IMPACTS INTO OCEANS AND SEAS

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Abstract. Impacts of cosmic bodies into oceans and seas lead to the formation of very high waves. Numerical simulations of 3-km and 1-km comets impacting into a 4 km depth ocean with a velocity of 20 km/sec have been conducted. For a 1-km body, depth of the interim crater in the sea bed is about 8 km below ocean level, and the height of the water wave is 10 m at a distance of 2000 km from the impact point. As the water wave runs into shallows, a huge tsunami hits the coast. The height of the wave strongly depends on the coastal and sea bed topography.

If the impact occurred near the shore, the huge mass of water strikes the cliffs and the near shore mountain ridges and can cause displacement of the rocks, initiate landslides, and change the relief. Thus, impact into oceans and seas is an important geological factor.

Cosmic bodies of small sizes are disrupted by aerodynamic forces. Fragments of a 100-m radius comet striking the water surface create an unstable cavity in the water of about 1 km radius. Its collapse also creates tsunami.

A simple estimate has been made using the light curves from recent atmosphere explosions detected by satellites. The results of our assessment of the characteristics of meteoroids which caused these intense light flashes suggests that fragments of a 25-m stony body with initial impact velocity 15 to 20 km/sec will hit the surface. For a 75-m iron body striking the sea with a depth of 600 m, the height of the wave is 10 m at 200-300 km distance from the impact.

1. Introduction

Impacts of a cosmic body (a comet or an asteroid) into an ocean or sea is more frequent than the impact on continents as the major part of the Earth's surface is covered by water. Such an impact leads to formation of a large unstable cavity in water which collapses. The compressive pulse and collapse of the crater produce a surge and huge waves that propagate to large distances. Numerical simulations (Ahrens and O'Keefe, 1987; Roddy et al., 1987) have given a detailed picture of the hydrodynamical processes caused by an impact of a large asteroid (5 km radius, modeled as a stony sphere) into the ocean with a depth of 5 km. At 5 sec after the impact, the water rim is located at 10-17 km from the impact point. At 30 sec, the water rim is at 35 km (the average velocity is 1 km/sec). The ratio of the crater rim diameter to the diameter of the impacting body is about 7. The depth of the crater is 39 km, or 8 times the body's radius. At 120 sec, the water rim height is 4 km and the velocity is still 0.2 km/sec. The interim crater radius

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in the Earth was 40 km. The water rim moves ahead of the ground rim. The huge tsunami may lead to disastrous consequences all over the world.

2. Impacts of objects a few km in diameter

Impacts of such asteroids and comets are rare events (Morrison et al., 1994). We have conducted similar numerical simulations for smaller bodies for which frequencies of the impacts are much higher. We describe the result of the vertical impact of a 3-km radius comet (modeled as a water sphere) into an ocean with a depth of 4 km (Nemtchinov et al., 1994b, 1994c). In this case the ratio of the impactor radius to the ocean depth is 0.75, whereas in the previous case this ratio was unity. In Fig. 1, the lines of equal density (isohores) are given at 10 sec after a vertical impact with a velocity of 20 km/sec. We used the same equation of state for the comet as for oceanic water. The semi empirical Equation of State (EOS) has been calculated and given to us by G.S. Romanov's group (Heat and Mass Transfer Institute, Minsk, Belarus). We suppose that rocks of the oceanic bed are similar to granite, and used Tillotsen EOS (see Melosh, 1989). The presence of air above the water surface, and of the wake formed after the body's flight through the atmosphere has been taken into account. The Eulerean numerical scheme of Belotserkovsky and Davidov (1982) was used to describe the axially-symmetric motion of water and granite. It was combined with Hirt and Nickols (1981) Volume of Fluid (VOF) method to track the interfaces between water and air, and water and granite.

Density contours labeled 1-9 correspond to densities of 0.01, 0.13, 0.26, 0.38, 0.50, 0.63, 0.75, 0.88 and 1.0 g/cm^3. The upper part of the water lip is a rarefied mixture of steam and water droplets. Dots correspond to the oceanic bed. The ejected material reaches the water wave at 18 km. The height of the rim of the ground is 5 km, its radius is 11-12 km, the depth of the interim crater is 12 km. In this case, the ratio of the radius to the ocean depth is 0.75, whereas in previous case this ratio was unity.

At 25 sec after the impact, the height of the wave is 4 km, and the velocity of the water rim is about 1 km/sec. The depth of the transient crater is 12 km, its radius is 12 km or 4 times the radius of the impacting body. The water rim breaks away from the ground rim, which is located at approximately 15 km radius. Thus, a decrease in the diameter of the impacting body changes the mechanism of water-wave generation.

