Chelyabinsk Meteoroid: Critique of Sources and Proving of Conclusions

Yury I. Lobanovsky

IRKUT Corporation

68, Leningradsky prospect, Moscow, 125315, Russia

E-mail: streamphlow@gmail.com

The greatest enemy of the truth is not the lie – deliberate, contrived, and dishonest – but the myth – persistent, pervasive, and unrealistic.
John F. Kennedy

Abstract

It is shown that the concept representing the events February 15, 2013 in the skies near Chelyabinsk as airburst of chondrite meteoroid, density of which was 3300 kg/m^3, size was of the order of 15 – 20 m, mass – 10 – 15 kt and explosion energy – 0.3 – 0.5 Mt of TNT, isn't consistent with the phenomena observed in the atmosphere and on the underlying surface. This thesis is proved on the basis of infrasound data, levels of overpressure on the shock wave in Chelyabinsk and surrounding areas, as well according to broken glass, damaged gates and curved supporting beams. Mass of trail of Chelyabinsk meteoroid is also evidenced about this. It is shown that the estimates of brightness of its flash were conducted in a way that cannot be the basis for any definite conclusions.

Computations show that all observations are corresponded to the destruction in the stratosphere of snow-ice fragment of comet, which was contaminated by chondrites, mean density of which was about 570 kg/m^3, size was 180 – 185 m, mass – of about 1.8 Mt, and its explosion energy was near 57 Mt of TNT. Surface of this celestial body was covered with a crust of chondrites, pieces of which were found after explosion on the ground. This crust was formed by ablation of the meteoroid material under the influence of solar radiation for a few thousands or tens thousands of years during its motion around the Sun.

Keywords: Chelyabinsk meteorite, Tunguska meteorite, Tsar Bomba, Krakatoa, meteoroid, nuclear explosion, trajectory, height, energy, epicenter, infrasound, brightness, flash, shock wave, pressure, distance

I. Introduction

Explosion of very large meteoroid in the skies near Chelyabinsk February 15, 2013 in the first hours after the event has led to numerous speculations both professional astronomers and amateurs. It was quite a natural reaction to the event, however, isn't a natural fact that these first hasty conclusions until now, after several years, after several years, are dominating in minds not allowing to evaluate this incident accurately and objectively.

The author of this work, not being a professional astronomer, but being a physicist interested in this extraordinary phenomenon, and without using any preconceived assumptions about the nature and characteristics of meteoroid has constructed during March 2013 a mathematical model relating the parameters of motion of celestial bodies in the sphere of activity of the Sun, and in the sphere of activity and atmosphere of the Earth, with mass-energy characteristics of these bodies and parameters of explosions caused by their destruction, which in turn are linked to the observed phenomena [1 – 4]. The most important part of this model is interactive online module that describes the destruction of meteoroids in the atmosphere and/or their fall on the Earth surface [5]. This comprehensive model for a known orbit of the meteoroid before its collision with the Earth allows going from a more or less plausible assumptions about the characteristics of meteoroids entering to the atmosphere to their straight calculations.

Application of this model to Chelyabinsk meteoroid has showed that as its characteristics so and parameters of explosion are significantly different from those that are declared as such in the modern papers and in their mass media interpretations, replicated in countless amounts by copying. Therefore, it is advisable to analyze the data presented by other authors, and identify the causes of conflict between these data and those obtained in [1 – 4]. For this reason are compared here in the main areas of research the results obtained by this mathematical model and data of two large groups of researchers (consisting on whole of 92 people) [6, 7], which were presented at the end of 2013 in the prestigious scientific journals Nature and Science, and which, in general, are correspond to the majority opinion.

The results of this paper were presented at XL Academic Space Conference, dedicated to the memory of academician S. P. Korolev [8].

II. Estimation of parameters and explosion characteristics of Chelyabinsk meteoroid according to infrasound data

It all started with NASA release from February 15, 2013. There was reported that the size of Chelyabinsk «meteor» before entering the atmosphere was 15 m, mass was 7 kt, the flight speed – 18 km/s, and the energy of explosion – «hundreds kilotons» of TNT [9]. Base of these estimations has not been specified. Later in the same day the explanation has followed that the object size is increased to 17 m, mass – up to 10 kt, «the estimate for energy released during the event has increased by 30 kilotons to nearly 500 kilotons of energy released», while according to the first release the kinetic energy of the meteoroid should be 270 kt, and it couldn't increased up to nearly 500 kt in this case. Grounds for these new assessments were data from «five additional infrasound stations located around the world – the first recording of the event being in Alaska» [9].

Given the fact that multiplying the stated speed of the object in the second power by the half of declared mass, and dividing the result by 4.185 MJ/kg (standard specific energy of TNT), anyone other than the authors of this release wouldn't get more than 390 kt of TNT instead of 500 kt in this case, there can be concluded that they are in such a hurry that they forgot even the law of energy conservation. In addition, JPL employees should know that for such relatively small objects the final explosion energy may be much lesser than their initial kinetic energy due to energy dissipation at a flat trajectory. For declared parameters of celestial body the calculations of trajectory with such small entry angle should to lead to the explosion energy, which isn't more than 100 – 150 kt of TNT. With such explosion energy the overpressure on the shock wave in Chelyabinsk should be, at least, 2 orders of magnitude lower than observed, and absolutely there would be no destructions on the ground, see Section V of this paper.

Obviously, the size of the object couldn't be directly determined with the aid of infrasound stations that measure only the atmospheric perturbations. Full confusion with the data on energy shows that the size of the object then couldn't be determined with their aid. Therefore, it remains the only logically proved version – the authors of release have taken as the size of the object «Chelyabinsk» maximum of that what in their opinion i isn't detectable in the near-Earth space with the aid of modern automated optical tracking systems. So called «scientific justification» of this approach has been found soon, see [10]. However, none of them has thought in a hurry that near the Sun angles aren't available for these systems. But Chelyabinsk object went so – its trajectory was inclined from the direction to the Sun at an angle of only about 10° (see [1, 2, 4]).

Two months after the incident, Peter Brown, which was presented in a newspaper article [11] as «the world's top expert in analyzing fireballs with infrasound» said at 2013 IAA Planetary Defense Conference that infrasonic waves generated by «Chelyabinsk meteorite» had such a low frequency that existing software «could not cope with them» [12]. Thus, he acknowledged publicly that his data, which were actually the only ground of NASA version of parameters of Chelyabinsk meteoroid, were mistaken. Around the same time he told to reporter Allen of Canadian newspaper Star that infrasound wave from the explosion of the meteoroid was registered three times in Greenland [11], that is, on the infrasound station I18DK International Monitoring System [13]. This means that the wave has ran along the Earth's surface not less than 85 thousand kilometers [14]. After all of this is difficult to imagine how not even «the world's top expert», but simply a person familiar with the basics of logic and arithmetic, could again to write a few months later in the article for Nature, that the explosion energy of Chelyabinsk meteoroid was 500 ± 100 kt [6], though almost the same path length of infrasound wave was from the largest man-made explosion of Tsar Bomba – AN602 warhead, energy of which was of about 58,000 kt, that is almost 120 times more [15]! Perhaps, however, that he had never heard about this explosion. The reader can see more accurate and detailed analysis of this situation in paper [16]. We will not repeat it here.

III. Flash brightness of Chelyabinsk meteoroid

Moreover, soon (in March 2013) there have appeared the «additional confirmations» of this, as calculations show, wholly inadequate assessment of the energy of Chelyabinsk object explosion – about 500 kt, see [17]. Through the correlation between the energy of the light flash and the energy of the explosion [18] there ostensibly was obtained this notorious value 500 kt of TNT again. However, such a correlation from source [18], only for one parameter, was held for the explosion energy 0.1 – 1 kt, and due to the fact that in reality there is a multi-parameter dependence, was characterized by a large discrepancy between the empirical points and the correlation curve. And the authors of paper [17] extrapolated this unreliable dependence, as they believed, on the order of 3, and in fact even of 5 (!). Obviously, due to the incorrectness of such extrapolation one can get absolutely any preassigned result.

Authors of papers [6, 7] have gone along the same path. Direct measurements of flash brightness of Chelyabinsk meteoroid haven't been conducted for obvious reasons, so the authors of the corresponding section of paper [7] had no another choice but to use the images obtained with a certain number of DVRs, mostly automotive. These images were created by light reflected from different solid surfaces with unknown brightness reflection coefficients. Besides, what were the spectral brightness characteristics at the light intensity and wavelength for these sensors, there remained unknown. In order to account for the effect of these uncertainties, the authors of the study [7] have carried out the correction of measurements of light intensity using the calibration arbitrarily selected camera (Mediox DVR100) by the brightness of the Moon. However:

1. Reflection coefficients of different materials in different spectral ranges and for different angles of reflection and brightness should be changed. Neglecting this fact may lead to a difference between the calculated results and the actual values of the brightness at times.

2. Such correction of sensor characteristics for blast of unknown brightness, but obviously lying beyond the installed borders of operation of these sensors, is actually equivalent to exponential extrapolation with undetermined coefficients in a very wide range of parameters. To what it might lead – clear for anyone who ever tried to do it. Errors are possible in the tens or hundreds of times. And how this exponent describes the real sensitivity of all these different types of DVRs – it's also a question.

3. Calibration of brightness curve on its lower boundary [7] with the use of the source with the intensity of light in millions or perhaps tens of millions of times smaller than the maximum brightness of the flash – this is the operation that is in no way not linked to adequate recalculation of data at its maximum brightness.

4. Change in the wavelength of the radiation in the calibration could and should affect the sensitivity of the sensors. In our case the maximum power is shifted from about 0.3 microns (a light of flash at ~ 10^4 K) to 0.5 microns (sunlight reflected by Moon, the spectral characteristics of which correspond to ~ $6 \cdot 10^3$ K, for example).

