectively; *b* is the ecliptic latitude; and ☊ is ascending node of the spacecraft orbit. This means that the Earth's coordinates are characterized by the spacecraft's position on the orbit.

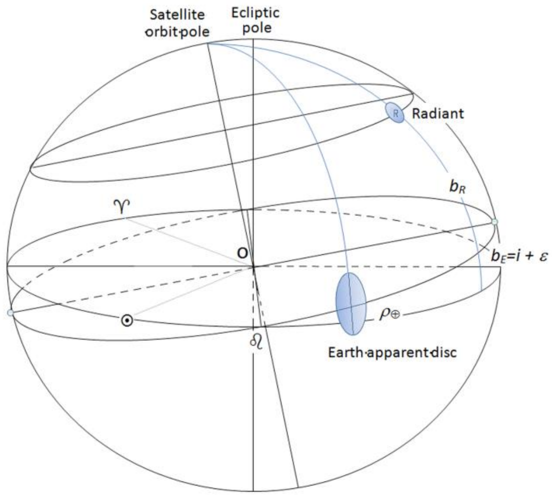

Figure 1: Satellite-centric reference system for calculation the number of collisions

The satellite-centered latitude of the center of the Earth's disk and the stream radiant can be easily determined as

$$\phi_R = b_R - i - \varepsilon;\ \phi_E = 0, \qquad (4)$$

where i is the inclination of the satellite orbit to the ecliptic and ε=23°27′ is the inclination of the ecliptic to the equator. Then, the condition that the spacecraft falls into the Earth's shadow is described by the inequality

$$b_R - i - \varepsilon \leq \rho_E, \qquad (5)$$

where ρ_E is Earth's angular radius visible from the spacecraft.

4. Meteoroid risk for main meteor showers

Here, the risk was estimated as the number N of collisions of dangerous meteoroids with the normal to the meteoroid flux flat unit during the maximum shower activity (3).

We calculated the provided model using both the IMO's and our own observation data [6].

During the maximum activity of meteor shower (half-width of the shower) the dangerous meteoroid flux rises steeply:

Quadrantids: during 0.25^d N=$1.2\cdot10^{-2}$ km^{-2} – 1 collision per 1 km^2 on the average during $21^{\mathbf{d}}$**;**

Eta Aquariids: during 1.0^d N=$5\cdot10^{-2}$ km^{-2} – 1 collision per 1 km^2 on the average during 20^d;

Perseids: during 1.0^d N=$1.2\cdot10^{-2}$ km^{-2} – 1 collision per 1 km^2 on the average during 80^d;

Geminids: during 0.25^d N=$1\cdot10^{-2}$ km^{-2} – 1 collision per 1 km^2 on the average during 25^d.

5. Summary and Conclusions

Thus, for a satellite with the midsection of 10 m^2, the meteoroid risk during most active meteor showers is about R=(1-5)$\cdot10^{-7}$. It is noticeably dangerous because the maximum allowable risk is defined as $R_{Lim.}$=10^{-6}, and such danger should not be neglected.

Of course, the risk from dangerous meteoroids in space is not very big but the circumterrestrial space is highly populated with satellites; therefore their total area of collisions is rather large. So the total risk for the whole of the satellite population may become significant.

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Spectral analysis of meteorites ablated in a wind tunnel

A. Drouard (1), P. Vernazza (1), S. Loehle (2), J. Gattacceca (3), T. Zander (2), M. Eberhart (2), A. Meindl (2), R. Oefele (2), J. Vaubaillon (4) and F. Colas (4)

(1) Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France (alexis.drouard@lam.fr)
(2) High Enthalpy Flow Diagnostics Group, Institut für Raumfahrtsysteme, Universität Stuttgart, Pfaffenwaldring 29, D–70569 Stuttgart, Germany (3) CNRS, IRD, CEREGE UM34, Aix Marseille Université, 13545, Aix en Provence, France (4) IMCCE, Observatoire de Paris, Paris, France

Abstract

Meteor spectroscopy is used to constrain the composition and thus nature of incoming meteoroids. Over the last decades, spectra have been recorded in the visible range (mostly between 360 and 700 nm), with typical spectrograph dispersions close to the namometer by pixel (e.g., 1.1 or 1.6 $nm.pix^{-1}$ for spectrographs in Czech Republic [2] or 2.5 $nm.pix^{-1}$ for those in Spain [5]). If the number of spectroscopic observations of meteors has globally increased, it remains low compared to the number of photometric records.

In complement to these observations, experiments in the laboratory have been undertaken to better understand meteor science. Specifically, various experiments were performed with the aim to study the process of meteorite ablation, but no experiment has so far recorded emission spectra of ablated meteorites, except [6] who recorded spectra of LASER irradiated meteorites. Recently and for the very first time, experiments simulating vaporization of a meteorite sample were performed in a wind tunnel near Stuttgart, Germany, with the specific aim to record emission spectra of the vaporized material [3]. Using a high enthalpy air plasma flow for modeling an equivalent air friction of an entry speed of about 10 $km.s^{-1}$, three meteorite types (H, CM and HED) and two meteoritical analogues (basalt and argillite) were ablated and high resolution spectra were recorded simultaneously.

The spectra were acquired with a spectrograph Aryelle 150. This instrument covers a large wavelength range (from 250 to 880 nm) with a high spectral resolution of 43 $pm.pix^{-1}$ at short wavelengths and 143 $pm.pix^{-1}$ at longer wavelengths [3]. We present a portion of the H chondrite spectrum in Fig. 1 and a list of the identified lines in Table 1.

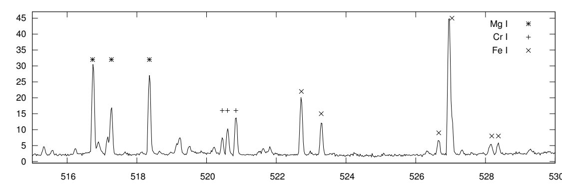

Figure 1: H chondrite spectrum over the 515-530 nm range.