For a 1-km radius comet, the ratio of the body's radius to the ocean depth is 0.25, much less than unity. Therefore, the shock wave created by the body's intrusion into water moves for a sufficiently long time in the water with a sufficiently high velocity, and all this volume of water (with mass of about 30 times larger than the mass of the comet) is vaporized before the

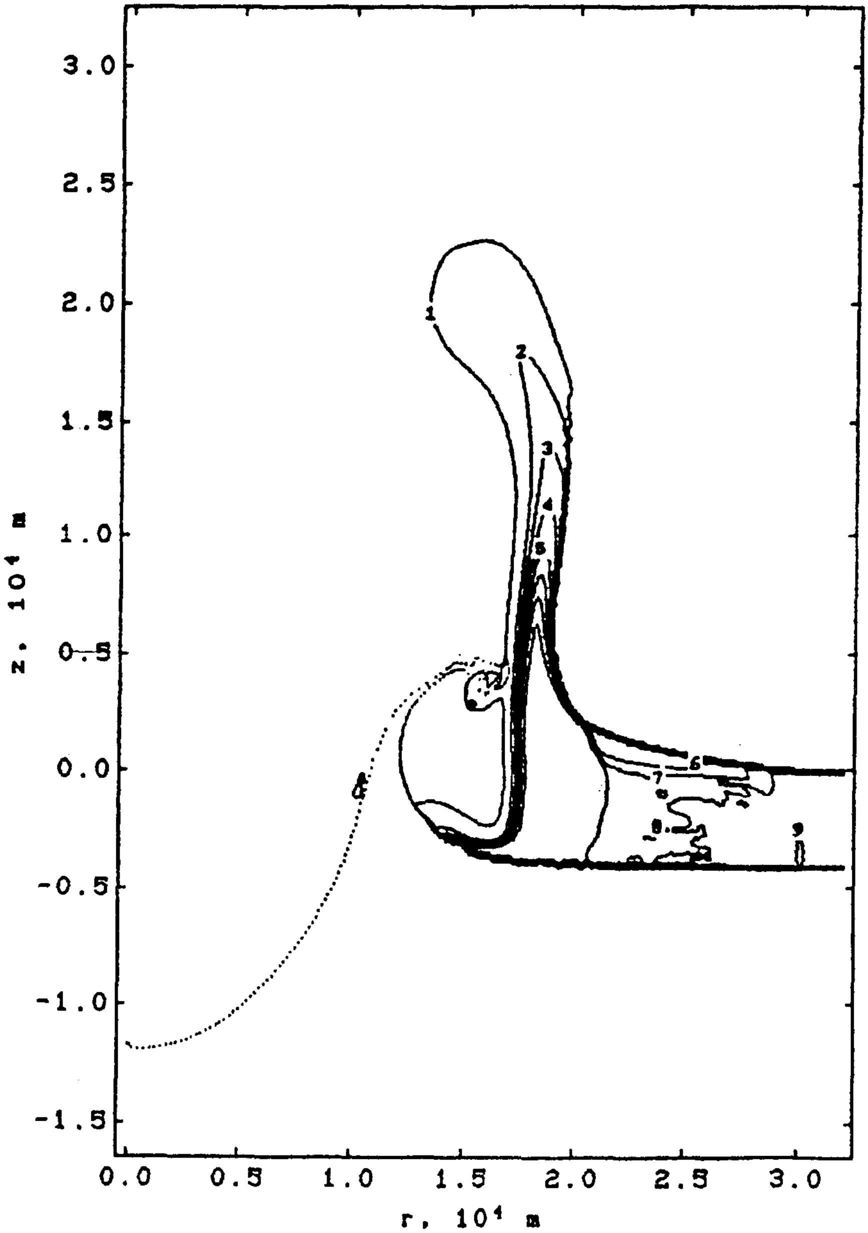

Fig. 1. Isohores at 10 sec after a vertical impact of a 3-km radius comet with a velocity of 20 km/sec into an ocean with a depth of 4 km.

body strikes the ocean bed. The results are presented in Fig. 2 at 20 sec after the impact. The height of the water wave is 4 km above the initial water level, and the water rim is located at 13 km from the impact. At 42 sec

