Historical Evidence of Recent Impacts on the Earth

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Global Planetary or Regional Defense Systems using any method to disrupt or (and) deflect small asteroids and comets needs information on their characteristics to predict the result. If the cosmic body is disrupted into small fragments, a new question arises: will these chunks reach the Earth's surface or explode at some altitude above the ground? Observations of current impacts of large meteoroids into the atmosphere both by ground based and satellite based networks give information on characteristics of impacting bodies (e.g. mass, energy, strength, structure, shape, density, composition) and on atmospheric interaction processes (ablation, luminosity, fragmentation, dispersion of fragments etc.). Such information has already been obtained for rather large meteoroids (up to several meters in size and energies up to 10-40 kt TNT). Space based infrared and optical sensors have detected over 200 meteoroid impacts since 1972. 16 light curves in visible have been obtained by optical sensors, mainly the last year. Special theoretical techniques have been developed for the analysis of these data.

Our definition of recent impacts is not very strict. We shall speak about the events that happened as long ago as 10 to 50 thousand years, or this century (after the Tunguska event of 1908), or last 25 years, when satellite observations have begun, and even last year, when systematic survey of satellite observations has started and a large number of events has been registered.

As the duration of the observations is not very long and large impactors are rather rare, our analysis is restricted to cosmic bodies with sizes from 30-100 m down to about 0. 1-1 m.

Sometimes these bodies are named "large meteoroids" or "small asteroids". Such bodies are studied using Spacewatch system (Scotti et al. , 1991; Rabinowitz et al., 1993; Carusi et al., 1994). These observations give us information on the current population of the near Earth objects, mainly on the objects with sizes of about 100 m and larger, though very small asteroids have been detected at small distances from the Earth. But using only telescopes we cannot obtain such important characteristics of these objects as their strength and composition.

Investigation of small lunar craters on the airless Earth's Moon (Neukum and Ivanov, 1994), with the diameters 10 m and larger, allows us to determine the size-frequency distribution of small objects, but only averaged over a very large period of time.

There are other clear signatures of such impacts, i.e., small craters on the Earth and atmospheric effects during the meteoroid's entry. Let us explain why we are interested in the observations of rather small objects, while the main goal of the Workshop is hazards and mitigation of hazards.

First, impacts of bodies with sizes close to the upper limit of the investigated range (30-100 m) may cause local and even regional catastrophes (Adushkin and Nemtchinov, 1994). Our analysis may give important information on structure, composition, strength of the bodies with the sizes only one or two orders of magnitude less than those which may cause catastrophes. Extrapolating the size-frequency distribution, we can obtain probabilities of such dangerous impacts. This information is important for prediction local and regional catastrophes and for investigation ways of mitigation.

Second, trying to defend the Earth from the impacts of these or even larger objects, i.e. 1 km in size or bigger, we may disrupt them into a cloud of fragments with smaller sizes. At least some of the fragments may hit the Earth, and we should know what will be the consequences.

Third, large meteoroids or small asteroids are probably least investigated bodies in the Solar System and their investigation is important from purely scientific reasons. There are other reasons, but these three are enough to justify our analysis.

In Table 1 (data are mainly from Grieve and Shoemaker, 1994) are given sizes of the craters, energy of the impactors hitting the Earth, and the approximate age. The largest (1 km in diameter) is the famous Meteor crater in Arizona. Recently (in 1992) another one has been discovered (1×3 km). It has been created about 10,000 years ago near Rio Cuarto, Argentina, and the impactor energy estimates are 350 Mt TNT (Schultz and Lianza, 1992).

Table 1.

	Time of formation, years	N	d, (m)	E, (kt TNT)
Meteor Crater, Arizona	~ 25000	1	1200	15000
Wolf-Creek, Australia	< 300,000	1	853	5000
Winkler, Kansas, USA		1	750	800
El Mreiti, Mauritania		1	700	650
Monturaqui, Chile	~ 1,000,000	1	455	110
Aouelloul, Mauritania	3, 100,000	1	390	20
Macha, Russia	<7, 000	1	300	15
Herault, France		7	217	10
Labrador, Canada		1	210	10
Gourmac, Mali		1	200	10
Boxhole, Australia	30,000	1	175	5
Henbury, Australia	4, 200±1, 900	14	220*110	4-5
Odessa, Texas, USA	~ 25,000	5	168	4
Kaalijärv, Estonia	~ 5,000	9	110	1.5
Wabar, Saudi Arabia	6, 400±2, 500	4	91	0.8
Campo Del Cielo, Argentina	< 4, 000	20	90	0.8
Ilumetsa, Estonia	> 2, 000	1	80	0.6
Veevers, Australia	< 1,000,000	1	80	0.6
Morasko, Poland	10,000	8	60	0.3
Sobolev, Russia	< 1,000	1	53	0.18
Sikhote-Alin, Russia	12 Feb. 1947	23	26	0.014
Dalgaranga, Australia	27,000	1	21	0.012
Haviland, Kansas	< 1, 000	1	15	0.010
Sterlitamak, Russia	17 May 1990	1	9	0.001