Table 1: List of the identified lines over the 515-530 nm range.

λ (nm)	Element	A_{ul} (s^{-1})
516.73	Mg I	1.13×10^7
517.27	Mg I	3.37×10^7
518.36	Mg I	5.61×10^7
520.45	Cr I	5.09×10^7
520.60	Cr I	5.14×10^7
520.84	Cr I	5.06×10^7
522.72	Fe I	2.89×10^6
523.29	Fe I	1.94×10^7
526.66	Fe I	1.10×10^7
527.04	Fe I	3.67×10^6
528.18	Fe I	5.00×10^6
528.37	Fe I	1.02×10^7

After the identification of all atomic lines, we performed a detailed study of our spectra using two approaches: (i) by direct comparison of multiplet intensities between the samples and (ii) by computation of a synthetic spectrum to constrain some physical parameters (temperature, elemental abundance) following the work by [1]. Finally, we compared our results to the elemental composition of our samples and we determined how much compositional information can be retrieved for a given meteor using visible sectroscopy.

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Close Encounter and Impact Scenarios on Earth from Small Solar System Bodies

A. Sekhar (1,2), G. B. Valsecchi (3,4) , D. J. Asher (2), S. C. Werner (1), J. Vaubaillon (5), G. Li (6)
(1) Centre for Earth Evolution and Dynamics, Faculty of Mathematics and Natural Sciences, University of Oslo, Norway (2) Armagh Observatory and Planetarium, Northern Ireland, United Kingdom, (3) IAPS-INAF, Roma, Italy (4) IFAC-CNR, Sesto Fiorentino, Italy (5) IMCCE Observatory of Paris, France (6) Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, United States (aswin.sekhar@geo.uio.no)

Abstract

1. Introduction

One of the greatest successes of the Einstein's General Theory of Relativity (GR) was the correct prediction [5] of the precession of perihelion of Mercury. The closed form expression [18] to compute this precession tells us that substantial GR precession would occur only if the bodies have a combination of both moderately small perihelion distance and moderately small semi-major axis [13].

Minimum Orbit Intersection Distance (MOID) is a quantity in celestial mechanics which helps us to understand the closest proximity of two orbits in space[15]. Hence evaluating MOID is crucial to understand close encounters and collision possibilities better[16]. In this work, we look at the possible scenarios where a small GR precession in argument of pericentre can create substantial changes in MOID for small bodies ranging from meteoroids, comets and asteroids and thereby leading to changes in close encounter and impact scenarios.

2. Methods and Techniques

Previous works have looked into neat analytical techniques [15] [16] to understand different collision scenarios and we use those standard expressions to compute MOID analytically. We find the nature of this mathematical function is such that a relatively small GR precession can lead to drastic changes in MOID values depending on the initial value of argument of pericentre. These cases are analysed for various examples of asteroids, comets and meteoroid stream particles. Past works [1][2][4][8][9][14][17][19] have looked into various interesting encounter geometries and impact cases on Earth and other planets from different classes of small body population. Recent works[6][7][10][12][13] have shows that GR effects can play an important role in the evolution of small bodies in solar system as well as exoplanetary systems.

Numerical integrations were done with package MERCURY [3] incorporating the GR code to look at the nature of their orbital evolution and double check the same effects. Numerical approach showed the same interesting relationship (as shown by analytical theory) between values of argument of pericentre and the peaks or dips in MOID values. There is an overall agreement between both analytical and numerical methods in understanding the pattern of MOID evolution for asteroids, comets and meteoroid stream particles which undergo measurable GR precession. Orbital elements are taken from IAU-Minor Planet Center, JPL-Horizons, Cometary Catalogue [11] and IAU-Meteor Data Center.

3. Summary and Discussion

We find that GR precession could play an important role in the calculations pertaining to MOID and close encounter scenarios in the case of certain small solar system bodies (depending on their initial orbital elements) when long term impact risk possibilities are considered. Previous works have looked into impact probabilities and collision scenarios on planets from different small body populations and this work aims to see how such contributions get affected by the role of GR in certain small bodies orbiting close to the sun.

Certain parallels in this GR influence are drawn between the cases of asteroids, comets and small perihelion distance meteoroid streams in the context of close encounter and impact scenarios on Earth.

Acknowledgements

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The Geminid meteoroid stream depletion and dispersion by planets

G.O. Ryabova
Tomsk State University, Russian Federation (goryabova@gmail.com)

Abstract

When a planet encounters a meteoroid stream, it removes some mass from the stream and disperses the stream. We study this process numerically in application to the Geminid meteoroid stream.

1. Introduction

The Geminids is the meteoroid stream producing one of the major annual meteor showers with maximum activity about December 14. The orbits of the Geminid meteoroid stream as well as that of the asteroid (3200) Phaethon (the Geminid's parent body) are located far inside Jupiter's orbit. Orbital elements of Phaethon (and the stream) are: semimajor axis = 1.27 au, eccentricity = 0.9, inclination = 22°, so the stream orbit intersects Mercury, Venus, Earth, and Mars orbits. The last 3 planets pass through the stream, remove meteoroids from the stream due to collisions and disperse other meteoroids due to close encounters perturbations. This problem was discussed by Valsecchi et al. [2], and some estimations were made using an analytical approach and the extended Öpik's theory of close encounters.

Inspired by this paper we decided to estimate the Geminids depletion and dispersion by Venus, Earth and Mars, using numerical approach.

2. Model

The method of modelling was described in details by Ryabova [1]. The main idea is simple: to simulate particles ejection, calculate their evolution and follow their encounter with planets.

Ryabova [1] integrated the equations of motion of the meteoroids using the Everhart 19th-order procedure, i.e. numerically. Numerical integration is expensive: to calculate a frugal model in 30 000 particles a usual desktop computer has to make calculations about one month [1]. So we decided to use also the Halphen–Goryachev method. This Gauss-type semi analytic method allows for only secular perturbations of the first order, but is very fast.