Thus, the attempts to get in paper [7] estimates of the absolute brightness of flash from Chelyabinsk meteoroid with acceptable accuracy due to objective circumstances, as well as due to the unwillingness or inability of them who did it, and spend a really adequate calibration, correction and recalculation, relied on poorly verifiable and also not documented actions. The authors of paper [6] have made reference to data of «government sensors», checking and analyzing of which is impossible.

And finally, most importantly – apparently impossible in principle using the data from the cameras and recorders to obtain a correct estimate of the intensity of light emitted by the flash, brightness of which surpasses the brightness of the Sun. As is known, there is so-called solarization at photographing the Sun with the help of modern cameras and camcorders – purple or black spots appear on the image due to saturation of appropriate sensitive areas of camera's matrix. And similar effect can be observed not only directing the camera at the Sun, but even at its reflection, for example, in the waters of the Dnieper near Kherson, see Fig. 1 [19].

Different technologies are used for improved cameras to prevent such saturation of matrix. But they all are reducing the luminous flux on the sensitive elements of the matrix at high brightness. For example, there are lenses with the so-called DC-iris: in low light, it is completely open, and during bright light aperture is covered to prevent the saturation [20]. That is, in modern video cameras and DVRs with a certain level of brightness comparable to the brightness of the Sun, is either programmed or spontaneous «circumcision» of brightness. And when processing the images from these cameras are basically impossible to get the brightness significantly greater than this maximal level.

In this regard, we note that the magnitude of absolute brightness of the flash (that is the brightness at a distance of 100 km) in the explosion of Chelyabinsk object according to the source [7] was -27.3 ± 0.5 or -28 according to «U.S. government sensors data» [6]. It is known that the apparent magnitude of the Sun is -26.7 [21], that is, its brightness in 1.7 – 3.3 times lower than that of the flash according to sources [6, 7]. Apparently due to the fact that the «government» (military) sensors were farther from the explosion than camcorders in Chelyabinsk and, probably, were of higher quality, they were registered the greater brightness of the flash. However, for specified reasons, it could still be much lower than the actual.

Fig. 1

We can estimate the minimum magnitude of light intensity at which takes place the saturation of usual camera matrix, using photo in Fig. 1. Angular height of the Sun over Small Potemkinsky Island on the Dnieper [22] is about 10º. In this case the brightness of light reflected from the surface of water is about ⅓ of the brightness of direct sunlight [23] that is close to –25.5 of magnitude. Since the cameras with which according to source [7] were determined the brightness of the flash, were located in Chelyabinsk, the distance to the point of maximum height of the flash 31.7 km [7] was about 50 km, and the brightness of it was 4 times greater than at distance of 100 km, at which its absolute value is determined. Since the cameras recorded the reflected light, its intensity could be an order of magnitude lower than that of direct light. Then the magnitude of reflected light flux was about –26.5 that is on ~ 1.0 higher than for the absolute brightness of flash according from the source [7], and that is on ~ 1.0 lower than the magnitude, at which the saturation of camera matrix was clearly recorded. Thus, from the above it follows that submitted data on the maximum brightness of the flash of Chelyabinsk meteoroid were received from cameras on which have occurred «circumcisions» of light intensity.

The day before the anniversary of the explosion of Chelyabinsk meteoroid the local television channel informed sensational news that on one of the previously recorded video there is the image of body that has caused this phenomenon [24]. This dark spot is best seen in the same video from YouTube [25], see screenshot of this video on Fig. 2. The spot is seen approximately at the center of bright area of the explosion in the upper right corner of the screenshot. Clearly, that it is the same as in Fig. 1 result of matrix saturation. This is one from two known to author of this article cases of registration of this phenomenon during the explosion of Chelyabinsk meteoroid. This fact clearly indicates again that the sensors have operated outside the area of their design characteristics, and the brightness of the flash couldn't in any way be determined with the aid of images obtained from them. Therefore the data on the brightness obtained in [6, 7], can't be considered as reliable because of very high light intensity of the blast. Therefore, estimations of the explosion energy of the meteoroid on the basis of these data the more can't be taken into account.

Fig. 2

IV. Overpressure estimations at shock wave through quantity of broken window glass

Consider estimations of overpressure on the shock wave required for destruction of window glass. In the appendix of paper [7] states: «The value of overpressure, Δp, needed to break window glass is dependent on the glass thickness and surface area». It is absolutely true statement, moreover, it is easy to give a formula that would allow to replace this quantitative assertion into qualitative. In addition, this value heavily depends by conditions of fixing the glass in the frame, direction of shock wave approach, geometry and orientation of building in which the windows are located, as well as the topography of surrounding countryside and even the direction of the wind. Since there is no way to take into account all these factors in a large city and several towns and villages of a smaller scale, we may use only a statistical approach to the issue. And therefore abstractly correct statements of authors of paper [7] are completely empty maxims, which have no relation to task solution.

About what statistics says? This boundary condition (overpressure on the shock wave needed to shatter the window glass in sizeable quantities) directly and immediately determines the scale of the explosion, and this is obvious a priori, without any calculation, from fundamental laws of occurrence and propagation of shock waves. From commentary of calculation's module of meteoroid explosions and collisions [5], it follows that massive destruction of window glass begins at the overpressure on wave of about 7 kPa. It is known that «in accordance with the Russian construction norms the resistance of glazed constructions to excessive blast pressure should not exceed 5 kPa» [26]. In accordance with the Russian Ministry of Emergency, the destruction of glazing window frames occurs when the excessive pressure is 5 – 8 kPa [27]. However, Wikipedia [28] is reported that usual glass can be broken by the overpressure on the shock wave of about of 2 kPa, with citing to a source [29], where, however, these data are absent. Thus, the overpressure of 5 kPa in the first approximation can be considered as the boundary of massive destruction of window glass. To written should be added that according to fundamental multivolume «Physics of Explosion» [30], the excess pressure on the incident shock wave needed to knock glass is 3.5 – 7 kPa, and in experimental studies made about of 60 years ago, «there may be cases of shattering of bad fixed glass» at 0.5 – 0.8 kPa [31].

Now cite supplementary materials of paper [7]: «These values (of overpressure – auth.) are not different between windows in Russia (most affected buildings being from the 20th century) and other locations in the world. Glasstone and Dolan [32] estimated the overpressure which caused essential glass damage at about Δp ~ 3,500 – 5,000 Pa. According to Mannan and Lees [33], an overpressure of about Δp ~ 700 Pa is able to shatter 5 % of glass windows, Δp ~ 1,400 Pa would break 50 %, and Δp ~ 3,500 (Pa – auth.) causes damage to about 90 % of glass windows». About the adequacy of Mannan and Lees data for this situation will be discussed below, and now we note the conclusion in the cited data, which can be not otherwise as a paradoxical: «This suggests that a value of $\Delta p \sim 500$ Pa would describe the extent of the damage area where just a few windows were broken ... while $\Delta p \sim 1{,}000$ Pa would result in significant window damage»... I would like to see in the passage quoted from the source of text [33] this overpressure value – 0.5 kPa, but such value is absent there. It should be mentioned in fairness that the source [31], which is unknown for authors of work [7], is referred to the level of overpressure on the shock wave of 0.5 kPa and greater *as extreme lower limit for shattering of bad fixed glass*, but in the past 60 years the culture of glass fixing in the former Soviet Union, seems, has somewhat increased.

So, according to Glasstone and Dolan «essential» that can be interpreted rather freely, and not even «massive» damages of glass occur at overpressure on the shock wave (during nuclear explosions) of about 3.5 – 5 kPa, what, perhaps, is consistent to data from all other sources, cited in the book [30]. Only Mannan and Lees evidently are knocked out of the total number, and only their data, reduced without any explanation even further in one and a half times, are used in paper [7]. And the question: why Mannan and Lees say that overpressure levels for glass destruction are significantly lower than in any other sources, is solved quite elementary. These data are presented in the third edition of known book about prevention of catastrophic situations in industry. As Frank Lees so Sam Mannan, which was the editor of the third edition of this book, were chemical engineers at major petrochemical plants. And they are talking about the impact of indoor explosions, likely volumetric, so as such conditions are created during petrochemicals explosions.

It's perfectly obvious from the sentence «... $\Delta p \sim 3{,}500$ Pa causes damage to about 90 % of glass windows». In the event of an internal explosion the glass flies to all 4 sides more or less equally and easy to imagine even wholly broken glass with absolutely intact walls. If a sufficiently strong external shock wave from a distant source is incident on a building with one side and doesn't destroy it completely, we can't speak about of order of 90 % damages glass even for very large values of overpressure. This wave may shatter the glass on the front side of the building and some quantity on its lateral sides that is, only a maximum of 30 – 40 %. Thus, against a large set of diverse sources on the impact of the external shock wave on the glass was used one source, which concerns to a completely different phenomenon – to the internal explosion. And even this pressure data – 90 % at 3.5 kPa (that is, 30 – 40 % for the external «unilateral» wave) and 5 % at 0.7 kPa (that is 5/4 ~ 1 % under external influence) are strongly underestimated. And how much will be at 0.5 kPa at extrapolating in such case – zero or negative value? Can it not see all of this without closing of eyes specially?

The following section of this article gives the real data about damages of glass during low-altitude thermonuclear explosions at overpressure levels on shock wave of the order of 0.5 – 2 kPa. In Belushya Guba – the central settlement of Novaya Zemlya Nuclear Test Site – at the explosion of Tsar Bomba the overpressure on the wave was about of 1 kPa and all glass were completely intact. In the similar point «M» of Semipalatinsk Nuclear Test Site (now is the city of Kurchatov) the overpressure was not below 1.5 kPa after the explosion of RDS-37, and there isn't known anything about the broken glass in the most minimal quantities, while in surrounding Kazakh villages with several greater pressure levels some incidents have occurred (see below).