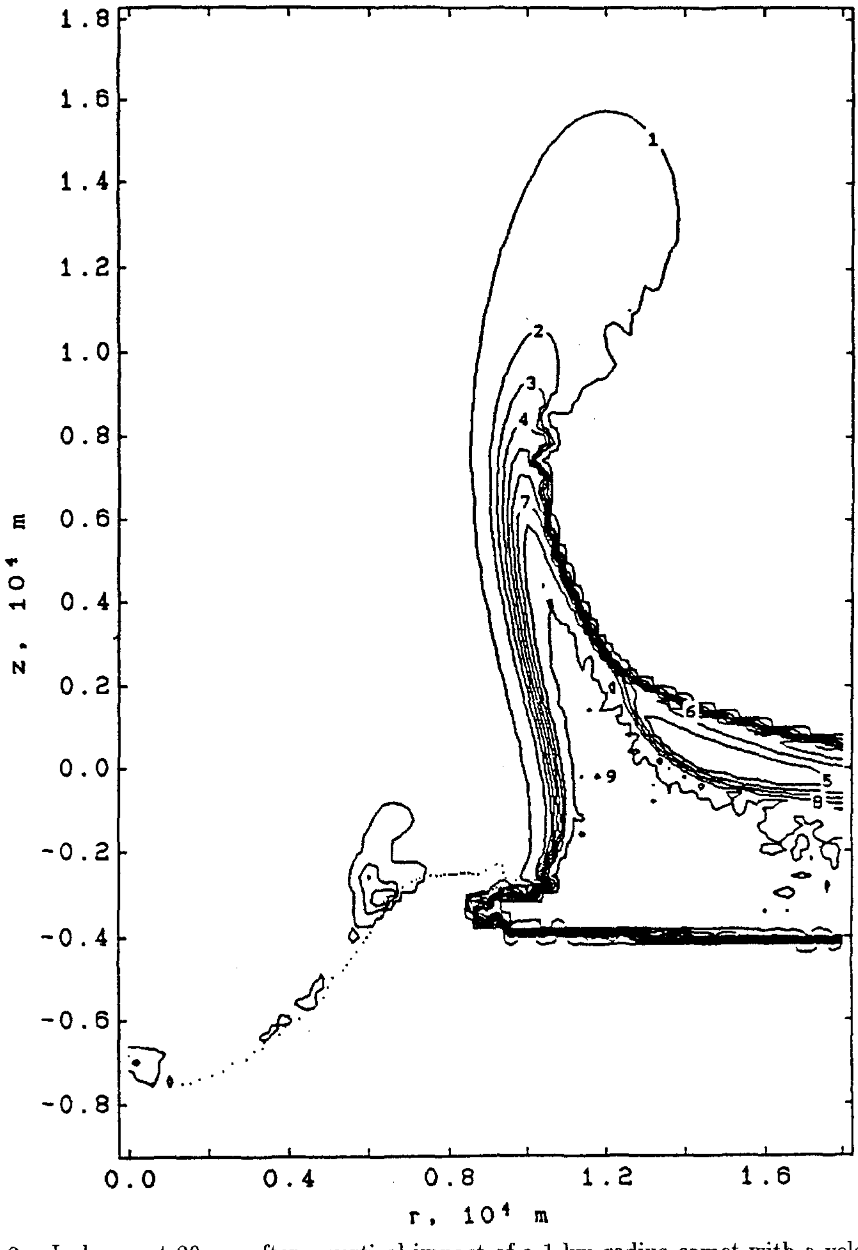

Fig. 2. Isohores at 20 sec after a vertical impact of a 1-km radius comet with a velocity of 20 km/sec into an ocean with a depth of 4 km.

(Fig. 3), the height of the wave is 1 km at 18 km from the impact point, and the average velocity of the rim propagation is still 0.4 km/sec.

The height of the ground rim is −2.5 km, thus it is below the initial water level. The height of the water wave decreased 4 times in the interval between