The smallest one is the Sterlitamak crater. The Sterlitamak event happened only 5 years ago, confirming that the Earth is still being bombarded and cratered. A very significant Sikhote-Alin event happened on 12 February 1947, almost 50 years ago. We have estimated that the preatmospheric energy of the iron body was 10 kt TNT, mass was 500 tons. About 99% of the energy have been released in the atmosphere, but 20% of mass have reached the ground, about 100 tons is in the strewn field. 27 tons have been really found as meteorites. Biggest fragments created rather large craters (up to 26 m in diameter). Large trees have been fallen around these craters. Geologists who have observed the strewn crater field (many of them have just returned from the World war II) said that the region of large craters resembled typical battlefield after the heavy military bombardment. The size of this heavily damaged region is 300×300 m (Krinov, 1981).

Counting craters discovered on the Earth we may severely underestimate the number of impacts and hazards which may be caused by these impacts. First, a large part of the surface of the Earth is covered by water of seas and oceans. In that case the impacting body creates unstable crater in the water which soon collapses and disappears. But impacts into oceans and seas may be very dangerous as they cause tsunami (Hills and Goda, 1993; Hills et al., 1994; Nemtchinov et al., 1994). Second, analyzing Table 1, one can see that craters are rather young and a large number of them is found in deserts or semideserts. This is due to the fact that scars on the Earth's surface are healed rather quickly, especially in the regions with wet climate. For instance, Sikhote-Alin crater field was created in the region with rough terrain, but it had been easily found from the airplane three days after the impact. Now even the largest craters are screened by trees in the taiga.

Third, we have already mentioned that energy which was released by fragments of the Sikhote-Alin iron meteoroid on the Earth's surface is only about 1% of the preatmospheric kinetic energy. In the case of the iron Arizona meteoroid it is almost 100%, but Tunguska meteoroid (there is still a controversy was it a comet or a stony body) with approximately the same initial energy has not created any crater at all. The Tunguska airblast might have caused demolishion of a big city, but happily it occurred in an almost inhabitant region.

Do cosmic bodies continue to fall? Yes, they do. A daylight bolide, 1972, grazing incidence, flew over the US and Canada and finally left the Earth with almost the same velocity of about 15 km/sec (Ceplecha, 1994). A minimum distance from the Earth was about 58 km. Another meteoroid of 1990 also left the Earth with only a slightly diminished velocity (42 km/sec) (Borovička and Ceplecha, 1992). But if the trajectory is steep, a meteoroid release all its energy in the atmosphere or even hit the ground.

As an example, a powerful bolide has detonated recently in 1993 over Italy (Korlevic, 1994; Cevolani, 1994).

A small fragment of Peekskill meteoroid hit a car (Brown et al., 1994). But these fragments may be much larger in mass. Several meteorites recently have been found near Montreal with the total mass of about 25 kg (Brown et al., 1995). They were the remnants of a meteoroid which has been detected in flight by a large number of eyewitnesses in USA and Canada and by a satellite.

Space based infrared and optical sensors operated by the United States Department of Defense have detected over 200 bright flashes in the atmosphere since 1972. These intense light impulses were caused by impacts of large meteoroids. The bright flash arises from energy released upon explosive disintegration due to action of aerodynamic forces. Usually meteoroids deposite their energy at high altitudes above the Earth's surface, mainly at altitudes of 30 to 45 km. But some of them penetrate the atmosphere to altitudes of about 20 km.

A relatively small number of satellites at high altitude orbits (20,000 km or higher) provide coverage of most of the Earth's surface. It is possible to have essentially continuous, day and night, all weather detection of meteoroids over the entire surface of the Earth (Tagliaferri et al., 1994).

Meteoroid fireballs detected by infrared radiation sensors, as it would be expected, are rather randomly distributed worldwide. Average number per year is about 30.

In addition, visible radiation sensors have recorded light curves for a subset of these events (Jacobs and Spalding, 1993; Tagliaferri et al., 1994).

Several techniques for the assessment of the meteoroid characteristics from the light curves have been developed (Nemtchinov et al., 1994, 1995; Golub' et al., 1995).