Nevertheless, the authors [7] have used the overpressure level of 0.5 kPa as a border of zone of broken glass and have received from this, as is shown below with very rough thirtyfold (!) mistake, that the energy of explosion isn't greater than 300 kt of TNT. Their desires and actions aren't clear in the case of reasonable and objective approach to the problem. And yet, they weren't able «to drag» into the zone of destruction some villages and settlements with broken windows. After all, apparently, not worth even mentioning that from 300 kt (or 500 kt?) of initial kinetic energy for the explosion would remain only about 100 – 150 kt of TNT. And the glaring discrepancy between the quantitative results presented in paper [7] and the reality constitutes up to 2 – 3 orders of magnitude.

We must add that after defined results of work [6], from which follows that the level of overpressure on the shock wave in the zone of Chelyabinsk zinc plant during the explosion of the meteoroid was 7 – 8 kPa, at least for this incident, the question has largely lost its sting and relevance, as these results should finally put everything in its place. Destroyed warehouse of zinc plant, collapsed supporting beam and curved several beams as well as destroyed cladding from the facade paneling in nearby Ice Palace «Urals Lightning» and several gates damaged in Chelyabinsk and in Yuzhnouralsk [1 – 4], are clear demonstrations of the reliability of these data from the paper [6].

V. Calculations of overpressure on a shock wave

We now define the overpressure on the shock wave. Obviously, that there are huge differences in the results of such calculations in papers [1 – 4] and [7], we should determine in which case the results of calculations correspond to reality. First, we will confirm that the method of calculation [1 – 4] leads to appropriate data. To do this, we will carry out the calculations of the overpressure on the shock wave with its help in a few cases where this parameter is determined experimentally and/or by other methods.

V. 1 – Verification of the method by calculating the parameters of three thermonuclear explosions

As mentioned earlier, the physical nature of the explosion plays a minor role in the formation and development of the shock wave. The explosion is any emission of a significant amount of energy in a time substantially less than the characteristic time of disturbances propagation in the near field of the process in a continuous medium. If the conditions, under which explosions occur, are the same, the perturbations (shock waves) propagating in the atmosphere regardless of whether it was a thermonuclear explosion, the entrance into the atmosphere of a celestial body or explosive volcanic eruption [16]. This is facilitated simplified («pin-point» and «quasi-static») consideration of explosive disintegration of celestial body in a software module of air explosion calculating of such process [5], which in this situation is no longer a disadvantage, but a kind of dignity, allowing to assess the impact on the underlying surface of any «air» explosions – from nuclear fusion up to volcanic eruptions. It is only necessary to calculate the entry of a «virtual meteoroid», decay of which leads to explosion with a given energy at a given height. This simple approximate semi-empirical module using «virtual meteoroids» can be used for assessing the impact on the underlying surface of explosions of any kind, provided that the distance at which the evaluation takes place is much larger than the size of the exploding object.

Using the results previously obtained in [2 – 4, 16], as well as the results of calculations carried out for the purpose of verification of the method, consider 6 actual events: the explosion of Krakatoa volcano, downfalls of Chelyabinsk and Tunguska meteoroids and 3 explosions of fusion devices. These include: AN602 (Tsar Bomba), RDS-37 (first Soviet two-stage thermonuclear charge, which has became the ancestor of all nuclear weapons USSR and Russia), as well as its American counterpart (in terms of construction, but not its importance for the U.S. nuclear arms) – Questa thermonuclear warhead, about explosion of which the author has learned a bit more than about other American nuclear explosions of the same power level. Its energy was close to the values of the explosion energy of Chelyabinsk meteoroid that are now attributed to it by most researchers of this phenomenon. Two examined Soviet thermonuclear devices are «cult objects» for the representatives of the Soviet nuclear industry, and, therefore, despite the secrecy of primary materials on these warheads, there are a large number of open sources, from which we can get all the information necessary for the verification with their help of method described in papers [1 – 4, 16].

In addition, that there are data about destructions (or lack thereof) for these three explosions of thermonuclear charges, these explosions are comfortable to assess the levels of pressure on the shock wave in some points on the ground by the fact that for their assessment as for any large low-altitude explosions, we may use the so-called Sadowski formula. It is the interpolation for the similarity parameter ξ of experimental data obtained, and it is a proven and widely accepted method for determining the overpressure on the wave of the explosion [30]:

$$\Delta p = a\xi^{-1} + b\xi^{-2} + c\xi^{-3}, \qquad \xi = RE_e^{-\frac{1}{3}}, \tag{1}$$

where Δp is the overpressure on the shock wave from the explosion with the energy E_e (that is, essentially, E_e is the equivalent mass of TNT) at some point, R is the distance from the center of the explosion to this point, and a, b and c are empirical coefficients.

This formula is valid for explosion in a homogeneous atmosphere. The characteristic scale of vertical heterogeneity of the Earth's atmosphere is about 8 km [30], therefore, strictly speaking, for particularly powerful explosions, such as, for example, the explosion of the volcano Krakatoa, to apply the formula, apparently, isn't possible. The height of the explosion H may influence the outcome only through increasing the radius R compared to the distance from the epicenter of L, so for low-altitude explosions one may use the Pythagorean Theorem, not taking into account the curvature of the Earth's surface. Despite all these limitations in applicability, the approximate formula (1) immediately reveals significant errors in more sophisticated calculations, if any.

The coefficients a, b and c represent values obtained by statistical processing of experimental data, and repeatedly corrected by the accumulation of information. Common values of these coefficients for spherically symmetric air explosions are those that have been obtained by M. A. Sadowski from experiments with TNT: a = 84, b = 270, c = 700 at mass of charge in kilograms, radius in meters and pressure in kilopascals (or when the «energy» E_e is measured in megatons of TNT and radius R – in kilometers). These coefficients were determined for $1 < \xi < 10$ (dimension of ξ is $m \cdot kg^{-1/3}$ or $km \cdot Mt^{-1/3}$), that is, approximately at 1 MPa > Δp > 10 kPa, which corresponds to the levels of overpressure in the main zone of destruction of buildings and structures, the most important for the military theory and practice.

However, these pressure levels are significantly higher than those, which are interesting to us in connection with the statistics of broken glass. Therefore, it is advisable to obtain the empirical coefficients a, b and c in the pressure range 8 kPa > Δp > 0.3 kPa. In addition, we are interested in parameters of thermonuclear explosions, and in this case to create a shock wave is spent only about half of the energy. Therefore, the coefficients in equation (1) must be reduced accordingly in order to take this fact into account [35]. But, on the other hand, the explosion for such values of ξ has semi-spherical symmetry. And its energy is distributed only in half-space, which the Earth's surface bounds from below. Due to this circumstance, the coefficients in equation (1) must be increased twofold for the explosion energy [30, 35]. The result is that the empirical coefficients, which are interesting for accurate approximation of the $\Delta p(\xi)$ in this range, in general, not change too much.

There is also the possibility to take into account height of the explosion. We can use the so-called generalized Sadowski formula [35]:

$$\Delta p = a\left(\frac{p}{p_0}\right)^{\frac{2}{3}}\xi^{-1} + b\left(\frac{p}{p_0}\right)^{\frac{1}{3}}\xi^{-2} + c\xi^{-3}, \qquad (2)$$

where p is the atmospheric pressure at the height of the explosion, p_0 is pressure at sea level. Apparently, the applicability of formula (2) for high-altitude explosions hasn't been tested seriously, but for estimates of low-altitude explosions it is quite possible to use.

In view of all these circumstances, we compared the calculated data obtained by the method of «virtual meteoroids» with approximations of Sadowski formula. The comparison was performed using the method of least squares in 9 control points – by 3 for each of the above 3 thermonuclear warheads. At first, the formula (1) with coefficients for air explosion of TNT, mentioned above was used. It was found that the standard deviation of overpressure calculated by these two methods was about 12.5 % (it should be noted that Sadowski formula was used outside its applicability).

In subsequent calculations formula (2) was used to account for the height of explosions, and empirical coefficients a, b, c were sought for the best approximation the results of the method of «virtual meteoroids». Pressure at the height of the explosion was determined by using interactive calculator of standard atmosphere [36]. In this case the standard deviation of the results has decreased by almost a factor of 2 – to 6.5 %, and the empirical coefficients in the range of $15 < \xi < 300$ (~ 8 kPa > Δp > 0.3 kPa) were as follows: a = 86.5, b = 285, c = 4900. That is, the parameters a and b have changed slightly, and only the coefficient c, which has the least influence on the result in this range of parameters, has increased markedly. However, the pressure themselves haven't changed more than a few percent, which can be seen from comparison of mean square deviations of two embodiments of discussed algorithm.

Table 1 shows: var is the variant of the calculation, E_e is the energy of warhead's explosion in megatons of TNT, H is the height of the explosion in kilometers, p is overpressure on the shock wave in kilopascals at a distance L from the epicenter, measured in kilometers along the ground and indicated in the column to the left of the column, where are presented the values of overpressure. Rows in the table are double – the first of the pair corresponds to the calculation of pressures with «virtual meteoroids» method based on interactive software module [5], the second (oblique fonts) – to assessment by Sadowski formula (2) with coefficients which values are given in the previous paragraph.