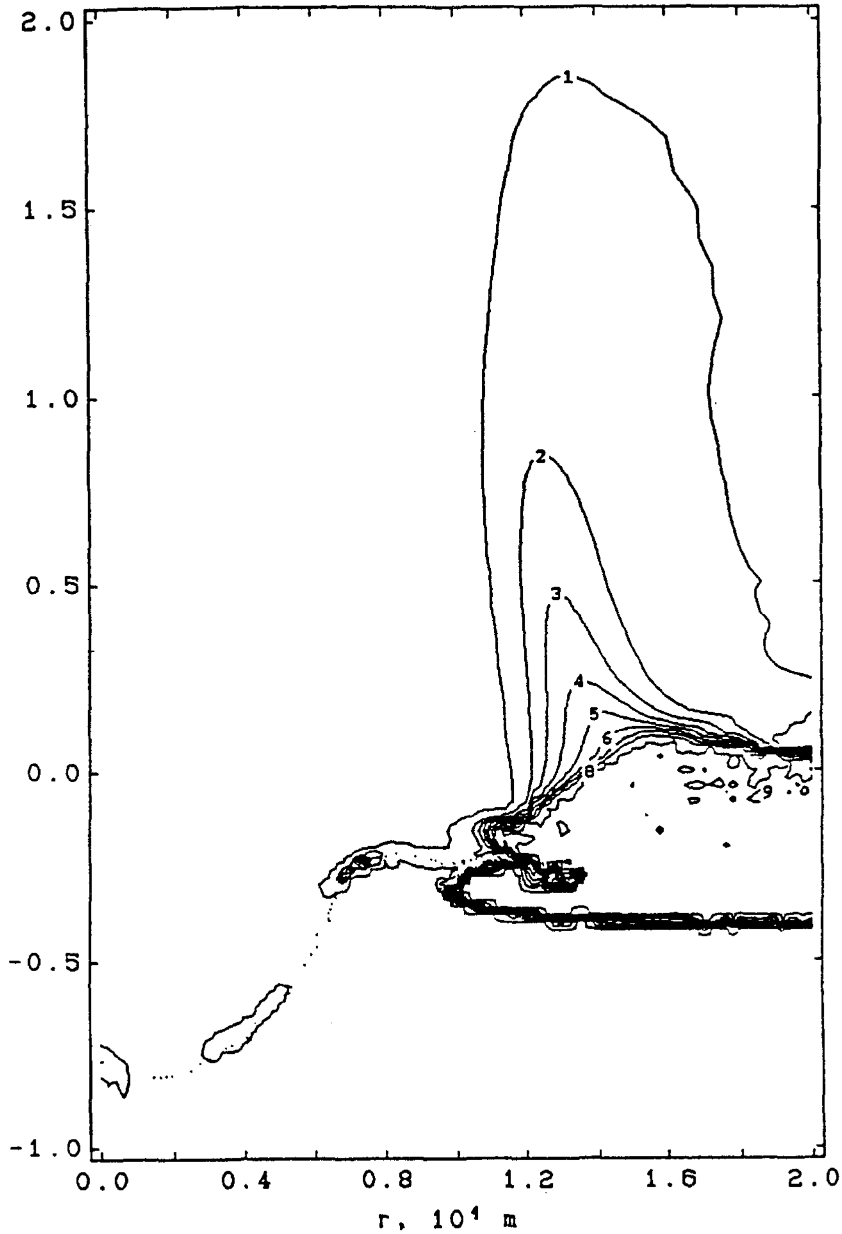

Fig. 3. Isohores at 42 sec after a vertical impact of a 1-km radius comet with a velocity of 20 km/sec into an ocean with a depth of 4 km.

20 sec and 42 sec, due to the break away of the water wave from the ground rim and filling the water crater. The depth of the interim crater in the sea bed is about 8 km, and its radius is also 8 km, which is 8 times the diameter of the body.

A simple geometrical similarity rule can be used to estimate the diameter of the water rim if it moves with the velocity higher than the velocity of the gravity waves ($V_g = \sqrt{gH}$, where g is gravity, H is the ocean depth, i.e. $V_g = 0.2$ km/sec for $H = 4$ km). The diameter is approximately proportional to the initial radius of the body. But this similarity rule is not a strict one, as other characteristics curl are important: the ratio of the depth of the water basin to the body's radius, and ratio of the velocity to the sound speed in water and in rock. So a large number of numerical simulations is necessary to predict the depth of the underwater crater.

Propagation of the water waves at large distances from the impact point has been calculated using the so-called shallow water approximation. An N-type wave is formed, and the height of the water wave decreases approximately inversely with distance from the impact point. If the "critical" height of the water wave ≈ 10 m – the height of the waves which have caused the most disastrous tsunami at the Kuril islands during this century (Shokin et al., 1988) – then the distance will be 2000 km.

The impact of the huge mass of water onto the coast at small distances from the impact point can initiate land slides, and change the relief. It is now well established that impacts onto the planet's surface are an important geological processes (Melosh, 1989). Our results suggest that the same may be true for impacts onto oceans and seas. We are going to investigate such processes in the future more thoroughly.

3. Impact of bodies smaller than 1 km in diameter

The impact of a 1 km body is still a rare event. Much more frequent are the impact of smaller bodies, e.g. 100 m or 200 m. Recent Spacewatch observations have led to the discovery of a near-Earth asteroid belt (Gehrels 1991, Scotti et al., 1991; Rabinowitz et al., 1993). These observations (during the last 4-5 years) have revealed that a large number of discovered bodies has a radius in this size (T. Gehrels and J. Scotti, 1994, personal communication). For these bodies a new problem arises – deformation and disruption by the atmosphere. Simple estimates (Melosh, 1981, 1989) have determined the following critical radius: 290 m for a comet, 160 m for a stony body, 100 m for an iron body. A meteoroid of the critical diameter, upon striking vertically, is spread to attain the aspect ratio ≈ 8. According to this model, the meteoroid's shape becomes that of the pancake.