3. Summary

On the moment of this abstract presenting there are no results to publish. We made preliminary runs and made some preliminary estimation, which needs refinement and qualification.

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Analytical modelling of the mass loss, light curve and energy deposition of the Chelyabinsk bolide using the developed fragmentation model

I. Brykina
Institute of Mechanics, Lomonosov Moscow State University, Moscow, Russia (shantii@mail.ru)

Abstract

The model of atmospheric fragmentation of large meteoroids is developed. The analytical solution of equations for meteor physics is obtained for the mass loss, energy deposition, light curve and the altitude, where the maximum of this curve is reached. This solution together with proposed fragmentation model are applied to study the Chelyabinsk event. Comparison of analytical solution for light curve and energy deposition with observational data is made.

1. Introduction

Most of large meteoroids are disrupted during their entry into the atmosphere. There are different approaches to modelling of meteoroid fragmentation. In some models it is assumed that fragments move independently (few large fragments or progressive fragmentation). In this study the other approach is applied – the breakup of a meteoroid into a cloud of small pieces which move with the common shock wave as a single body. This liquid-like model was proposed in [7] for small melt meteoroids when sphere is continuously deformed to flattened spheroid by the aerodynamical loading. This model when a body is expanding in a lateral direction and reducing in thickness in a flight direction was developed in detail in [4]. Later similar models were used in other papers [5, 6] and were named [6] "pancake" models.

2. Fragmentation model

We suggest a spherical shape of the meteoroid before start of breakup, then the meteoroid continues its flight as a cloud of fragments and vapor which fill in holes between fragments. We assume two related processes: flattening – the sphere is deformed to the flattened spheroid with ratio of axes k ($k \geq 1$), and the decrease of density of the fragmented meteoroid due to the increase of spacing between fragments.

The velocity of lateral expanding of the fragmented meteoroid was obtained by Grigoryan [4] in the form

$$\frac{dR_S}{dt} = 2k_r V \left(\frac{\rho}{\delta}\right)^{1/2} \tag{1}$$

Here V is the meteoroid velocity, δ is its density, R_s is the lateral cross-section radius, ρ is the atmosphere density, k_r is some function from the surface pressure distribution. Grigoryan assumes $k_r = ½$, that is for sphere. Then

$$\frac{dR_S}{dt} = V \left(\frac{\rho}{\delta}\right)^{1/2} \tag{2}$$

This formula is used and cited in many papers. We found function k_r for spheroid and obtained from (1)

$$\frac{dR_S}{dt} = \frac{V}{k} \left(\frac{\rho}{\delta}\right)^{1/2} \tag{3}$$

Hence the velocity of lateral expanding (flattening) essentially depends on degree of the flattening.

3. Analytical solution

The equations for meteor physics – equations of motion and ablation (mass loss) [2, 7] include drag and heat transfer coefficients. The analytic solution for the drag coefficient of spheroid in dependence on parameter k is obtained. The expression for radiative heat transfer coefficient of a spheroid is obtained with using literature data. In the assumption that the meteoroid mass decreases more rapidly than its velocity, the analytical solution for a large meteoroid of a spheroidal shape (with change of its density and parameter k along flight trajectory) is obtained for the mass loss, energy deposition, light curve and the altitude where the maximum of this curve is reached, in dependence on entry parameters of the meteoroid.

4. Chelyabinsk meteoroid

Based on the analysis of various video records of the Chelyabinsk superbolide on 15 February 2013, the trajectory, velocity, light curves of the bolide and energy deposition per unit height were determined [1, 3, 8]. Using the fragmentation model presented in this study, we obtained the analytical solution for the mass loss, light curve and energy deposition for the Chelyabinsk meteoroid and compared this solution with results based on the video data [1, 3, 9].

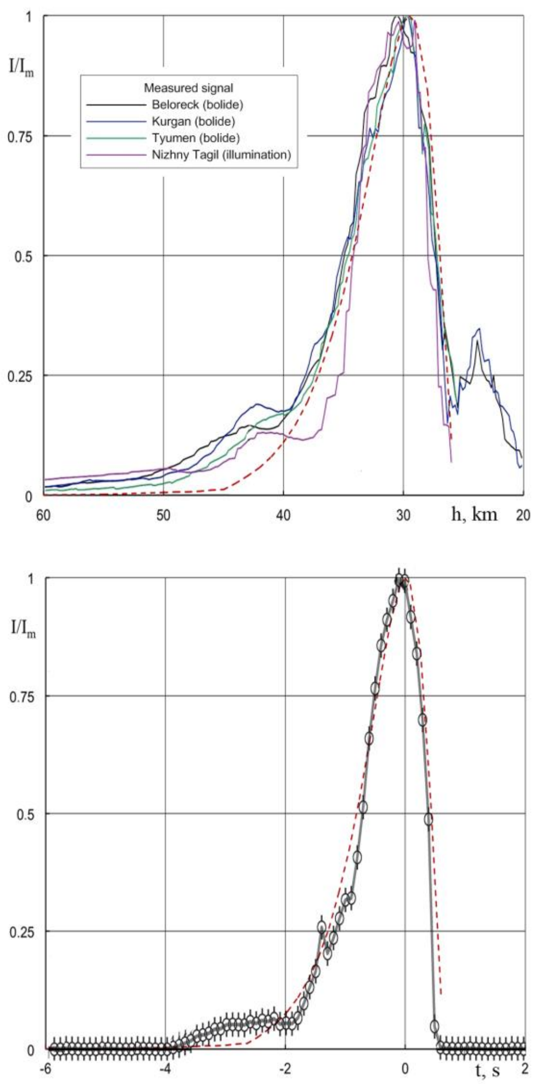

Figure 1: Light curves for the Chelyabinsk bolide. Comparison of the analytical solution (red dashed line) with the video data [1] (upper figure) and [9] (lower figure); *h* – the altitude, *t* – the time from the peak brightness.