Table 1

var	E_e (Mt)	H (km)	L_1 (km)	p_1 (kPa)	L_2 (km)	p_2 (kPa)	L_3 (km)	p_3 (kPa)
RDS-37-1	1.6	1.55	54.5	1.7	61.5	1.5	175	0.48
RDS-37-2	*1.6*	*1.55*	*54.5*	*1.8*	*61.5*	*1.6*	*175*	*0.52*
Questa-1	0.67	1.60	24	3.5	47.5	1.6	55	1.3
Questa-2	*0.67*	*1.60*	*24*	*3.4*	*47.5*	*1.5*	*55*	*1.3*
AN602-1	58.0	4.20	53.5	7.5	267	1.0	810	0.33
AN602-2	*58.0*	*4.20*	*53.5*	*7.5*	*267*	*0.95*	*810*	*0.30*

From all the above follows that any adequate version of Sadowski formula in the pressure range 0.3 kPa < Δp < 8 kPa leads to difference with the calculations based on a «virtual meteoroids» mainly in the range near 10 %. The best agreement, of course, was obtained when the approximation coefficients were calculated according to the same area, in which the comparison is made, but the difference between the results of both options is slim.

Inter alia, the distances from the epicenter, shown in Table 1, almost for all points considered there (except one point of Questa), are such that we can make the estimations of overpressure on the wave there according to available experimental data. Let us describe their briefly.

RDS-37 (coordinates of the explosion at point P-5 of Test Field are 50.53º N, 77.75º E [37, 38]):

1. Range 54.5 km is the distance from the point P-5 to the village Maisky, in which by fragments of glass were injured part of the 26 people, which were victims in this and in neighboring somewhat more distant (up to 57 km) settlements [38]. In poor Soviet Kazakh villages certainly had enough not too well fixed or just cheap and very thin glass that could to be shattered and to injure of some people when the overpressure level on the wave was 1.7 – 1.8 kPa.

2. Range 61.5 km is the distance from the epicenter to the point «M» (where were lived the participants of nuclear tests), which is now called the city of Kurchatov. Nobody was wounded there at overpressure 1.5 – 1.6 kPa, but some damage to building elements was marked [38].

3. Range 175 km is the distance to the western suburbs of Semipalatinsk (now is Semey city). There, according to local authorities were broken glass and was 16 wounded [38]. As follows from the source [31], these accidents, probably, may be even at overpressure of about 0.5 kPa at the corresponding state of urban farming.

Questa (coordinates of the explosion – near 1.47º N, 157.20º W [39]):

1. Range 24 km is the distance from the epicenter to the nearest point of the coast of Christmas Island (now is named as Kiritimati). At level of the overpressure on the shock wave of 3.5 kPa one couldn't expect any noticeable loss for shrubs and thickets in inland lagoons of the island in this zone of the coast.

2. Range 47.5 – 55 km is the distance to the place of gathering of experiment participants (at airfield on the northern coast of the island), the state of which at the time is depicted in the photographs presented in [40]. It is quite consistent with the level of overpressure of about 1.3 – 1.6 kPa – all were standing firmly on their feet and didn't feel any problems when they were watching the explosion. Note that in Chelyabinsk during the stratospheric explosion supposedly with a half of this energy (according to opinion of authors of papers [6, 7]) and the same distances from the center of the explosion to the city center turned out more than 1,600 wounded [7]. If Questa would exploded at the altitude of 28.2 km, as well as Chelyabinsk meteoroid, the maximum pressure at such distances would be close to 0.2 kPa only.

AN602 (coordinates of the explosion at D-2 area of Novaya Zemlya Test Site are 73.85º N, 54.50º E [15]):

1. Range 53.5 km is the distance from the epicenter to township Lagerny (about 73.39º N, 54.74º E), which was built in the summer of 1955 on the southern shore of Matochkin Shar Strait in order to organize the resettlement of all hunters-fishers in Novaya Zemlya because of to the opening of Novaya Zemlya Test Site [31]. By the autumn of 1961 all the inhabitants of the township were evacuated, and the colony itself, built up of standard panel houses, was completely destroyed during the test of AN602 warhead October 30, 1961. «There remained only brick chimneys, and bath-house built by miners in 1959 of thick logs, on the bank of Shumilikha River» [41]. Then there was re-built township Severny (see the lower left edge of Fig. 3 [42]). It would seem that the calculated overpressure on the shock wave around 7.5 kPa (see the last two lines of Table 1) doesn't correspond to damages observed after the explosion. And indeed it is.

   Matochkin Shar Strait is a wide gap with the width of 2.3 km in the mountains with a minimum height of about of 600 – 700 m on its both sides. Axis of the strait here is substantially perpendicular to the direction of the shock wave from the explosion of charge AN602. Mountain ridge to the west of the township are cutting through a long and narrow valley of Shumilikha River, see Fig. 3 (talus, which is cutting off across the valley and located in the center of the image did not exist yet, it has emerged later as a result of one of the underground thermonuclear tests). Direct shock wave from the explosion at low-altitude (see [2 – 4]) on the northern slope of strait unfolded, became an oblique, and then it should to reflect itself irregularly from the water surface, forming a «Mach leg» [43] and above – the leading oblique shock wave. This oblique wave should act approximately normal to the slope of the southern shore of the strait, creating interference of impinging and reflected from the slopes of the southern shore of the strait shock waves. Moreover, the oblique reflection of these waves from the western slope of the valley of Shumilikha River (see the right edge of Fig. 3) with re-reflections from its eastern slope should to bring together the shock waves to the coast in the vicinity of the river mouth. Therefore, the real pressures at this mess of incident, reflected and re-reflected shock waves could be in several times greater than nominal level of the overpressure on the incoming wave.

Fig. 3

There may be indicated also that even for a much more simple case of interference of stationary shock waves, which are forming the so-called «bridge-like shock wave» – a structure consisting of two mirrored «Mach legs», was received on 6 – 7-fold increase of pressure [44]. And, author of this paper must say that approximately triangular in cross-section valley of Shumilikha River leads to association with the aerodynamic structure, in which was realized a «bridge-like shock wave». It seems that in Fig. 3 we can see the worst place of all possible locations for the construction of the settlement in Novaya Zemlya for air thermonuclear explosions at the D-2 zone (not counting, of course, this zone itself), so as the level of pressure of order of 30 – 40 kPa that we could easily expect in this place because of interference of waves from powerful thermonuclear explosions, what are very poorly contributes to preservation of ordinary residential houses. Only after the transition at this Test Site solely to underground explosions they could start here again for construction, that immediately was done.

2. Range 267 km is the distance from the epicenter of AN602 explosion to the main settlement of Novaya Zemlya Test Site – township of Belushya Guba and nearby located Rogachevo airfield. «In Belushye and Rogachevo everything was normal. No one was hurt in these garrisons and ships (at nominal overpressure of about 1 kPa it wasn't surprising – auth.), but from the stressful conditions of the explosion, several people were hospitalized» [41].

3. Range 810 km is the distance to the island and the township of Dixon. «With Dixon ... observation picket reported that the explosion was visible, and suddenly an air shock wave of small force came to there, and window glass was cracked in several houses. A day later, the restoration party had put in all the window glass – even the ones that were broken up before the test» [41]. Calculated overpressure on a shock wave was there about 0.3 – 0.35 kPa (see Table 1), which is below the lower limit of glass breakage. Perhaps some features of local topography, or art of building there contributed to the growth of pressure on the wave to the lower limit. But it is also possible that in Dixon they just used the emergency situation for unscheduled repairs of windows at the expense of test site.

On the whole from the examination of computational results of powerful low-altitude thermonuclear explosions we can conclude that the algorithm used in program [5] leads to fully adequate data that are in good agreement with the estimates on Sadowski formula, and with the effects observed in reality.

V. 2 – Verification of the method by calculating the parameters of three natural incidents

Let us consider now three natural disasters – thermal explosions of Krakatoa volcano and Tunguska and Chelyabinsk meteoroids. The coefficients in the generalized Sadowski formula (2) were obtained by fitting the data to low-altitude explosions, so the errors when they are using at high altitudes may be great, and 4 from 9 calculation points discussed below, are beyond the zone of the applicability of this approximation. So just let us compare the obtained results with the observed. Data are presented in Table 2; the parameters therein are completely analogous to those shown in Table 1.

Table 2

var	E_e (Mt)	H (km)	L_1 (km)	p_1 (kPa)	L_2 (km)	p_2 (kPa)	L_3 (km)	p_3 (kPa)
Krakatoa	1090	1.50	50	30.0	130	6.5	155	5.1
TM	14.4	8.25	20	30.0	30	15.2	64	4.9
ChM	56.8	28.2	0	11.1	39.5	7.5	80	5.0

Krakatoa (coordinates of the explosion are 6.10º N, 105.42º E [45]):

1. Range 50 km is the distance from the epicenter to the boundary of the zones of full tree-felling on flat terrain in the jungle on both sides of Sunda Strait (see [16]), that is up to the level of overpressure on the shock wave of 30 kPa.

2. Range of 130 km is the distance to the boundary of destruction area of window glass in fully and damage to the lungs tropical roofs and doors [16].

3. Range of 155 km is the distance to the European settlement in Batavia, where many windows were broken [16] that leads to the level of overpressure of about 5 kPa.

Note that the simultaneous use in calculation of three distances to the levels of certain overpressures on shock wave, which themselves were obtained, of course, with a certain tolerance, leads to cross-checking the accuracy of their determination. In addition, the adequacy of these results obtained for explosion of Krakatoa is confirmed with the aid of acoustic assessments [16].

Tunguska meteoroid (TM) (coordinates of the explosion are 60.89° N, 101.90º E [1 – 4]):

1. Range 20 km is the distance from the epicenter to the boundary of the zone of full tree-felling on flat terrain in the forest (see [1 – 4]), that is up to the level of overpressure on the shock wave of 30 kPa.