Radiation-hydrodynamic 1D, 2D and even 3D numerical simulations of the flight in the atmosphere of meteoroids with different sizes, velocities, heights of flight have been conducted. They were based on detailed tables of spectral opacities for hot air and ablated material of meteoroids (iron, H-chondrites, cometary material) which have been calculated by us for a wide range of temperatures, densities and wavelengths. As an example, in Fig. 1 spectral absorption coefficients for H-hondrite are given.

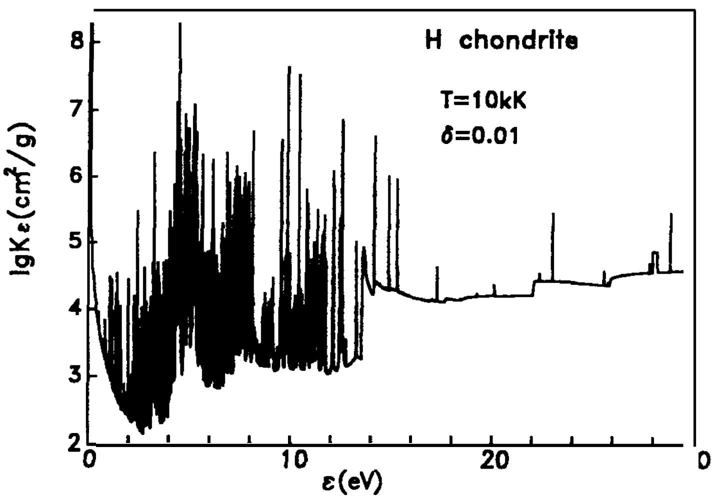

Figure 1. Absorption coefficient K_ε versus photon energy ε.

Equations of radiative transfer have been solved for as much as 10,000 wavelengths (or photon energies) both in air and in the vapor of meteoroid. An amount of meteoroid's energy released in the atmosphere, radiation emitted, and spectrum of radiation have been obtained. This is important because the visible sensors are spectrally selective while a spectrum substantially differs from that of a blackbody, and changes with size, velocity and altitude of flight.

The results of a large number of numerical simulations are the tables of ablation coefficients and luminous efficiencies for different velocities, sizes, altitudes of flight, and composition. They are given for an iron body in Golub' et al. (1995).

Velocity versus time and altitude can be determined from the usual equations of meteoroid's motion, deceleration and ablation. Companion burst-locating sensors can detect an altitude of peak intensity of large events. For some fraction of small events infrared sensors can provide the location of cloud of debris (Tagliaferri et al., 1994).

Intensity of light is proportional to the cross-sectional area and luminous efficiency. Comparing the observed intensity of light with theoretical values for different sizes of the body, we can estimate the effective instantaneous size of the body and can follow an increase of the size of the cloud of fragments after the meteoroid's breakup and rotation of the body which causes the variations of cross-section.

The results of simulations for the 4 October 1991 event are given in Fig. 2. Here the effective radius of the body is the solid curve (1), and a radius calculated by two different models (Hills and Goba, 1993; Chyba et al., 1993) is the dashed and dotted curves (2,3). At high altitudes the radius does not change in time. At an altitude of 40 km the radius begins to grow, and the stagnation pressure at the blunt nose of the meteoroid at the moment of the breakup gives an apparent strength of the body. In this case the meteoroid was a chondritic or stony body, its strength was 10 to 20 Mdyn/cm^2. In the theoretical models we have used empirical values of the body's strength and height of breakup. At an altitude of 35 km radius increases 3 times and at an altitudes of about 30 km increases several times. After the breakup meteoroid was heavily fragmented due to aerodynamic loads but a single-body model of the cloud of fragments and vapor has still been used.