Figure 1 shows comparison of the analytical light curve I/I_m normalized to maximum brightness (entry angle – 18°, velocity – 19 km/s, mass – $1.3 \cdot 10^7$ kg, bulk density – 3.3 kg/m^3, bulk strength – 0.7 MPa) with results of [1] and [9].

5. Summary and Conclusions

The proposed model of atmospheric fragmentation of large meteoroids differs from other pancake models in that it takes into account the decrease of density of the fragmented meteoroid and the dependence of the velocity of flattening on degree of this flattening. This model made it possible to obtain the simple analytical solution for the mass loss, energy deposition and light curve of the Chelyabinsk superbolide, which is in a satisfactory agreement with video observations down to altitude of 27 km.

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About catalogue of orbit and atmospheric trajectory of 4500 radio meteors brighter $+5^m$

M.Narziev, R.P.Tshebotaryov.
Institute of astrophysics AS Tajikistan, Dushanbe, Buhoro 22, 6. mirhusseyn_narzi@mail.ru

Abstract

Published by this time the majority of catalogues of a radiant, speeds and elements of orbits of meteors, basically, are based on a interpretation of the given radio observations by diffraction-time a method. However the given method is applicable for processing of 15-25 % of observed meteors that leads to loss of the most part of an observed material. Besides, the error of measurement of an antiaircraft corner of a radiant σZr with increase in a corner to 60°÷70 ° will be increased in 2-3 times, and at the further increase in a corner the error grows even faster, so measurements lose meaning.

In 1968-1970 in action period of the Soviet equatorial meteor expedition to Somalia, simultaneously and radio observations of meteors in HisAO from four points have been resulted. For interpretation of the radar data the bearing-time method radio method developed and applied for the first time in Tajikistan is used. This approximately twice increases number of the measured radiant and speeds. What's more, the error of measurement of an antiaircraft corner does not depend on antiaircraft distance of a radiant. The velocity of meteor is determined by the bearing-time method, and by the diffraction picture.

In the catalogue along with a radiant, speeds and elements of orbits, for the first time the height, value of linear electronic density, radio magnitude and masses of each of 4500 radio meteors registered since December 1968 till May, 1969 are resulted.

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How are the bubbles formed in the fusion crust?

A. Nicolau-Kuklińska (1) and A. I. Łosiak (2)
(1) Space Research Centre, Polish Academy of Sciences, Warsaw, Poland (2) Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland (ank@cbk.waw.pl)

Abstract

Fusion crust is developed on the outermost part of an object entering a planetary atmosphere by melting this object due to heating induced by hypervelocity collisions with air molecules. Vesicles (bubbles) are the most characteristic features of stony meteorites' fusion crust. There is a hypothesis that they are formed by "exsolution of volatile components from the silicate melts" due to high temperature [1]. We try to explain the mechanism of vesicles formation by counting the number of vesicles per area (the "level of vesicularity"), and checking if it correlates with the content of volatile elements in bulk composition and the numerical simulation of melting cosmic object during entering into atmosphere.

1. Introduction

Cosmic objects entering a planetary atmosphere, reach a very high temperature, as a result of hypervelocity collisions with air molecule. The outermost part of the objects is completely melting and during cooling is transforming to glassy layer, usually between 100 mm and 1000 mm thick, named fusion crust [1]. The most characteristic features of stony meteorites' fusion crust are vesicles. On the microscope images they looks like round empty objects with different size and density. There is a hypothesis that they are formed by "exsolution of volatile components from the silicate melts" due to high temperature [2].

The aim of this project is to explain the mechanism of vesicle formation within the fusion crust of eucritic meteorites (achondritic stony meteorites of basaltic composition, likely originating from asteroid Vesta-4). Completion of this study will improve understanding of interaction of bolides with the atmosphere, and determine the amount of volatiles delivered to past and present atmospheres of terrestrial planets by flux of cosmic particles.

1.1 Level of vesicularity

In order to determine the mechanism of vesicles formation it is necessary to quantitatively determine the „level of vesicularity" of the fusion crust. In order to do so we developed a Matlab code that is identifying vesicles on the SEM images and automatically calculates simple statistic of these objects (number, size, percent occupied area, etc.).

The first step of the algorithm is to determine the boundary of the fusion crust. In the SEM images the boundary of the crust is not easy to trace, but it can be distinguished automatically by four steps presented on Figure1.

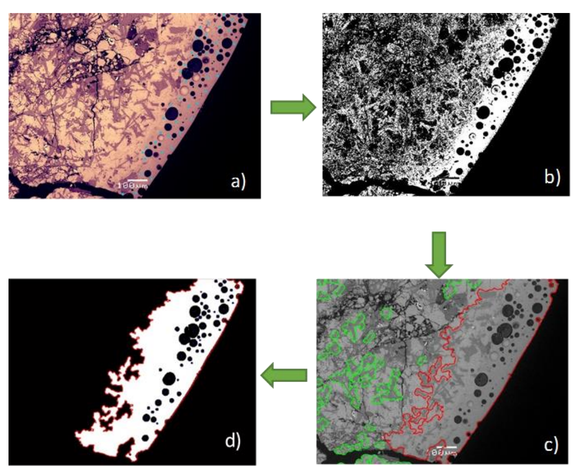

Figure 1: a) selecting pixels from the melted zone and collecting its value, b) finding the higher density of the pixels with specific range of value, c) define the boundaries of areas with high density of pixels, d) selecting the fusion crust area and separating it from the picture in order to further analysis.

The developed program was used to quantitatively determine the „level of vesicularity" of the fusion crust of the fragment of meteorite PCA91007.32 (Table 2).