We have conducted numerical simulations of the deformation and disruption of a comet with a radius of 100 m, 3 times less than the critical radius by Melosh (1989), and approximately equal to the critical radius by Chyba et al. (1993).

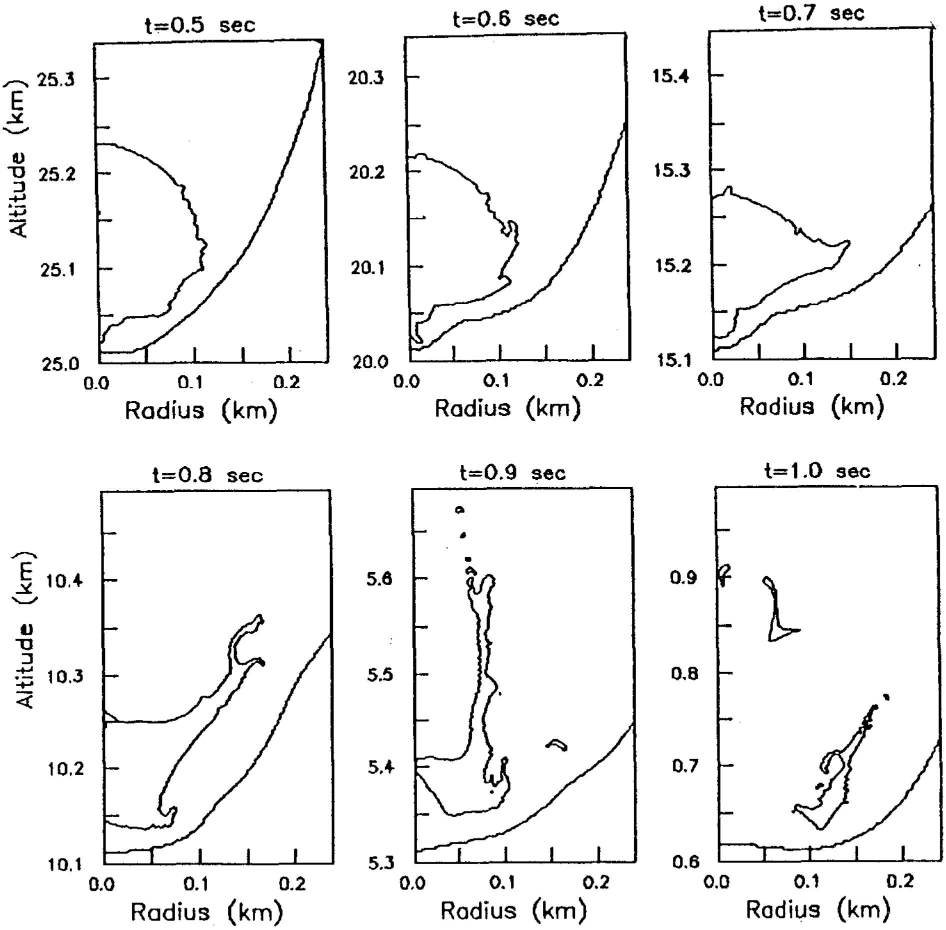

Fig. 4. Density contours at different moments of time of a 100-m radius comet striking the atmosphere with an initial velocity of 50 km/sec (at t=0 the comet was at the altitude of 50 km).

The results of the numerical simulation are presented in Fig. 4 (initial position of the body was 50 km, initial velocity 50 km/s). The body is becoming flat, but its radius is increasing only 1.5 times. Later, a cavern is formed in the blunt nose, the body becomes a hollow shell (at a height of 5 km above the surface), and its fragments impact on the surface. Such a collection of fragments do not produce the same kind of craters as a sphere (O'Keefe and Ahrens, 1982).

In Fig. 5, the result of the impact on a water surface is given (here time is after the impact, in sec). The impact of a hollow shell creates a hollow cavity in water, but a large water wave is formed. Later a large cavity in water, 1 km in radius, is formed (10 times the initial radius of the body). This is due to the high compressibility of water. The disruption of the 100 m radius body did not prevent the impact, and the mechanical effect is only slightly less than for a sphere with the same initial density. The waves which are clearly seen at 1 sec after the impact are not tsunamis. These waves are created by instability of the water surface caused by the wind blowing above the surface behind the shock wave of the air blast. The real high water waves leading to tsunami are created later – about 5 sec after the impact, when the 1 km radius cavity in the water collapses. Thus, small comets (larger than 100 m radius) create cavities in the water and tsunami.

Stony bodies penetrate into the Earth's atmosphere better than comets. As intricate numerical simulations for such bodies have not been finished yet, we shall avoid them and resort to experimental data and simple scaling laws.