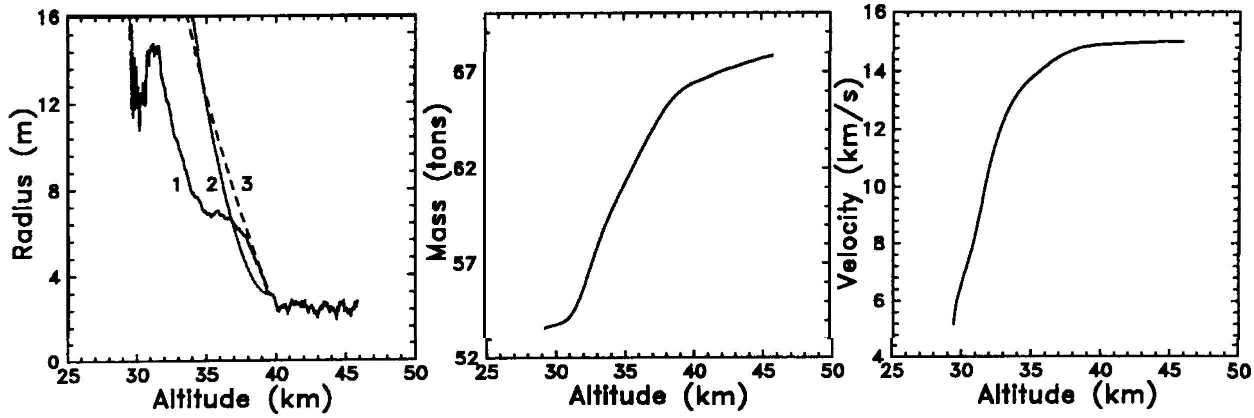

Figure 2. The 4 February 1994 event. Altitude dependence of radius, mass, and velocity resulted from numerical simulations. Initial mass 25 to 75 tons, initial velocity 15 to 20 km/sec, initial energy 1.2 to 2 kt TNT. Breakup at the altitude of 40 km. Substantial (about 6 to 7 times) increase in the radius leads to drastic deceleration of the meteoroid, while mass losses are rather small.

Meteoroid which caused 4 October 1991 event had a radius of about 2 m, initial mass 25 to 75 t, and kinetic energy of 1 to 2 kt, velocity 15 to 20 km/sec.

In Fig.3 the results of numerical simulations of 1 February 1994 even are presented. We have used data on the initial velocity (24 km/sec), and angle of trajectory inclination (45^0) which have been determined by McCord et al. (1995). We have also used a single-body model and obtained initial radius $R = 1.7$ m, and mass $M = 400$ tons, and energy $E = 30$ kt TNT, the obtained initial density is 13 g/cm^3 which is almost twice higher than the density of iron. This is due to rather low precision of determination of this particular parameter and due to usage of a single-body model.

Calculated radius exhibits two distinct maxima, due to the two-stage disintegration. Two patches of debris have been detected, i.e. one at an altitude of 34 km and another at an altitude of 21 km. In 15 sec, the high altitude debris cloud falls to about 33 km due to gravity. The low altitude object stabilizes at an altitude of 19 km.

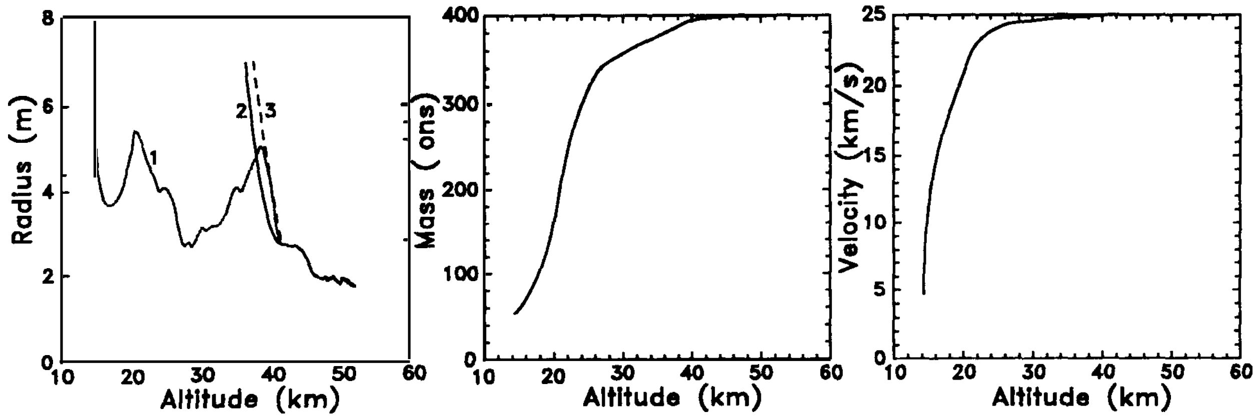

Figure 3. The 1 February 1994 event. Altitude dependence of radius, mass, and velocity. The calculated dependence of radius (1) is compared with analytical models (2, 3) in the left hand side of the figure.
Preset parameters: initial velocity V = 25 km/sec, angle of trajectory inclination $\theta = 45°$, height of peak intensity h_m = 21 km, ablation energy Q = 6.3 kJ/g.
Obtained parameters: initial radius R = 1.7 m, mass M = 400 tons, kinetic energy E = 30 kt TNT, density ρ_b= 13 g/cm^2.