Table 1: Statistical analysis of the vesicles in fusion crust of fragment of meteorite PCA91007.32 presented on Figure 1.

the number of vesicles	**49**
percentage of vesicles in fusion crust [%]	7
median of vesicles radius (M) [mm]	9
percentage of vesicles with radius > M [%]	12
percentage of vesicles with radius < M [%]	41

1.2 Volatile elements

In order to correlate the occurrence of vesicles with specific chemical components (especially volatile S) in bulk meteorite, microprobe analysis of three meteorites was performed. For this purpose selected the representative area of the bulk meteorite and analyzed the chemical components of 25 points on it, distributed like on the Figure 2.

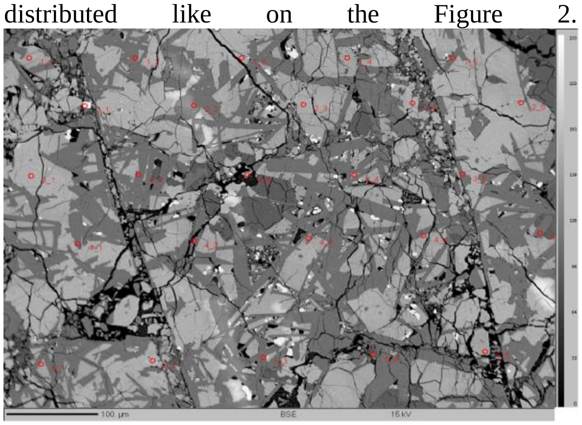

Figure 2: Reprezentative area of the bulk of the meteorite PCA91007 and points distribution for chemical component analysis.

The average contents of volatile element S in different bulk of meteorites are presented on Figure 3.

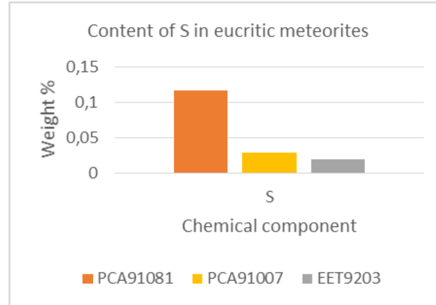

Figure 3: The average content of volatile element S in bulk of the eucritic meteorites.

It was observed the differences between the chemical composition of the eucritic meteorites, and textural of the fusion crust and the parameters of vesicles within it as well (Figure 4).

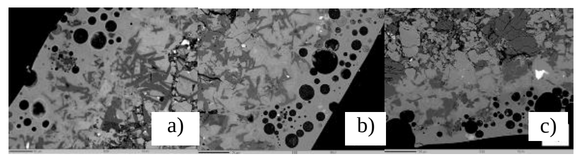

Figure 4: Comparison between textural and number of vesicles in fusion crusts by SEM images of eucritic meteorites: a) PCA91081, b) EET9203, c) PCA91007

The correlation between volatile element S and present vesicles in the fusion crust will be presented on poster session during conference.

Acknowledgements

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Novel Experimental Simulations of the Atmospheric Injection of Meteoric Metals

J. M. C. Plane (1), J. C. Gómez Martín (1), D. Bones (1), C. Empson (1), J. D. Carrillo-Sánchez (1), A. D. James (1), A. Dobson (1), J. M. Trigo-Rodríguez (2), B. Fegley Jr. (3)
(1) School of Chemistry, University of Leeds, Leeds, UK
(2) Institute of Space Sciences, CSIC-IEEC, Barcelona, Spain.
(3) Washington University, St. Louis, MO, USA
(j.m.c.plane@leeds.ac.uk / Fax: +44-113-3436401)

Abstract

A newly-developed Meteor Ablation Simulator (MASI) is the first laboratory experimental set-up to study atmospheric ablation in a time-resolved manner under realistic heating rates. The MASI has been used to observe the absolute rates of ablation of Na, Fe, Mg and Ca from a number of meteoritic and synthetic cosmic dust particles. The comparison of the monolithic, single mineral simulations by the Leeds Chemical Ablation Model (CABMOD) to the MASI experimental data highlights the complexity of the process of melting and evaporation of IDP mineral assemblages, but also the usefulness of CABMOD for calculating elemental yields of volatile (e.g. Na), moderately refractory (e.g. Fe, Mg) and highly refractory (e.g. Ca) elements. This work confirms differential ablation in laboratory experiments for the first time, and provides confidence in CABMOD as an important tool for linking the cosmic dust input to a planetary atmosphere with a variety of atmospheric phenomena.

1. Introduction

There have not been may attempts to simulate micrometeoroid ablation in laboratory experiments. Most previous studies have focused on understanding the thermal processing of micrometeorites retrieved on the ground both from a textural and compositional perspective, in order to infer their origin [1]. More recent experiments using pyrolysis and gas-phase infrared spectroscopy have also attempted to quantify the yield of sulphur, CO_2 and H_2O in order to estimate the potential impact of micrometeoroids on planetary atmospheres [2].

The Chemical Ablation Model (CABMOD) [3], developed at the University of Leeds, estimates the ablation rate profiles of individual elements for a meteoroid with specified composition, mass, velocity, and entry angle. This model has been at the core of recent efforts to quantify the input of IDPs into the terrestrial atmosphere by reconciling observations including IR emission from the Zodiacal Cloud, the vertical fluxes of Na and Fe atoms in the upper mesosphere, and cosmic spherule accumulation at the surface [4]. The mass and velocity distribution of IDPs derived from High Performance Large Aperture radar observations [5] are very different from those inferred from orbital impact detectors and astronomical dust models [6]. This may reflect a bias of radars towards fast/large meteoroids; quantification of this effect requires a model such as CABMOD [7]. Therefore, in order to reduce uncertainties in ablation modelling it is necessary to set CABMOD on solid experimental ground.

2. Experimental

The MASI was designed to carry out controlled flash heating of IDP analogues over the range of atmospheric ablation temperatures, while the vaporisation rates of two elemental constituents are monitored using time-resolved atomic laser induced fluorescence (LIF). The instrument, shown schematically in Figure 1, consists of a vacuum chamber fitted with an electrical feed-through on which a tungsten ribbon is mounted as a filament. Samples of IDP analogues are deposited on the filament surface and then the chamber is closed and evacuated. The filament is resistively heated using a programmable power supply up to 3000 K. The temperature of the surface is measured using a 1 ms time response pyrometer camera and each experiment is recorded using a video camera to track the particle evolution on the surface of the filament.