2. Range 30 km is the distance to the camp of two brothers Evenk, which became known to the researchers of Tunguska event. According to the testimony of these hunters, the shock wave destroyed their hut, threw them on the ground, and they were littered with the remains of the hut, but «they heard as trees were falling» [46]. It is known that the pressure level of 15 kPa is «the border of zone of numerous injuries from the fall» and fall «about of 30 % of trees» [28]. Typically, hunters know how to fall, and in general they are usually more prepared for the unexpected than the typical townsman, so that even the fall of one of the brothers into the hearth didn't result in serious injuries and burns, despite the fact that «the trees around were on fire».

3. Range 63.5 – 64 km is the distance from the explosion epicenter to the nearest village – a trading post for hunters, which is named Vanavara. Eyewitnesses, Vanavara residents, reported the following: «Then it turned out that many of the windows were smashed» [46]. This indicates on the level of the overpressure on the shock wave of about 5 kPa, which is consistent with the calculated value.

In addition to data about this incident, there is a good agreement between the calculated energy of the meteoroid explosion, which is E_e = 14.4 Mt [2 – 4], with the data obtained from seismograms – E_e = 12.5 ± 2.5 Mt and barograms – E_e = 12 ± 2.5 Mt [47], as well as the data about explosion heights – 8.25 km [2 – 4] and 8.5 km [48].

Chelyabinsk meteoroid (ChM) (coordinates of the explosion point are 54.87° N, 61.20° E), characterized from the previously discussed cases in that its explosion took place in the stratosphere, which leads to a qualitative difference from the explosions at low-altitude or in troposphere in effects on the underlying surface as long as the reflection of shock wave will not become irregular [2 – 4]:

1. Range 0 corresponds to a point on the ground directly below the center of the explosion. This place was located near the Pervomayskiy settlement in which overwhelming number of houses, according to satellite

images, has gable or hipped, not flat roofs. In this case, the real pressure from the explosion nearly to zenith decreases on the roofs significantly compared with the calculated of nominal value equal to approximately 11 kPa (see the value of p_1 in the last row of Table 2). The few high-rise houses of the settlement, roofs of which were flat, withstood also this overpressure that is not surprising, since the rated snow load only on the flat roof at a typical safety factor of 3 in the third – fourth snowy characteristic areas of Chelyabinsk region is 5.4 – 7.2 kPa [49]. And that's just one of the design loads for the roof. Due to the fact that the shock wave near the epicenter has moved generally parallel to the walls from top, the overpressure on them was significantly lower than the nominal and the number of broken glass there should not be too large [2 – 4], as was observed in reality [7].

2. Range 39.5 km is the distance to Chelyabinsk zinc plant, around which the overpressure on the shock wave was 7.5 ± 0.5 kPa [6]. Mach reflection is implemented at this distance to transform the oblique shock wave near the ground into a straight wave. It allows using the data on the broken glass from the area near zinc plant for comparison with the data from the low-altitude thermonuclear explosions [2 – 4].

3. Range 80 km is the radius at which the equivalent area of the circular zone is approximately equal to the area of real zone of broken glass in noticeable quantities [2 – 4].

Acoustic estimates also confirm the values of the explosion energy for both considered meteoroids [16].

Thus, the analysis of 6 catastrophic incidents has shown that the calculation module of air blasts [5], despite the simplicity of used model, describes their adequately and with an acceptable degree of accuracy. Therefore, it can be used to assess the adequacy of the results obtained by other methods.

V. 3 – Demonstration of parameters' inadequacy of Chelyabinsk meteoroid explosion received by hydrodynamic code SOVA

We will apply the method [5] in order to understand how the results of calculations by numerical hydrodynamic code SOVA [50], which was used in paper [7] for receiving of conclusion about explosion energy of Chelyabinsk meteoroid, corresponds to reality. In table 3 (the notation is the same as before) are presented calculation data for explosion of Chelyabinsk meteoroid made by authors of [7] – the energy yield is of 300 kilotons of TNT at the altitude of 31.7 km (Case 300-1). Data of explosion's version calculated by the «virtual meteoroids» method is shown under the same index, only with ending by 2 – Case 300-2. Despite the notoriously inaccurate use of the formula (2) for the explosion at such high altitude, the results of calculation option are demonstrated also for the generalized Sadowski formula with coefficients for explosion with the double diminishing of energy due to the doubling of space, in which shock waves are propagated (see [30]): a = 68.5, b = 180, c = 2450 (Case 300-3).

Table 3

var	E_e (kt)	H (km)	L_1 (km)	p_1 (kPa)	L_2 (km)	p_2 (kPa)	L_3 (km)	p_3 (kPa)
Case 300-1	300	31.7	0	2.6	25	2.1	50	0.95
Case 300-2	300	31.7	0	0.086	25	0.082	50	0.077
Case 300-3	*300*	*31.7*	*0*	*0.100*	*25*	*0.070*	*50*	*0.042*
Case 300-4	*300*	*0*	*0*	*–*	*25*	*2.0*	*50*	*0.96*
Case 500	*500*	*29.5*	*0*	*0.18*	*25*	*0.11*	*50*	*0.065*

Comparison of options computed for the height of the explosion 31.7 km shows that the overpressures on the shock wave, received with the aid of a numerical SOVA code, leads to an overestimation of this parameter in 12 – 30 times. Discrepancies between two other approximate methods at different points are amounting from 15 % to 45 % that was to be expected. But overall, the calculations by formula (2) confirm the pressure levels obtained by the method of «virtual meteoroids». Level of the overpressures on the shock wave, calculated using SOVA code, is obtained from the formula Sadowski only at zero altitude of explosion (see option Case 300-4). Other options of meteoroid explosions presented in [7] have the different distribution of energy along the trajectory that affects the shape of the destruction zone, but not on the level of pressure, which remains close to values of the Case 300-1. And we know not only from the formulas but from experience that «the shock wave is almost not formed» at the heights of the explosion of about 40 km and higher [30].

Moreover, there is a phenomenon called «breakthrough of the atmosphere». In an inhomogeneous atmosphere shock wave in moving up in the direction of the sharp decrease in the density not diminishes the speed and even is accelerated, and goes up to «infinity» in finite time. From huge cavity formed by explosion, air goes out into space. Pressure drops in the cavity to almost 0, and the motion of the shock wave down is stopped [51]. All of this occurs when the overpressure on the shock wave on the characteristic length of the inhomogeneity of the atmosphere (about 8 km for the Earth) is higher than the ambient pressure level on 2 orders of magnitude. At the same time the wave goes down during the breakthrough of the atmosphere only on the distance of about of two lengths of atmospheric heterogeneity [51]. Based on this theory estimates show that at the energy of the explosion of 57 Mt, as for Chelyabinsk meteoroid, the lower height limit of the atmosphere for such phenomenon is about 31.5 – 32 km. So the theory, which is more sophisticated than a simple approximation of the empirical data, shows that the explosion from the source [7] even with energy in two or more orders of magnitude greater could not produce any appreciable overpressure on the Earth surface.

The latest estimate in Table 3 of overpressure on the wave by the formula (2) – Case 500 shows the options for air explosion of a meteoroid from source [6]. Increasing the energy of the explosion to 500 kt and reducing its height by 2.2 km leads to the increase in pressure in the 1.5 – 1.8 times. However, nothing changes qualitatively; perturbation's level remains the same, and for the overpressure on the wave equal to 7 – 8 kPa at the distance of about 40 km from the epicenter (see Section 4 – «Airblast Damage – Measurements and Analysis» in the Appendix of the same work [6]) lacks two orders of magnitude of explosion energy.

Thus, we can see a huge discrepancy between the results of calculations of overpressure levels during the explosion of Chelyabinsk meteoroid presented in source [7], and reality. And, therefore, all the data about of energy of Chelyabinsk meteoroid in papers [6, 7] are also completely mythical. These inflated, at least on 1 – 1.5 orders of magnitude for the calculated overpressure, combined with reduced (in paper [7] only) at 0.5 – 1 order of data about broken glass, creating a completely distorted picture of phenomenon, in which the energy of the explosion lower than the actual more than 2 orders of magnitude And this time, in contrast to the estimates of the flash's brightness of Chelyabinsk meteoroid, we can no longer deny the adjustment of results to a predetermined value made by so-called Chelyabinsk Airburst Consortium – the evidences of this seem to be quite conclusive. At the same time, in source [6] such an obvious aim wasn't noticeable – apparently necessary estimates have not been made and estimates, which were made, have not been understood or proved to be erroneous.

VI. Mass of trail of Chelyabinsk meteoroid

Trail of Chelyabinsk meteoroid is another valuable source of information about it. The simplest thing we can do, examining photos of this trail, is to estimate its mass. Let's do it in this section of the work and let's compare mass of trail with the estimates of mass of the entire object in whole according to data from papers [6, 7].

In a homogeneous medium, in accordance with the Bouguer law the attenuation of directional radiation occurs exponentially with the dimensionless index of the exponent τ, called optical thickness of the medium [52]. Since in this case the optical thickness in the first approximation is related linearly to some basic physical parameters of its constituent particles, it is easy to link the optical and mass characteristics of this layer.

Optical thickness of aerosols τ, as is known, is defined as follows:

$$\tau = n\sigma D,$$

where n is the concentration of particles, σ is the section of interaction of aerosol particles, D is the layer thickness along the line of radiation. When considering the characteristics of the meteoroid trail in the optical range, the interaction section of the aerosol particle with a characteristic size of about 1 micron is equal to the cross sectional area of this particle.

The trail of aerosols arisen behind Chelyabinsk meteoroid, as seen in photo taken by weather satellite DMSP F-16 [53], in the first approximation was conical in shape, see Fig. 4.