In Fig.4 a light curve for the 1 February 1994 event is given (in the right panel in a logarithmic scale). Assuming two-stage disintegration, we have numerically reproduced the light curve during all the flight. The initial kinetic energy was about 40 kt TNT, mass of about 520 tons, strength of the second fragment of about 100 Mdyn/cm^2, its mass and energy are 430 t and 32 kt TNT correspondingly. The first fragment had very low apparent strength of about 5 Mdyn/cm^2, and probably this iron meteoroid was a binary object. The 1 February 1994 event is an analogue of the Sikhote-Aline iron shower - we have approximately the same mass and initial radius. But initial velocity was twice higher, and this leads to more intense fragmentation process, though we can not exclude that some fragments may have fallen into the Pacific Ocean, causing hydroacoustic signals.

If we do not use data on the initial velocity and trajectory inclination, the range of the energy and mass is wider: 40 to 70 kt TNT and 1,200-2,000 t. Our estimates of the initial velocity are 15 to 20 km/sec.

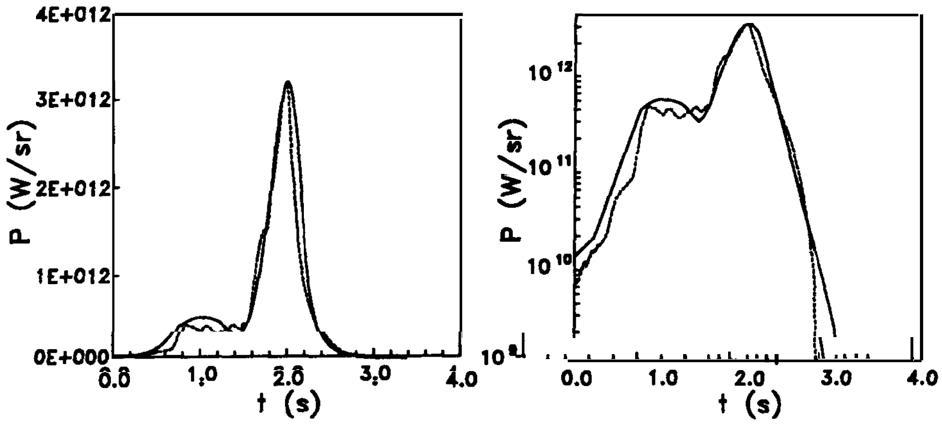

Figure 4. The observed light curve of the 1 February 1994 event (dashed curve) and the light curve obtained in numerical simulations for two fragments with the initial velocity of 25 km/sec (mass and energy of the first fragment M_1 = 84 t, E_1 = 6.2 kt TNT and mass and energy of the main body M_2 = 436 t, E_2 = 32.5 kt TNT). A peak intensity is reached at a height of 21 km. The first breakup occurred at an altitude of 52 km (an apparent strength is 5 Mdyn/cm^2) and a major breakup occurred at an altitude of 31 km (an apparent strength is 100 Mdyn/cm^2).

Increase in the initial velocity (up to 34 km/sec) leads to substantial decrease in mass but not very large decrease in the initial energy. This gives additional foundation to the estimates of kinetic energy for those events for which we do not know initial velocity. On the other hand, it clearly demonstrates that velocity/trajectory tracking substantially increases the precision of the assessment of meteoroid's characteristics.

In both events mentioned above luminous efficiency was in the range 7-1 1%. What is the reason for this big difference between luminous efficiency for nuclear detonation (30%) (Glass tone and Dolan, 1977) and that for the meteoroids explosive disintegration?

The shape of the fireball for the meteoroid impact is quite different from the quasi-spherical shape of the nuclear detonation fireball. It is an elongated quasi-cylindrical luminous plasma column. It is more like a pencil or a slightly diverging cone, not a sphere with the characteristic size much less than for the nuclear detonation of the same yield, as the energy release is gradual.

In some cases a situation when a single body model is not valid may be even much more complicated. In Fig.5 the flow pattern is presented for a case when two fragments of similar size move in the same direction, one after another, and a distance D between them is not very large.