We use as a model of the motion of the fragment cloud the following system of equations:

$$M\frac{dV}{dt} = C_D \rho_a V^2 A, \qquad A = \pi R^2 \tag{1}$$

where M is the mass, V is the velocity, C_D – the drag coefficient, A is the cross section area, R is the radius of the body, and of the cloud of fragments (after the breakdown), ρ_a is the atmospheric density. To obtain the time dependence of the radius we used the same approximation as in (Melosh, 1989):

$$\frac{dR}{dt} = V\sqrt{\frac{\rho_a}{\rho}} \tag{2}$$

Here ρ is the density of the body, but we do not keep the density of the body constant as it was assumed in the so called liquid approximation (Grigorian, 1979; Melosh, 1981; Chyba et al., 1993). Instead we suppose that the density of the "sand-bank" (the cloud of fragments filling the volume and creating a common bow shock, see e.g. Teterev and Nemtchinov, 1993) is determined by the conservation of mass

$$\rho R^3 = \rho_0 R_0^3 \tag{3}$$

where R_0 is the initial radius, and ρ_0 is the initial density. If we assume that the atmosphere is exponential:

$$\rho_a = \rho_E \exp(-h/H) \tag{4}$$

where h is the height above the Earth's surface, ρ_E is atmosphere density at the height $h = 0, H$ is the characteristic scale of the atmosphere. The system (1) – (4) has an analytical solution:

$$\left(\frac{R}{R_0}\right)^{\frac{5}{2}} - 1 = \left(\frac{\rho_E}{\rho_0}\right)^{\frac{1}{2}} \frac{5H}{R_0 \sin\theta}\left[\exp\left(-\frac{h}{H}\right) - \exp\left(-\frac{h_b}{H}\right)\right] \tag{5}$$