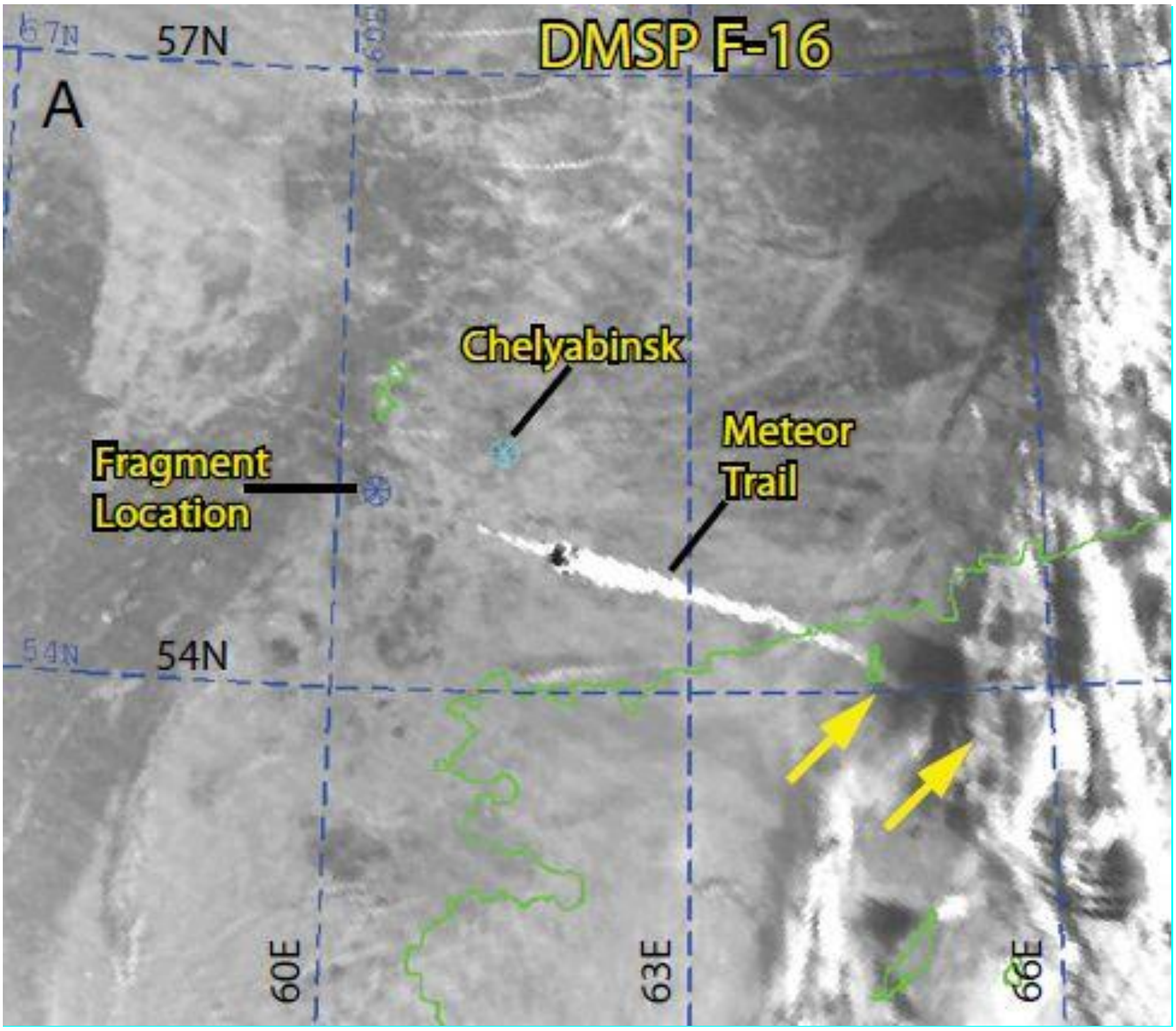

Fig. 4

Easy to estimate the number of particles in this trail:

$$N = \frac{\pi D^2 L n}{3},$$

where D is the average diameter of the trail, L is its length.

Then its mass m will be equal to:

$$m \approx \frac{2\pi\tau\rho D L d}{9}, \qquad (3)$$

where ρ is the average density of aerosol particles, d is mean diameter if they are spherical. If we know at least approximately the average density and size of aerosols, and evaluating of its optical thickness, according to the formula (3), we can easily calculate mass of matter, which is forming this trail.

However, before doing it for the trail of Chelyabinsk meteoroid, it is advisable to verify this procedure on a trail, characteristics of which are known much better. As such an object was selected the trail arisen in the initial phase of the trajectory of partially reusable space launcher Space Shuttle, see Fig. 5 [54].

Fig. 5

This trail is almost entirely composed of aerosols created by two solid-propellant boosters SRM, which are operated from start to a height of about 45 km. Through the slope of the trail at the top in Fig. 5 (the path angle to the horizontal is equal to 28º during the moment of separation of SRM's from Space Shuttle) we can conclude that this foto depicts a moment just before the booster's shutdown and in Fig. 5 the trail is seen almost entirely from the beginning to the end. From this photo we can also conclude that the optical characteristics of the trail are changed a little – a decrease in density due to the expansion of aerosol trail offset by an increase in its thickness, so that the formula (3), derived for the mean values of all variables, is well suited for estimations of this trail.

Full height of trail is 45 km, its length along the curved path $L \approx 75$ km (see [55]), the average thickness from Fig. 5 is $D \approx 0.7$ km. Mass of solid fuel contained in two SRM boosters, is 1.0 kt [56]. Three SSME – hydrogen-oxygen rocket engines operated in parallel with the SRM on the initial part of launch trajectory [57]. Because of the less engine thrust and greater specific impulse, three SSME emit into the atmosphere of about 0.15 kt of propellant, which consists almost entirely of water vapor with a small amount of hydrogen.

In paper [58] is described the chemical composition of the two-phase medium (gas and condensed substances) emitted from the SRM. It is showed two columns of Table 4 – in the first column is demonstrated the name of the substance, in the second – its mass fraction in the exhaust jet. Nitrogen, which is about 10 % of exhaust mass of SRM, is transparent and therefore is excluded from the substances responsible for the trail formation. Instead of, water vapors of SSME are added to the substances of SRM. As a result, the total mass of aerosols, created with all engines of this launcher on the path section from start to cutoff of solid-propellant boosters, was 1.05 kt, and the primary chemical composition of this combined exhaust is shown in the third column of Table 4.

Table 4

Substance	Fraction – SRM	Fraction – Space Shuttle	Fraction – trail	Density·10^{-3} (kg/m^3)	Volume fraction
Corundum	0.303	0.289	0.289	4.0	0.115
Soot	0.111	0.106	0.106	2.25	0.075
Water vapor – SRM	0.267	0.255	–	–	–
Water vapor – SSME	–	0.143	–	–	–
Hydrogen chloride	0.217	0.207	–	–	–
Nitrogen	0.102	–	–	–	–
Hydrochloric acid solution	–	–	0.605	1.18	0.81
Total	1.000	1.000	1.000	–	1.000

Hydrogen chloride and water vapor from the engine exhaust form immediately hydrochloric acid, and the mass fractions of the three main substances of Space Shuttle trail – corundum (Al_2O_3), carbon black (C) and a solution of hydrochloric acid (HCl) in the water (H_2O) at a concentration of about 35 % are shown in the fourth column of Table 4. Volume fractions of components of trail in accordance with their densities are shown in the last column of the table. So that, the trail of Space Shuttle in volume consists by more than 80 % out of hydrochloric acid droplets contaminated with dust of carbon and corundum. The average density of these droplets is about 1600 kg/m^3. The average size of aerosol emissions for solid-propellant rocket engines for 5 types of fuel formulation was approximately 0.50 micron (see [59]). However, most likely, these data refer to the ballistite, not mixed, like in SRM, powders.

Therefore, we may define all the parameters in the formula (3), and estimate the possible limits of their variations. To do this, it remains to find the level of the optical thickness of trail of Space Shuttle's exhaust. Consider another picture of its take-off on the background of clouds in Fig. 6 [60].

Fig. 6

Typical optical thickness of the clouds over the land is 30, over the sea is 20 [52]. Launch positions of Space Shuttle were located on the sea shore at Cape Canaveral. It can be seen that the trail is denser than clouds, so it is possible to estimate its optical thickness of not less than 25 – 30. We may possible to make another assessment – the trail is quite comparable with dense fog, for which the average visibility is about 0.1 km, which corresponds to the index of scattering σ_p = 39 km^{-1} [61]. With the average thickness of 0.7 km of jet and with such index of scattering, its optical thickness is found to be about 27.5, which does not differ from the foregoing assessment. Then, it follows from formula (3) that the average size of aerosols d = 0.65 microns. This is a good agreement with the estimate of the source [59], whereas at d = 0.50 microns the average optical thickness of the trail would be considered approximately equal to 35. So from all these argumentations we can conclude that the parameters of jet aerosols of rocket engines can be evaluated in terms of its optical characteristics literally «by eye» with an accuracy not less than 20 – 30 %.

Basing on this information, we will now consider the trail of Chelyabinsk meteoroid. There are photographs with candling by Sun's rays of these trails, see Fig. 7 – 9.

Fig. 7

In Fig. 7 we can see the well-known photograph where fairly dense shade from the trail of Space Shuttle is projected at sunset right on the Moon [57]. And about trail of Chelyabinsk meteoroid (see Fig. 8, [62]) we can only say that it was truly luxurious.

Fig. 8

However, analogous candling of trail of Chelyabinsk meteoroid at sunrise clearly indicates that its optical thickness (see Fig. 9, [63]) is actually in many times lower than for the trail of Space Shuttle. But it is superior the latter by a half of the order in length, and more than an order of magnitude in the transverse dimensions.