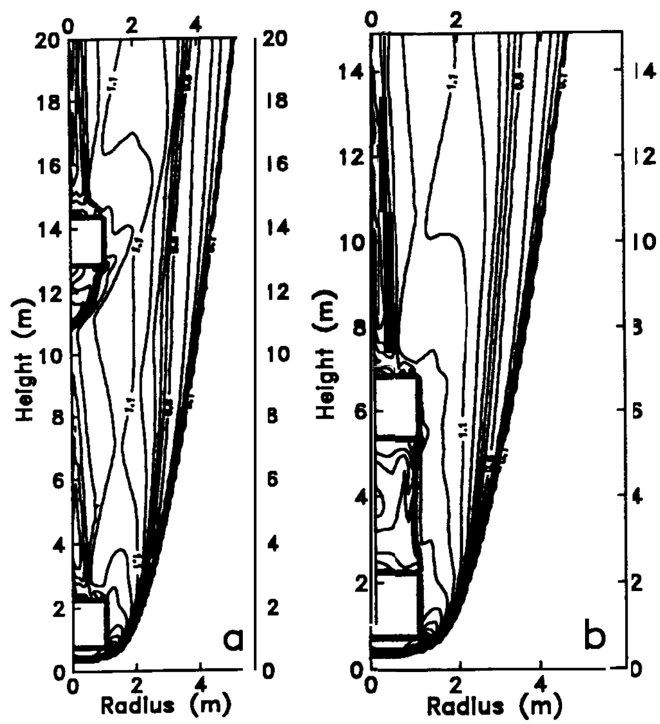

Figure 5. Temperature contours for the flow around two identical fragments moving along the same trajectory one after the other at distance D = 12R (a) and D = 4R (b)

Temperature contours for cylindrical fragments with radius R = 1 m and length L = 1.5 m moving with velocity V = 20 km/sec at a height of flight h = 40 km are shown. Temperature is in eV, distances between fragments are 12R (a) and 4R (b).

Usually aerodynamic interaction between the fragments leads to dispersion of the cloud of fragments with a lateral velocity which is about the velocity along the trajectory multiplied by the square root of the ratio of the air density to the density of the meteoroid (Passey and Melosh, 1980; Melosh, 1989). But in the analyzed case the second fragment moves in the rarefied wake of the first one. It is almost invisible as the radiation is mainly emitted from the shock wave front created by the first fragment. When the second fragment experiencing less drag than the first one leaves the wake and encounters the dense air, a sudden flash occurs which is not associated with fragmentation at this moment of time. For this complicated situations another techniques based on the energy balance considerations have been used.

We have calculated motion, luminosity and mass losses of meteoroids with various initial radii and velocity using a single-body model and assuming that a breakup occurred when the stagnation pressure at the blunt nose reached a definite critical value. As an example, the results of the simulation are given in Tables 2-4 for impact of iron bodies with a strength of 100 $Mdyn/cm^2$ and with an angle of trajectory inclination of 45°.

In Table 2 a fragmentation height is given for various radii and various velocities, in Table 3 heights of maximum intensity are given. For the assumed strength no fragmentation occurs at all for a body with radius 10 cm. A height of maximum intensity for a 10 cm radius is larger than that for radius 30 cm. It is due to substantial deceleration and ablation of such rather small meteoroid. For radii 0.3 m and larger, a height of maximum intensity is usually 2-3 km lower than the height of the breakup, and a peak intensity is associated with the rapid expansion of the cloud of fragmentes. A ratio of the radiated energy absorbed by the Sandia sensor to the initial kinetic energy is given in Table 4.

Table 2. Fragmentation height h_b (km).

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	0	21.0	21.6	21.5	21.5
15	0	24.4	24.3	24.2	24.3
20	0	28.1	27.9	27.9	27.8
25	0	30.9	30.8	30.8	30.8
30	0	33.1	33.1	33.0	33.0

Table 3. Height of maximum intensity h_m (km).

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	33.3	18.4	20.2	18.8	14.5
15	32.5	22.4	22.8	21.1	15.3
20	33.4	26.8	26.3	22.9	14.5
25	36.8	29.8	28.9	23.1	14.5
30	38.8	32.2	31.0	23.5	13.2

Table 4. Ratio of radiated energy to initial kinetic energy (%)

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	0.5	1.4	4.3	8.0	8.7
15	1.4	4.0	7.3	10.8	11.9
20	2.5	7.9	10.8	13.6	15.6
25	2.8	10.0	12.2	14.5	17.1
30	3.0	11.1	12.7	14.6	17.3

A luminous efficiency (taking into account the radiation emitted during the whole flight and taking into account fragmentation and expansion of the cloud of fragments) depends on the initial velocity and radius, but for radii more than 0.3 m and velocities higher than 15 km/sec values of luminous efficiencies are in the range of 4 to 17%, they differ from the average values of 7-11 % no more than 2 times.

An individual analysis of the light curves for several events(15 April 1988, 4 October 1990, 1 October 1991 and 1 February 1994), taking into account real altitudes of breakup (h_b) and of maximum intensity (h_m), has confirmed this conclusion. And for crude estimates here we shall use a constant value of luminous efficiency, i.e. 10%.