A Nd:YAG laser operating at 250 Hz is used to pump two dye lasers, one tuned to the atomic Na and the other to either the Fe, Mg or Ca resonance transitions. The resulting LIF signals are collected through monochromators by orthogonal photomultipliers. These signals are proportional to the concentration of atoms in the gas envelope ablated from the particle, and hence to the particle mass loss rate. Different heating programs can be chosen, including ramps of different slopes, step functions, and modelled atmospheric ablation temperature profiles.

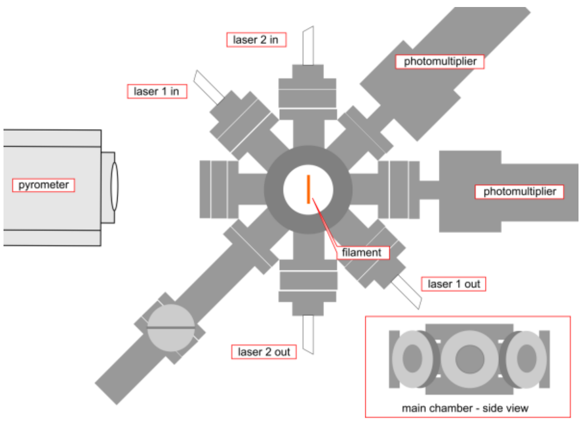

Figure 1: Top view of the MASI

3. Results

Figure 2 is a comparison of the elemental ablation profiles predicted by CABMOD and measured by MASI. The general features of *differential* ablation – sequential evaporation of Na, Fe, Mg and Ca – are correctly predicted by the model. However, the measured ablation profiles of Na and Fe are broader than predicted – clear evidence for these elements evaporating from different minerals contained in the meteorite matrix.

4. Summary and Conclusions

The new ablation simulator is an important tool for testing and refining the ablation models which are central to predicting where different meteoric elements are injected into a planetary atmosphere. This is crucial information for modelling the atmospheric impacts of cosmic dust. Modifications have been introduced in CABMOD to better match the Na velocity and mass-specific experimental profiles, which has implications for meteor radar detectability of slow and light particles. Most recently, the input of cosmic dust to the terrestrial atmosphere has been determined to be 43 ± 14 t d^{-1}, or which around 18% ablates [4].

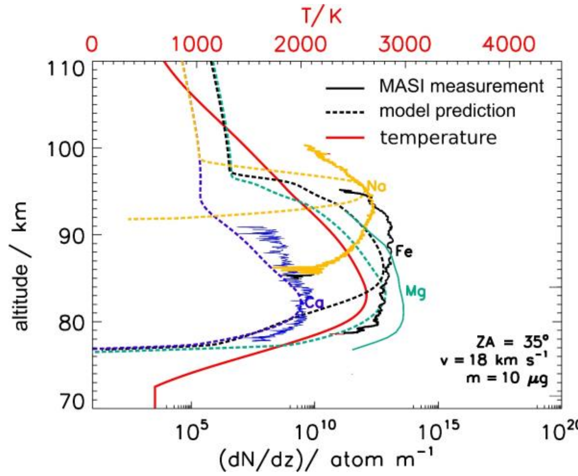

Figure 2: Comparison of CABMOD predictions (dashed lines) with MASI measurements of ablating of Na, Fe, Mg and Ca from Allende meteoritic particles, radius ~64 μm, entry velocity = 18 km s^{-1}

Acknowledgements

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Chelyabinsk event: injuries

A. Kartashova (1), O. Popova (2), P. Jenniskens (3, 4), D. Glazachev (2)
(1) Institute of Astronomy of the Russian Academy of Sciences, Moscow, Russia (2) Institute for Dynamics of Geospheres of the Russian Academy of Sciences, Moscow, Russia (3) SETI Institute, Mountain View ,USA (4) NASA Ames Research Center , Moffett Field, USA (akartashova@inasan.ru / Fax: +7-495-9515557)

Abstract

Data on injuries caused by the impact of the Chelyabinsk meteoroid are reported. The data were collected based on interviews of eyewitnesses and on the official sources.

1. Introduction

In the morning of 2013 February 15 (at 3:20 UT), a 20m in size meteoroid entered the Earth atmosphere in the Chelyabinsk Region of Russia and caused an airburst strong enough to create widespread glass damage [1]. This event is the first impact which resulted in numerous injuries in the surroundings. Most recent tally shows that 1613 people asked for medical assistance at hospitals, much more people were affected but didn't ask for medical help.

2. Main sources of the information

Most people asking for medical assistance did so on the day of the event (~1200, Figure 1) [2]. Most injuries were caused by cuts from broken glass and by trauma from the impact of the shock wave (falls and being hit by objects, causing brain concussions, bruises, etc.). In the next days, more people reported in. The reasons given were vegetative-emotional syndrome, reaction to stress, hypertension. The same tendency was for hospitalized people. A "call-in phone line" was organized for psychological help.

69 people were hospitalized, 2 in serious condition (1-cut eyeball, 2-spinal fracture, both from Kopeysk, evacuated for treating to Moscow). The fraction of injured people was largest in regions closer to the trajectory the most populated One week after the event 38 people still were in hospitals (Figure 2-3).