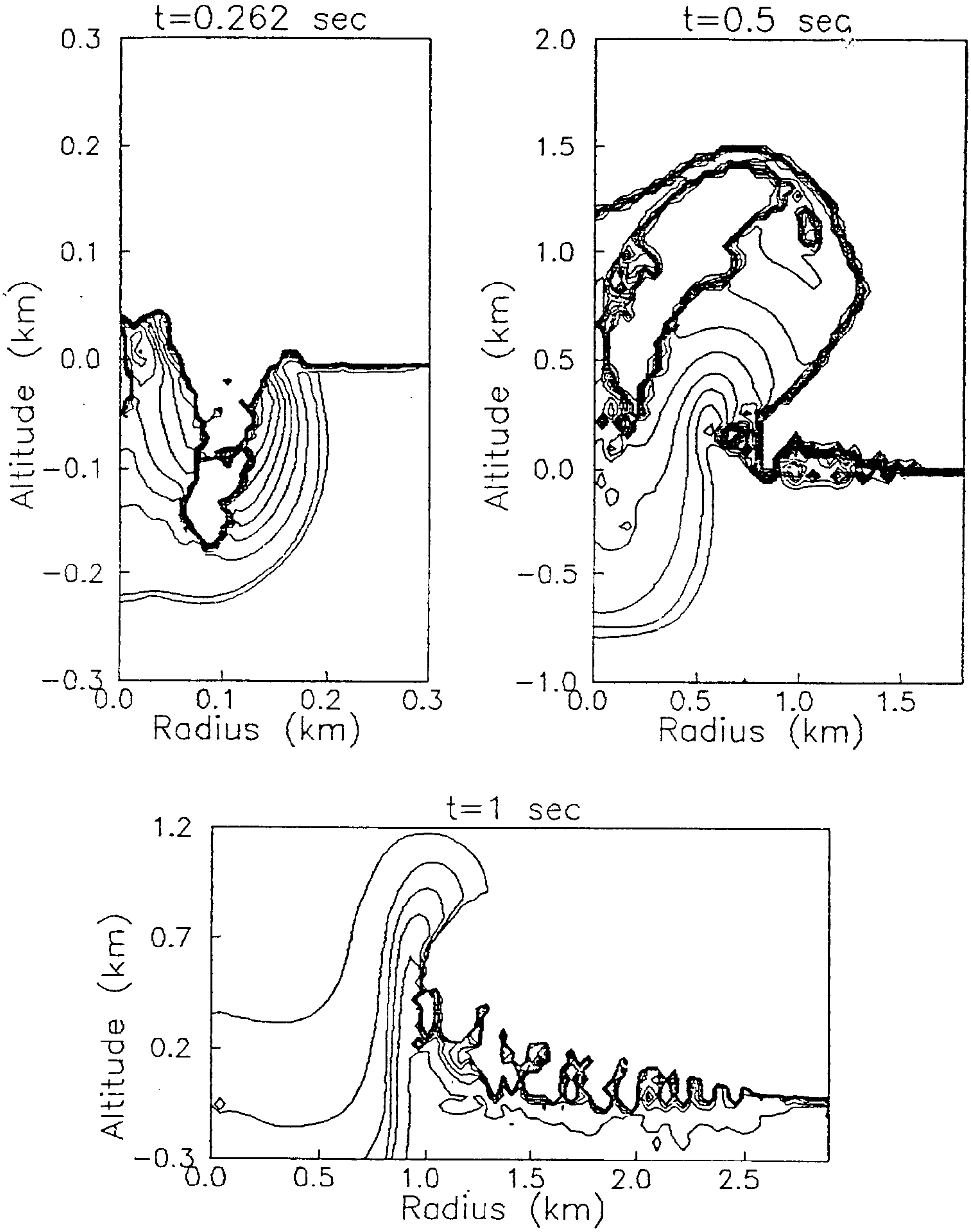

Fig. 5. The result of the impact on a water surface of a 100-m radius comet with an initial velocity 50 km/sec.

where θ is the angle of the trajectory inclination to the horizon and h_b is the height of the breakup. Using formula (4) once more we rearrange Eq.

(5):

$$\left(\frac{R}{R_0}\right)^{\frac{5}{2}} - 1 = \frac{5H}{R_0 \sin\theta}\left(\sqrt{\frac{\rho_\omega}{\rho_0}} - \sqrt{\frac{\rho_b}{\rho_0}}\right) \tag{6}$$

where ρ_b is the density at the altitude of the breakup, and ρ_ω is the density at altitude h_ω, where the radius R is by a factor of ω higher than the initial radius R_0. If the inequalities $(\rho_\omega/\rho_b)^{1/2} >> 1$ and $\omega^{5/2} >> 1$ are satisfied, then we obtain

$$\omega^{5/2} = \frac{5H}{R_0 \sin\theta}\sqrt{\frac{\rho_\omega}{\rho_0}} \tag{7}$$

We shall use experimental data from US DOD satellites equipped with detectors from Sandia National Laboratories (Reynolds, 1992; Jacobs and Spalding, 1993; Tagliaferri et al., 1994).

Several light curves are presented in Fig. 6. These light curves have been analyzed by us (Nemtchinov et al., 1994a, 1995; Svetsov, 1994), and some results are given at Table I. Here h_m is the height of maximum brightness, and ρ_m is the air density at this height. We have identified the impactors as chondritic or stony bodies, except the meteoroid causing the 1 February 1994 event, which we identify as an iron. Our analyses have shown that at the height h_m, the radius of the fragment cloud and of the bow shock is about 4-7 times the initial radius R_0, and the body breaks down due to aerodynamic forces at the height h_b, which is 10-20 km higher than h_m. If $h_m = 0$ the cloud of fragments reaches the Earth's surface with a rather high velocity.

We have assumed that for each event the angle of the trajectory, the initial velocity, density and factor ω are the same, but the size of the body increases and the altitude of the peak intensity decreases according to Eq. (7). We have extrapolated data presented in Table I to determine the size of the body R_*, for which h_ω is zero, and $\rho\omega = \rho_E$, using the following scaling laws.

$$\frac{R_*}{R_0} = \left(\frac{\rho_m}{\rho_E}\right)^{-\frac{1}{2}}, \qquad \frac{E_*}{E} = \left(\frac{\rho_m}{\rho_E}\right)^{-\frac{3}{2}} \tag{8}$$

For the 1 October 1990 event, when R_b = 2–3 m, it follows from the relation (8) that R_* = 17–26 m. Thus, a 25 m stony body (its mass is 120×10^6 kg) reaches the Earth surface. There are two consequences. First, the Tunguska meteoroid, which has this size or even larger, cannot have been a stony body, as suggested by Chyba et al. (1993), but a comet, as it did not reach the Earth surface, but exploded at the height of about 8 km. Second, such a body striking the surface will create a crater in the water and resulting tsunami. Radius of the iron body for which height of the peak intensity $h_m = 0$ is 13 to 15 m. A stream of fragments and vapor impacting the ocean surface, though with the average density much less than the density of water, will still create water waves and tsunamis. Thus