We have calculated number of events with kinetic energy in discrete intervals i with the lower limit E_i and upper limit $2E_i$. This energy - frequency distribution is given in Fig.6. Continuation of observations and their analysis for one or several years will increase statistical significance of such distribution, and extrapolation of this distribution will give us probability of impacts with higher energies. A crude estimate gives us prediction that for a 1 Mt impact an average interval between impacts is about 10-15 years. This is in correlation with the analysis by ReVelle (1995) of atmospheric effects caused by large bolides (acoustic gravity waves).

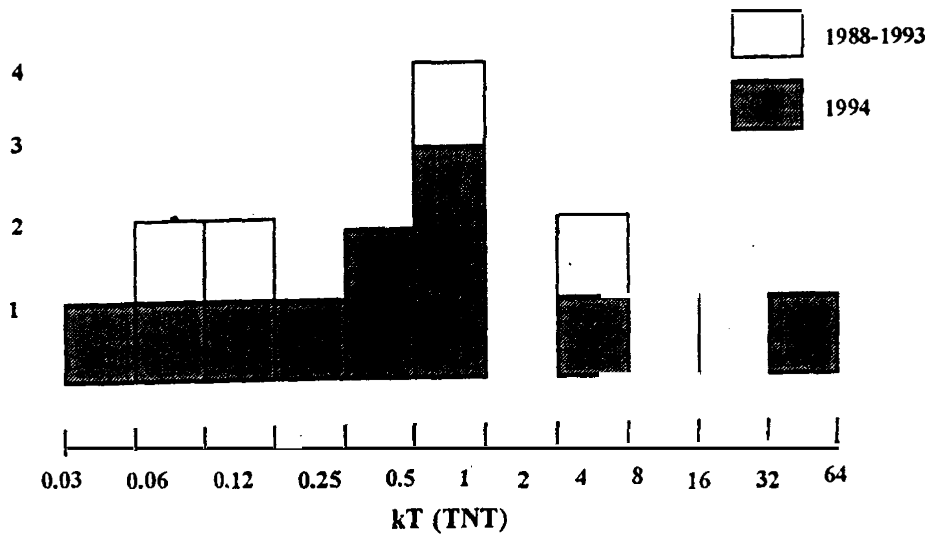

Figure 6. Frequency versus energy of the impactors. Energy derived by the Sandia optical sensors light curves with the assumption of 10% luminous efficiency.

During a period from 1960 to 1972 the US Air Forces have registered 10 events with sufficiently large energies. Taking into account percentage area coverage for each station and each event, ReVelle (1995) has obtained cumulative number N of bodies with a source energy more than E, kt TNT, per year over the entire Earth:

$$N = 7.2\ E^{-0.73}$$

We should underline that during this period of 12 years one event with an energy of about 1 Mt has been registered.

So it seems reasonable to be prepared for observation and analysis of the event with rather large energy. While the fireball caused by the explosive desintegration of a meteoroid exhibits many features of the nuclear detonations with the same yield, there are specific differences. We have already mentioned some of them, let us describe another.

We carried out numerical simulations assuming that an impactor with an energy of 1 Mt broke up at an altitude of 21 km. At an altitude of 5.5 km it has a shape of a cylinder with a radius of 50 m and the same height. This body falls vertically at 15 km/s. We also assume that at the chosen altitude the body has a low density, implying that the body is a mixture of debris and vapor due to action of aerodynamic pressure and ablation. It is adopted that in this stage of flight the body material behaves as compressible gas.

Computations of the fall and gasdynamic motion in the atmosphere were made using a free-Lagrangion method of Hazins and Svetsov (1993). The results of simulation are shown in Fig. 7. The body is pulverized during the fall in the atmosphere, and a maximum radius of a swarm of fragments grows. The body is decelerated and loses its kinetic energy. A maximum of energy deposition is at an altitude of about 4.5 km. But the swarm of debris and the air have significant momentum and persist in moving down till the ground despite their average velocity and kinetic energy become small. The stream of vapor and entrained and compressed air acts like a piston.

After reflection from the ground, the shock wave travels along the Earth surface. At time t = 1.5 sec (measured from the starting moment of the computations) we changed a method of computation for Eulerian one because the particles of the body are entirely pulverized (the process of the fragmentation is over), and we could take finer mesh at the late stage of the fall using Eulerian hydrocode.