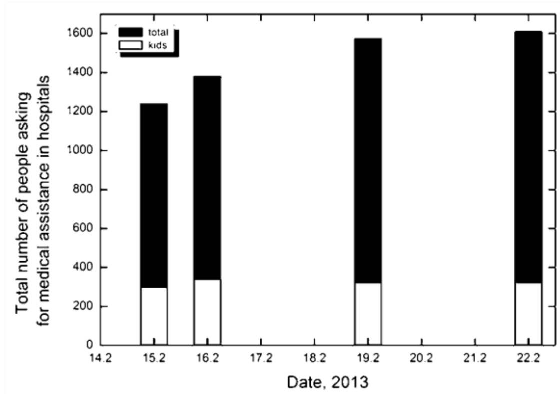

Figure 1: Summarized number of people asking for medical assistance in hospitals (empty days – absence of precise data).

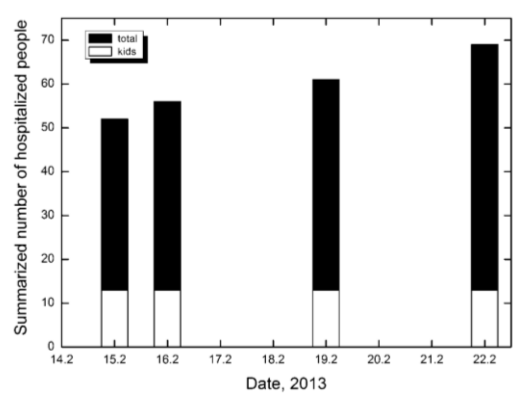

Figure 2. Increase of summarized number of hospitalized people (empty days – absence of precise data).

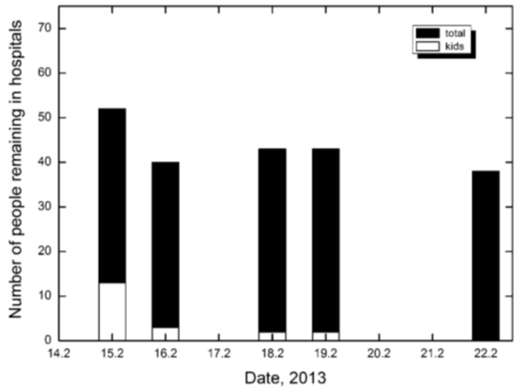

Figure 3. Number of people remaining in hospitals (empty days – absence of precise data).

1754 residents filled out web-based query forms, which provide information about sensations of heat, smells, sounds, the occurrence of sunburn, and the nature of injuries. Of the 377 people affected, 22 (5.8%) reported sunburn, 210 (55.7%) felt eyes hurt, 14 (3.7%) sensed retinal burns (no official data), 82 (21.7%) sensed temporal stunning, 37 (9.8%) reported the brain concussion.

Telephone interview with residents of Chelyabinsk 23-24 February 2013 (500 respondents) was organized by Public Opinion Foundation (FOM). Two percent of respondents reported personal injuries, 7% of respondents said that relatives were affected.

There were no reported damage of eardrums, so we may suppose that overpressure never exceeded 16.5 kPa (threshold level, probability of eardrum rupture is 1% [3]). According to Gel’fand and Sil’nikov [4] 10% of people suffer from temporal hearing loss when shockwave pressure is 1.4 kPa. So we can suppose that overpressure might be 1kPa and higher, which also agrees with the data on the broken out glass [5].

New information was obtained from official data kindly provided by few hospitals in the area. Few bone fractures cases were confirmed (previously not reported).

3. Summary

As it was mentioned above the impact of relatively small asteroid caused numerous injuries. The detail study of their reasons, types and distribution in the impact area provides important information. A better understanding of what happened might help future impact hazard mitigation efforts.

Acknowledgements

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Numerical Simulation for Dark Flight Stage of Meteoroid Fragments

V. Vinnikov (1,2), **M. Gritsevich** (2) and L. Turchak (1)
(1) Federal Research Center of Informatics and Control of RAS, Moscow, Russian Federation (vvinnikov@list.ru), (2) Department of Physics, Univ. of Helsinki, Helsinki, Finland (maria.gritsevich@helsinki.fi), (3) Ural Federal University, Institute of Physics and Technology, Ekaterinburg, Russian Federation

Abstract

This paper is concerned with numerical simulation of meteoroid dynamics. The simulations of bolide ballistics are carried out via hard sphere approximation. System of differential equations for movement and heat transfer is solved in Lagrange variables via Runge-Kutta methods. The drag force of atmospheric air is computed via Henderson formula, valid for wide ranges of Reynolds and Mach numbers. The parameters of surrounding gas are obtained from standard atmosphere model. Meteoroid fragmentation is modeled as sequential division of parent body into two parts using random weighting coefficient for parent mass. Computational results show that maximum splinter masses are in good agreement with corresponding observations and measurements.

1. Introduction

Meteoroid passage through the Earth atmosphere usually exhibits two consequent stages, namely: atmospheric entry as a bolide, and dark terminal part of the trajectory. Only exceptions are the massive dense bodies like metalic meteorites having completely bright path down to the planetary surface, and micrometeorites and space dust, losing velocity in upper atmosphere. Generally, the initial bright part of the trajectory is considered linear [1], however, more dense atmospheric layers promote the aerodynamic drag as a main contributing factor to meteoroid deceleration below speed of sound. The accurate estimation of dark flight trajectory is essential at determining the search area of meteorite fragments. Therefore, the numerical simulation becomes the most reliable mean to obtain dark flight trajectories.