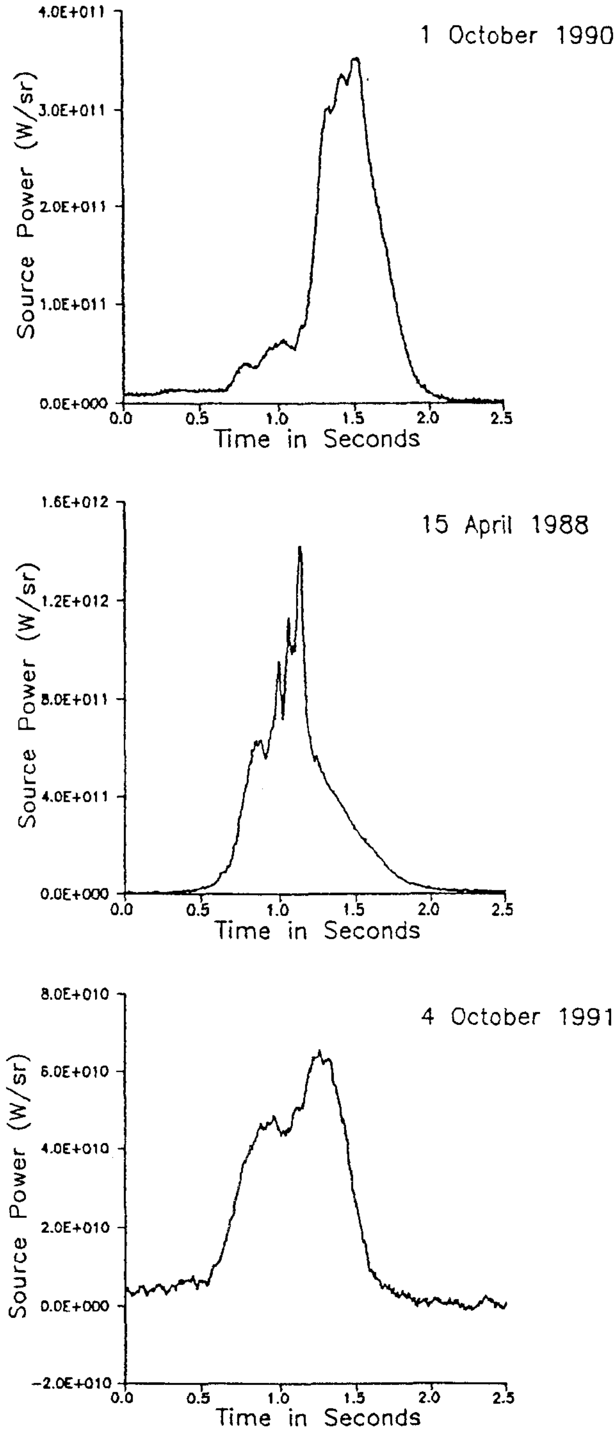

Fig. 6. The light curves detected by Sandia's detectors.

TABLE I

The results of the analysis of the light curves detected by Sandia's detectors

Event, Date	15 April 1988	1 October 1990	4 October 1991	1 February 1994 *)
h_m, height of maximum brightness, km	43	30	33	21
Energy of light impulse, E_s, kt TNT	1.7	0.57	0.14	4.4
Velocity V, km/sec	40-50	15-20	15-20	15-20
Mass, tons	25-45	100-300	25-75	1,200-2,500
Radius R, m	1-2	2-3	1-2	3.4-4
Kinetic energy E, kt TNT	8-9	5-8	1.2-2	40-70
Density at height h_m, ρ_m, g/cm^3	2.7×10^{-6}	0.18×10^{-4}	0.11×10^{-4}	0.89×10^{-4}
$(\rho_m/\rho_E)^{-1/2}$	22	8.5	11	3.8
R_*, m	22-44	17-26	11-22	13-15
$(\rho_m/\rho_E)^{-3/2}$	10,000	600	1300	55
E_*, Mt TNT	83-94	3.0-4.8	1.5-2.5	2.2-3.8

*) preliminary data.

the minimum energy of the blast causing devastation, including tsunamis, is about 2 to 4 Mt (for an iron body and the velocity 15–20 km/sec).

If a 75-m radius iron body having a mass of 12×10^9 kg moves with the velocity 20 km/sec, it has kinetic energy of 600 Mt TNT (such a body is greater than that which caused the famous Meteor crater, see Melosh (1989). If it strikes the water surface of the sea with the depth $\approx$ 600 m (average depth of the Baltic Sea), then it will reach the sea bed and explode creating hydrodynamical processes similar to that of an underwater nuclear explosion. For energies above this level, we can use experimental data and scaling laws obtained in the course of nuclear tests (Glasstone and Dolan, 1977; Hills and Goda, 1993). The amplitude of the water wave is 300–800 m at a distance of 3 km from the impact point, and is 10 m at a distance of 200–300 km.

As the water wave runs into shallows, its speed decreases and its front increases in sharpness, and a huge tsunami hits the coast (Hills and Goda, 1983; Hills et al., 1994; Yabushita and Hatta, 1994). The heights of the deep-water waves, and of the tsunami wave, strongly depend on the coastal and sea bed topography, including the shape of the coast line, and the existence of underwater ridges and canyons (Nemtchinov et al., 1994).

Acknowledgements

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