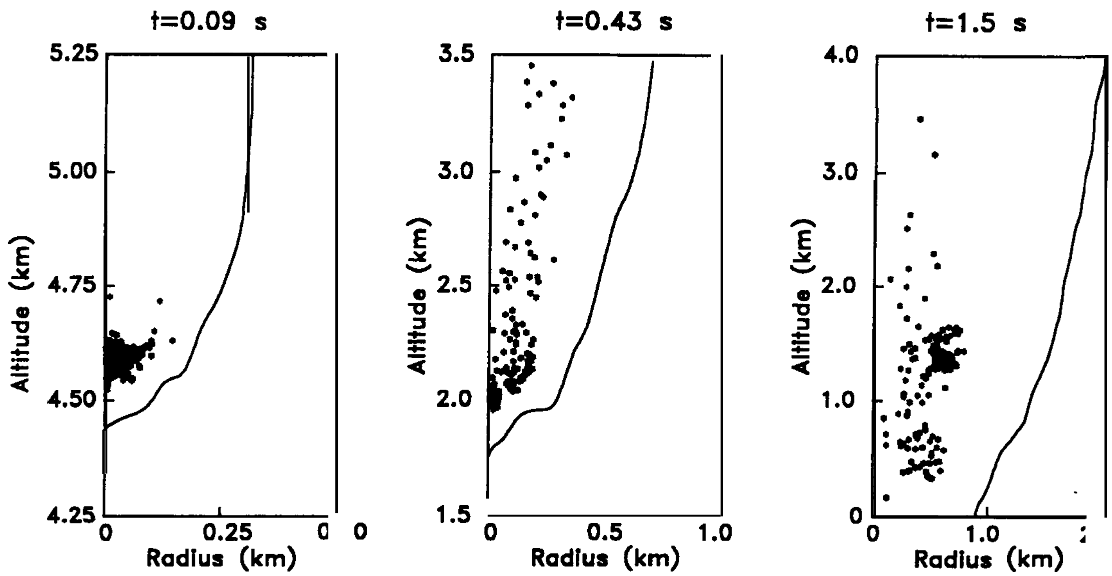

Figure 7. A simulation of a vertical fall of a heavily pulverized impactor. Computations have started at an altitude of 5500 m where a low density body (0.1 g/cm^3) has a radius of 50 m and velocity of 15 km/s. A shock wave is plotted by a solid line. Solid circles are particles of the body material.

A maximum pressure as a function of a distance along the Earth surface is shown in Fig. 8. We have also calculated two idealized variants of instantaneous explosions assuming that the total energy of impactor is released at an altitude of 5 km and at the ground. The results are compared in Fig. 8.

Pressure at the ground for an explosion at an altitude of 5 km is lower than obtained in the simulations of a pulverized impactor all over the surface. An explosion at the ground produces higher pressure at distances smaller than 4 km. But at large distances, to 20 km, the pressure in the surface explosion with equivalent energy is lower. Thus, an airblast caused by the meteoroid creates shock waves with larger amplitudes than the instantaneous explosion with the same energy.

Continuation of satellite based observations and their analysis will give us statistically significant information on the size-frequency distribution of impacts and probability of large (including the Tunguska-class) airblasts. This can also elucidate the scientific problem of meteoroid origin and their relation to the near - Earth asteroid belt discovered by the ground based Spacewatch system (Scotti etal., 1991; Rabinowitz et al., 1993; Carusi et al., 1994).

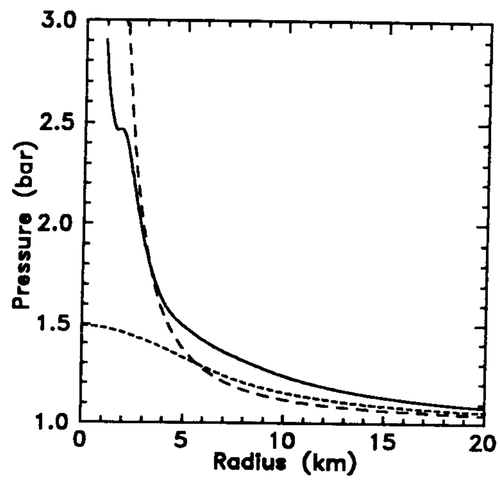

Figure 8. Pressure caused by a shock wave at the Earth surface as a function of a distance from the fall epicenter. Three variants have been computed: a fragmented and pulverized impactor falling vertically at V = 15 km/s (solid line), an equivalent explosion at the ground (dashed line), and an explosion at an altitude of 5 km (dotted line).

The precision of determination of meteoroid characteristics may be increased not only by usage of more sophisticated codes, which are now being developed, but by a larger amount of observational data, e.g. on the angle of trajectory inclination and the velocity of the meteoroid body along the trajectory. Spectral instruments being installed in upgraded satellite systems may also give very important information on chemical composition of the impacting cosmic bodies.

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