Fig. 9

Taking into account the portion of the trail, formed after the explosion, we can estimate that its length can be at 10 km longer than the length from the beginning to the point of explosion that was about 210 km [53]. The average width of the trail from Fig. 4 was about 10 km. Since it was formed from silicate (chondrites) dust, the density of this dust was 3300 kg/m^3 [7]. Professional astronomer-observer has concluded from Fig. 6 that the optical thickness of the trail of Chelyabinsk meteoroid was a few less than 10 [64]. Based on the successful assessment made for the trail of Space Shuttle, we will assume that Chelyabinsk trail is comparable to a light haze, for which the average visibility is about 6 – 6.5 km, which corresponds to the index of scattering $\sigma_p \approx 0.6$ km^{-1} [61]. Then, when the average thickness of the trail is 10 km, its optical thickness isn't less than 6, what is consistent with what was determined from Fig. 9. So, we suggest for the trail of Chelyabinsk meteoroid estimations that $6 \leq \tau < 10$.

Then, for the average diameter of aerosols such as in the trail of Space Shuttle, it turns out that the mass of silicate meteoroid trail can't be less than 20 kt. However, we should note that aerosols of Shuttle's trail are condensed in tiny drops of hydrochloric acid formed after combustion, mainly, of SRM solid fuel. In such processes of condensation and coagulation are formed micro particles with size of about of 0.5 – 1 microns [65]. In the formation of the trail of stone (silicate) meteoroid or snow-ice meteoroid covered by silicate crust, this trail is the result of thermo-mechanical erosion of its surface. Researches of silicosis indicate, that the typical size of dust in a more or less similar production processes is usually not less than 1 – 2 microns [66].

Then, by formula (3) turns out that the minimum mass of the trail of Chelyabinsk meteoroid at $\tau = 6$ and d = 0.65 microns was 20 kilotons. When d = 1.0 microns, mass of this trail is already about 30 kt. At the same time the most part of known mass estimations of Chelyabinsk meteoroid during entering to the atmosphere was allegedly no more than 10 – 15 kt, for example, in paper [6] – 13 kt), and the greater part of the order of 7 – 10 kt was to remain up to the point of explosion, to ensure the energy at least at the level of 300 – 400 kilotons of TNT. Scattered, «burnt» and converted in the explosion meteoroid material isn't included in the trail. Then, in the trail was in 5 – 10 times more material than could give the object of such type, which is described in most articles on Chelyabinsk meteoroids, including papers [6, 7]. Therefore, the data on the explosion energy of the meteoroid come into an insoluble contradiction with the data on the mass of its trail. But if the mass of Chelyabinsk meteoroid was 1.8 – 1.85 Mt, the trail mass of 20 – 30 kt was only about 1 – 1.5 % of the original mass of the object, and couldn't be any contradiction between these characteristics.

VII. Discussion of results

Thus, the consideration of the conception describing the input to the atmosphere and the explosion of Chelyabinsk meteoroid, started in agiotage and haste [9 – 11] and continued by most researchers in the same vein, demonstrates clearly and obviously that this conception – fall of chondrite meteoroid, size of which was about 15 – 20 meters, mass was 10 – 15 kilotons and explosion's energy – of about 300 – 500 kilotons of TNT [6, 7], is not consistent with those phenomena that were observed in the atmosphere and on underlying surface. This is elementary proven with using of infrasonic data, with levels of overpressure on the shock wave in Chelyabinsk and the surrounding areas, on broken glass, as well as by mass of trail of Chelyabinsk meteoroid. It is also shown that the estimates of brightness of its flash were conducted in such a way that they can't be the basis for any definite conclusions.

But the data from papers [6, 7] carried out by large groups of investigators, of course, are valuable sources of primary information, which isn't yet distorted by this erroneous conception. And the correct interpretation of collected data is one of the foundations on which the adequate theoretical description of this extraordinary phenomenon is constructed.

Conclusions

1. The proximity of the maximum path lengths of infrasonic waves from the stratospheric explosion of Chelyabinsk meteoroid and from the largest in the history thermonuclear explosion of Tsar Bomba – AN602 warhead produced in the troposphere, clearly indicates the closeness of the energies of these phenomena (as is known, the explosion energy of AN602 warhead was about 58 Mt of TNT).

2. Flash brightness estimations of Chelyabinsk meteoroid were conducted in such a way that they can't be the basis for any definite conclusions about the energy of this explosion.

3. Shattered glass in Chelyabinsk and its surroundings, broken gates, warped supporting beams in Ice Palace «Urals Lightning» and destroyed warehouse of zinc plant correspond to the level of overpressure on the shock wave, at least to a few kilopascals (7 – 8 kPa at a distance of about 40 km from the epicenter according to the paper [6]).

4. As shown by calculations carried out in various ways, such pressure level for the height of the explosion, which was observed during this incident, can only provide the explosion with energy of about 50 – 60 Mt of TNT, which is 2 orders larger than the initial kinetic energy of meteoroid with size of 15 – 20 m and mass of 10 – 15 kt before entering the atmosphere.

5. The estimations of the trail mass created by Chelyabinsk meteoroid leads to a level of not less than 20 – 30 kt, which is also contrary to the hypothesis about this meteoroid as the object with mass of 10 – 15 kt, especially given the fact that for its explosion, even with the energy, which was declared by supporters of erroneous conception, should be spent not less than ⅔ of initial mass.

6. The destruction in the atmosphere of snow-ice fragment of comet, which was contaminated by chondrites, with the mean density of about 570 kg/m^3, the size 180 – 185 m, the mass of about 1.8 Mt and 57 Mt of TNT of the explosion energy corresponds to all phenomena during the incident over Chelyabinsk.

7. Meteorites found on ground are pieces of the surface crust of this cometary fragment. This crust was dispersed and vaporized in most part under the action of powerful explosion. The chondrite crust had formed by ablation of meteoroid material under the influence of solar radiation during numerous flybys around the Sun.

References

1. Yu. I. Lobanovsky – Parameters of Chelyabinsk and Tunguska Objects and their Explosion Modes. *Arxiv.org*, July 08, 2013, pp. 1–13 // http://arxiv.org/abs/1307.1967
2. Yu. Lobanovsky – Refined Parameters of Chelyabinsk and Tunguska Meteoroids and their Explosion Modes. *Arxiv.org*, March 28, 2014, pp. 1–12 // http://arxiv.org/abs/1403.7282

3. Yu. I. Lobanovsky – Parameters of Chelyabinsk and Tunguska Meteoroids and Revaluation of Level of Celestial Bodies' Threat. *XL Academic Space Conference, dedicated to the memory of academician S. P. Korolev and other outstanding national scientists – pioneers of space exploration*, January, 2016 (in Russian)
4. Yu. I. Lobanovsky – Parameters of Chelyabinsk and Tunguska Meteoroids. *Synerjetics Group*, February 15, 2016 // http://www.synerjetics.ru/article/objects_3_eng.htm
5. R. Marcus, H. J. Melosh, G. Collins – Earth Impact Effects Program. *Imperial College (London), Purdue University* // http://impact.ese.ic.ac.uk/cgi-bin/crater.cgi?dist=20&diam=17&pdens=1000&pdens_select=0&vel=18&theta=30&tdens=&tdens_select=3000
6. P. G. Brown et al. – A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors. *Nature Letter*, **503**, no. 7475, 14.11.2013, pp. 238–241 // http://www.nature.com/nature/journal/v503/n7475/full/nature12741.html
7. O. P. Popova et al. – Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization. *Science*, **342**, no. 6162, 29.11.2013, pp. 1069–1073 // https://www.sciencemag.org/content/342/6162/1069
8. Yu. I. Lobanovsky – Chelyabinsk Meteoroid: Critique of Sources and Proving of Conclusions. *XL Academic Space Conference, dedicated to the memory of academician S. P. Korolev and other outstanding national scientists – pioneers of space exploration*, January, 2016 (in Russian)
9. Russia Meteor Not Linked to Asteroid Flyby. *JPL, Caltech, Latest News*, 15.02.2013 // http://www.jpl.nasa.gov/news/news.php?release=2013-061
10. W. Cooke – Why wasn't the Russian Meteor detected before it entered the Atmosphere? NASA News, Watch the Skies, 20.02.2013 // https://blogs.nasa.gov/Watch_the_Skies/2013/02/19/post_1361308690869/
11. K. Allen – Chelyabinsk fireball: Canadian scientists still sizing it up. *Thestar.com, World*, 12.04.2013 // http://www.thestar.com/news/world/2013/04/12/chelyabinsk_fireball_canadian_scientists_still_sizing_it_up.html
12. O. Dobrovidova – From Chelyabinsk with Love: How Meteorite was discussed in America. *RIA-Novosti*, Science, April 15, 2013// http://ria.ru/science/20130415/932637522.html (in Russian)
13. IMS Infrasound Network. *DTRA Verification Database* // http://www.rdss.info/infrastat/network/map.html
14. A. Le Pichon, L. Ceranna et al. – The 2013 Russian Fireball largest ever detected by CTBTO infrasound sensors. *Geophysical Research Letters*, **40**, issue 14, 28.07.2013, pp. 3732–3737 // http://onlinelibrary.wiley.com/doi/10.1002/grl.50619/abstract
15. Tsar Bomba. *Wikipedia* // http://en.wikipedia.org/wiki/Tsar_Bomba
16. Yu. I. Lobanovsky – Acoustic Methods for Evaluation of High Energy Explosions. *Arxiv.org*, November 26, 2013 – March 06, 2014, pp. 1–8 // http://arxiv.org/abs/1311.6565
17. D. Yeomans, P. Chodas – Additional Details on the Large Fireball Event over Russia on Feb. 15, 2013. *Near Earth Object Program, NASA*. 01.03.2013 // http://neo.jpl.nasa.gov/news/fireball_130301.html
18. P. Brown, R. Spalding et al. – The Flux of Small Near-Earth Objects Colliding with the Earth. *Letters to Nature*, **420**, 2002, pp. 294–296 // http://www.nature.com/nature/journal/v420/n6913/full/nature01238.html
19. V. Litovka – Strange disk reflected in the river. *Ukraine anomalous* // http://ufodos.org.ua/photo/ufoinukraine/strannyj_disk_otrazhaetsja_v_dnepre/2-0-509 (in Russian)
20. E. Schneider – Cameras of machine vision and IP-cameras: the optimal combination for intelligent transport systems. Security Technology Forum International // http://www.secuteck.ru/articles2/videonabl/kamery-mashinnogo-zreniya-i-ip-kamery-optimalnoe-sochetanie-dlya-intellektualnyh-transportnyh-sistem (in Russian)
21. D. R. Williams – Sun Fact Sheet. *NASA Goddard Space Flight Center*. 01.07.2013 // http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html
22. Kherson, Potemkin Small Island // http://khersonphoto.blogspot.ru/2013/07/Herson-Malyj-Potemkinskij-ostrov.html (in Russian)
23. Reflectivity. *Wikipedia* // http://en.wikipedia.org/wiki/Reflectivity
24. Resident of Troitsk unveiled a sensational video with an explosion of the meteorite a year later. OTV, First regional // http://www.1obl.ru/news/eto-interesno/sensatsionnoe-video-so-vzryvom-meteorita-spustya-god/?sphrase_id=3112063 (in Russian)
25. K. Bagirova – Meteorite in Troitsk. *YouTube* // http://www.youtube.com/watch?feature=player_embedded&v=3yEei1bDNeo
26. Glass and glazing for plastic windows. Ekookna // http://ecookna.com.ua/articles/steklo/ (in Russian)
27. M. S. Vasil'ev, M. A. Komova, G. A. Prytkov – About Fire Safety. Textbook, Emergency Situations Ministry of RF, 2003, 181p. // http://www.pandia.ru/text/77/168/15165.php (in Russian)
28. Atmospheric Nuclear Explosion. *Wikipedia* // http://ru.wikipedia.org/wiki/Атмосферный_ядерный_взрыв (in Russian)