2. Mathematical model

To efficently estimate the dark flight trajectory we consider following assumptions. First, we assume that the simulated meteoroid is subjected to fragmentation and can become an ansemble of fragments at the end of bolide stage of the trajetory. Second, due to large number of simulated fragments reaching orders of 10^3–10^4, we consider a simplified ballistic model, which represent the fragments as homogeneous balls with specified density. The dynamics for each fragment is governed by a system of differential equations accounting for drag and gravity. To increase accuracy of the simulation, the drag coefficient is computed via Henderson formula [2]. The atmospheric properties are calculated via 1976 US Standard Atmosphere model [3], which is sufficient for endoatmospheric simulations. The temperature correction for air viscosity is carried out via Sutherland formula [4]. The gravity acceleration and the shape of Earth are modelled according to WGS84 model [5]. For better representation of fragments scatter area we consider Earth landscape via global satellite digital elevation map GTOPO30 wth precision of 30 arcseconds. The fragmentation processes are described via expression [6] for stagnation pressure threshold

$$p^*_{imp} = \sigma_0 m_0^\alpha m_P^\alpha, \tag{1}$$

where m_0 is the initial mass of meteoroid, $\alpha = 0.25$ is a scaling factor, σ_0 is the mean static strength of the meteoroid material. The sizes of the resulting pair of fragments are computed with stochastic model [6]:

$$\xi \sim R\left[0;1\right], r_{P,1} = \xi r_P, r_{P,2} = \left(1-\xi^3\right)^{1/3} r_P. \tag{2}$$

The presented model was implemented in the form of computational algorithm. The numerical simulations were carried out with initial parameters, corresponding to Chelyabinsk meteorite (see tables 1-2)

Table 1: Initial conditions [7] for numerical simulation.

Parameter	Value
Altitude, km	32.47
Longitude, deg.	62.06
Lattitude, deg.	54.92
Velocity, km/s	13.43
Descent angle, deg.	-16.33
Azimuth angle, deg.	271.60

Table 2: Meteoroid properties [8, 9].

Parameter	Value
Initial diameter, m	18.0
Initial mass, t.	11000
Density, g/cm^3.	3.6
Strength, MPa	10.0

During the computational experiments we corrected initial material strength to 0.6 MPa, as estimated in [6] for Benesov bolide.

3. Summary and Conclusions

Computational results show that terminal velocities and maximum splinter masses are in good agreement with corresponding observations and measurements. For example, the computed mass for the largest Chelyabinsk meteorite fragment is 692 kg and the piece recovered from Chebarkul Lake has mass of 654 kg. The following research will be aimed for implementation of more detailed atmospheric models, including simple modifications for cold and hot climates, wind charts and jet streams, and more complex multiparametric models such as NRLMSISE-00, as well as accounting for lift force of irregular shaped fragments. More accurate models would give better estimations for dark flight trajectory, would help to define robust location of fallen fragments and significantly speed up their recovery.

Acknowledgements

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Atmospheric trajectory and orbit of the Osceola meteorite

M. Gritsevich (1,2,3,4), E. Lyytinen (2), M. Hankey (5), M.M.M. Meier (6), R. Matson (7), and M. Fries (8)

(1) Department of Physics, University of Helsinki, Finland, email: maria.gritsevich@helsinki.fi, (2) Finnish Fireball Network, Helsinki, Finland, email: esko.lyytinen@jippii.fi, (3) Institute of Physics and Technology, Ural Federal University, Mira St. 19, 620002 Ekaterinburg, Russia, (4) Department of Computational Physics, Dorodnicyn Computing Centre, Russian Academy of Sciences, Vavilova St. 40, 119333 Moscow, Russia, (5) American Meteor Society, (6) ETH Zurich, Institute of Geochemistry and Petrology, Zurich, Switzerland, (7) Leidos, 11955 Freedom Drive Reston, VA 20190, USA, (8) NASA Johnson Space Center, Houston, TX, USA.

Abstract

The aim of this study is to present a summary on the trajectory reconstruction, dark flight simulations and the Solar System orbit estimate for the day-light fireball widely observed over northern Florida (USA) on January 24, 2016 at 10:27 EST (15:27 UTC).

1. Introduction

Out of a total around 50,000 meteorites currently known to science, the atmospheric passage was recorded instrumentally in less than 0,1 % cases with the potential to derive their atmospheric trajectories and pre-impact heliocentric orbits. Similarly, while observations of meteors generate thousands of new entries per month to existing databases, it is extremely rare they lead to meteorite recovery [1].

We have conducted the detailed trajectory reconstruction, dark flight simulations and the pre-impact orbit estimate for the day-light Osceola fireball observed over northern Florida on January 24, 2016 at 10:27 EST.

The lower part of the atmospheric trajectory was retrieved from the weather radar indicating meteorite signatures shortly after the fall. The radar returns were strong, found at multiple altitudes and located on multiple stations: KJAX, KVAX and KTHL. There were also seismic recordings of the fireball which helped to specify, in particular, timing of the fireball.

2. The analysis of the luminous flight

A publicly available dash-cam video with the day-light fireball recording made by Erick Williams, was carefully calibrated [2] and taken into account in reconstruction of the luminous part of the trajectory. The original dash-cam was kindly provided to us by the owner, so as to enable derivation of the exact camera properties and for star calibration. This facilitated the robust extraction of key characteristics of a meteoroid based on the available data.

Figure 1: One of the frames extracted from the dash-cam recording of the day-light Osceola fireball.

We have estimated dynamic meteoroid mass (and also the way it changes along the trajectory) using analysis of drag and mass-loss rate [3] derived from the observations. The data were treated thoroughly with account for the actual weather conditions at the time and location of the fireball [4]. The heliocentric orbit was derived using numerical integration of the equations of motion implemented in a software “Meteor Toolkit” [5, 1]. The Osceola has the most evolved orbit of all known L chondrites with orbits [6], with an aphelion sunward of the inner rim of the asteroid belt.

The derived values of the ballistic coefficient and mass loss parameter indicate [7, 8] that significant part of the meteoroid's mass survived the atmospheric entry and reached the ground.

3. Details on the recovered Osceola fragments

Based on the weather radar data analysis Mike Hankey found the first meteorite fragment weighting 8.5 g on the eastern edge of the primary radar return on January 31, 2016. Within 2 hours Larry Atkins found the second 18.5 g fragment directly under the radar signature. In the following searches 6 more fragments of the meteorite were recovered with the masses of 5.5 g, 48.5 g, 839 g, 75.5 g, 90.5 g and 18.6 g.

The meteorite was classified as L6 ordinary chondrite.

Figure 2: The recovered 839 g fragment of the Osceola meteorite.

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