29. V. R. Mirgorodsky – Life Safety. Section III. Protecting print objects in an emergency. Moscow State University of Press, Lectures // http://www.hi-edu.ru/e-books/xbook074/01/index.html?part-001.htm (in Russian)
30. Physics of Explosion, ed. L. P. Orlenko, vol. 1. Moscow, Fizmatlit, 2002, 832 p. // http://padabum.com/d.php?id=20818 (in Russian)
31. E. A. Shitikov – Create polygon on Novaya Zemlya. In the book: USSR Nuclear Tests, vol. 1. VNIIEF, 1997 // http://www.wsyachina.narod.ru/history/testing_ground_23.html (in Russian)
32. S. Glasstone, P. J. Dolan – The Effects of Nuclear Weapons. U.S. Department of Defense, U.S. Department of Energy, Washington, 1977, 657 p. // http://www.deepspace.ucsb.edu/wp-content/uploads/2013/01/Effects-of-Nuclear-Weapons-1977-3rd-edition-complete.pdf
33. S. Mannan, F. P. Lees – Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, 3rd edition. Elsevier Butterworth-Heinemann, 2012, 3642 p.
34. V. I. Binenko, Г. N. Chramov, V. V. Yakovlev – Emergencies in the modern world and the problems of safety. St. Petersburg, 2004, 400 p. // http://mchs.gov.by/_modules/_cfiles/files/ips_15.10.2010_.pdf (in Russian)
35. G. I. Pokrovsky – Explosion. Moscow, Nedra, 1980, 180 p. // http://bookre.org/reader?file=475855 (in Russian)
36. 1976 Standard Atmosphere Calculator // http://www.digitaldutch.com/atmoscalc/
37. Semipalatinsk Nuclear Test Site. *Wikipedia* // http://ru.wikipedia.org/wiki/Семипалатинский_ядерный_полигон (in Russian)
38. V. N. Mikhailov, ed., USSR Nuclear Tests. Volume 1: Aims. General Characteristics. Organization of the USSR Nuclear Tests. The First Nuclear Tests. Sarov, VNIIEF, 288 pp. (1997) (in Russian)
39. Operation Dominic 1962. *Janes's Oceania Home Page* // http://www.janeresture.com/christmas_bombs/operation_dominic_1962.htm
40. Christmas Island Bomb Tests. Picture Gallery 1. *Operation Dominic 1962* // http://www.janeresture.com/christmas_bombs/picture_gallery1.htm
41. G. G. Kudryavtsev – Memories of Novaya Zemlya. *Sundries*, 16.12.1992 // http://www.wsyachina.narod.ru/history/testing_ground_26.html
42. Google-Earth // https://maps.google.ru/maps?hl=en&tab=wl
43. Fundamentals of Gas Dynamics, ed. H. Emmons. Princeton Univ. Press, 1958, 784 p.
44. V. V. Keldysh, Yu. I. Lobanovsky – Some Features of three-dimensional Flows with Bridge-like Shocks. *Proceedings of TsAGI*, **7**, N 5, 1976, pp. 1–8 // http://cyberleninka.ru/article/n/nekotorye-osobennosti-prostranstvennyh-techeniy-s-mostoobraznymi-skachkami-uplotneniya (in Russian)
45. Krakatoa. *Wikipedia* // http://en.wikipedia.org/wiki/Krakatoa
46. V. Bronshtein – Meteors, Meteorites, Meteoroids. Chapter 4. Tunguska Meteorite. Moscow, Science, 1987, 173 p. // http://tunguska.tsc.ru/ru/science/1/BronstenMMM/Glava4/ (in Russian)
47. A. Ben-Menahem – Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations. *Physics of The Earth and Planetary Interiors*, **11**, no. 1, 1975, pp. 1–35 // http://65.54.113.26/Publication/40382391/source-parameters-of-the-siberian-explosion-of-june-30-1908-from-analysis-and-synthesis-of
48. V. Svetsov, V. Shuvalov – Tunguska Catastrophe of 30 June 1908. *In Book: Catastrophic Events Caused by Cosmic Objects*. Springer, 2008, 361 p. // http://confessedtravelholic.com/doc/download-ebook-Catastrophic-Events-Caused-by-Cosmic-Objects-pdf-amazon-304051.html
49. SNiP 2.01.07-85. Loads and impacts, 88 p. // http://www.alientechnologies.ru/docs/snip-2-01-07-85.pdf (in Russian)
50. V. V. Shuvalov – Multi-dimensional hydrodynamic code SOVA for interfacial flows: Application to thermal layer effect. *Shock Waves*, **9**, 1999, pp. 381–390.
51. Ya. B. Zel'dovich, Yu. P. Raizer – Physics of shock waves and high-temperature hydrodynamic phenomena/ Moscow, Nauka, 1966, 688 p. // http://www.twirpx.com/file/46551/
52. K. S. Shifrin – Optical thickness. *Physical Encyclopedia* // http://www.physicum.narod.ru/vol_3/443.pdf
53. S. D. Miller et al. – Earth-viewing satellite perspectives on the Chelyabinsk meteor event. *PNAS*, **110**, no. 45, 19.09.2013, pp. 1–6 // http://www.pnas.org/content/early/2013/10/15/1307965110.full.pdf+html
54. Student Balloon Photographs Shuttle Endeavour's Launch Into Orbit. SPACE.com Staff, 16.05.2011 // http://www.space.com/11683-shuttle-endeavour-launch-balloon-photos.html
55. Space Shuttle Launch Trajectory – I. *Space Math*, pp. 1–2 // http://spacemath.gsfc.nasa.gov/Calculus/5Page40.pdf
56. SRM Engine // http://wmpt.narod.ru/tt8.htm (in Russian)
57. Space Shuttle. *Wikipedia* // http://en.wikipedia.org/wiki/Space_Shuttle
58. Yu. I. Lobanovsky – Conservation Laws and the Phenomenology of Rocket Engines. *Synerjetics Group*, 30 June, 2008, pp. 1–21 // http://www.synerjetics.ru/article/rocket_engines.htm (in Russian)

59. M. P. Musyakov, I. D. Mitsenko, G. G. Vaneyev – Problems of laser location at short distances. Moscow, Publishing House MSTU named after Bauman, 2000, 296 p. // http://www.ozon.ru/context/detail/id/113012/ (in Russian)
60. Our Strange Sky: The Many Views of Endeavour's Last Launch: APOD's Space Shuttle Rising Tribute // http://www.groonk.net/blog/2011/05/our-strange-sky-the-many-views-of-endeavours-last-launch/
61. D. N. Zubarev – Transparency of Earth's atmosphere. *Physical Encyclopedia*, pp. 135–137 // http://www.physicum.narod.ru/vol_4/137.pdf (in Russian)
62. Meteorite explosion in the sky over Chelyabinsk («Chelyabinsk» meteorite). Full foto-report with comments // http://marateaman.livejournal.com/27910.html (in Russian)
63. Trace of meteoroid. *Miracles and Adventures* // http://chudesamag.ru/wp-content/uploads/2013/04/Meteorit-Miass-32.jpg (in Russian)
64. Yu. V. Pakhomov – Private message, 12.12.2013.
65. Investigation of the processes of evaporation and condensation of liquid droplets, pp. 1–10 // http://ref.rushkolnik.ru/v3608/ (in Russian)
66. Pathogenesis and clinic of basic pneumoconiosis. *Occupational Health*, pp. 1–13 // http://userdocs.ru/medicina/138729/index.html?page=4 (in Russian)

15 February 2016 Yu. I. Lobanovsky