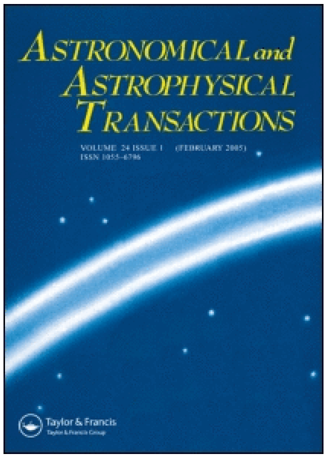

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THE COLLISION OF THE COMET SHOEMAKER – LEVY 9 WITH JUPITER

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The passage of a separate large piece of the Shoemaker–Levy 9 nucleus through Jovian atmosphere is considered. It is assumed that the initial size (diameter) of the spheric body is 1 km, its mean density is 0,8 g/cm^3, the velocity of entry is 60 km/s, the zenith angles of entry are 45° and 0°. We assume the dependence of the atmospheric density on height according to the usual barometric law in which the conventional zero height corresponds to the atmospheric pressure of 5×10^4 Pa. Heights of the homogeneous atmosphere are assumed to be 20 and 25 km. The following parameters were calculated: maximum deceleration height; velocity, mass, and body deceleration at this height. It takes 9–12 seconds for the fireball to reach this height. The central idea of this is that, by analogy with the known terrestrial phenomena (Tungusskiy, Sikhote–Alin, etc.) we assume that the comet body will explode in the Jupiter's atmosphere at a height which is not lower than that of maximum deceleration. At this height, the aerodynamic load will reach $\approx 10^{11}$ dyne/cm^2, and the rest of the cometary substance may completely evaporate on the way of 50–100 m length. Having applied the well-known theory (Kompaneets, 1960; Zel'dovich and Rajzer, 1966), we calculated the shock wave velocity in vertical direction from the site of explosion and the time of its exit to the atmosphere's "surface". Depending on the adiabatic index (1.2–1.4), the time of exit is 10–7 min. The result is in a nice agreement with the data of observations from space vehicles.

KEY WORDS Jupiter, comet body, explosion, shock wave, plume

The minimum velocity at which space bodies following heliocentric orbits collide with planetary atmospheres equals the parabolic velocity V_p for the given planet. If a body travels in its closed planet-centric orbit, the velocity of its entry into the atmosphere will be less than V_p, and in the limit it can reach 0.707 V_p. If a body belongs to the planetary system, the maximum entry velocity is determined by the formula:

$$V_m = [V_p^2 + (1+\sqrt{2})^2 V_0^2]^{1/2}.$$

where V_0 is the average velocity of the planet.

Therefore, for Jupiter the range of velocities of entry into its atmosphere is from 59.4 to 67.3 km/s (the orbit being planet-centric, the range is 42.0 to 59.4 km/s).

For model calculations of the collision of a large fragment of the comet Shoemaker–Levy 9 core with the Jovian atmosphere, we adopted the following parameters: the initial velocity, $V_0 = 60$ km/s; the initial size (diameter) of the body, 1 km; the mean density of the body, δ, 0.8 g/cm; the zenit angles of entry, $Z_R = 45°$ and $0°$. The dependence of the atmospheric density on height we describe with the usual barometric law in which the conventional zero height coresponds to the atmospheric pressure of 5×10^4 Pa. The heights of homogeneous atmosphere are taken equal to $H^* = 20$ and 25 km, because the average molecular mass is 2.26, the gravitational acceleration is 24.9 m/s^2, effective temperatures at the heights in the Jovian atmosphere we are interested in are 140 to 170 K (Hunten, 1976). Such temperatures approximately equal the equilibrium temperature of the body's surface prior to its entry into the Jupiter's atmosphere.

The shock wave accompaning the body's flight in the atmosphere is already formed at the height of 400 km, where the size of the body exceeds the molecules free run length tenfold. Heating of the body's surface will predominantly occur through the shock wave radiation. It is possible to assess the range of heights ΔH at which the temperature T_s of the meteoroid surface will reach the value necessary for intensive evaporation ($T_s = 2500$ K) using the formula obtained by Kruchinenko (1993):

$$T_s = \frac{\Lambda_R \sigma_s T_U^4 \Delta H}{x_0 c \delta V_0 \cos Z_R} \tag{1}$$

Here Λ_R is the radiation transfer coefficient (at the initial site, its maximum value is about 0.1). σ_s is the Stefan–Boltzmann constant; T_U, the shock wave front temperature; $T_U = 2 \times 10^4$ K (Biberman *et al.*, 1979); x_0, the characteristic depth of heating (Levin, 1956); c, the specific heat. It follows from Eq. (1) that ΔH value equals several kilometers only. The convective component in the surface body heating is of minor importance. To the height of $H_1 = 400$ km, convective heating will increase the body's surface temperature by the value (Levin, 1956):

$$T_1 - T_0 = \frac{\Lambda x_0 V_0^3 \rho(H_1)}{2\lambda} \tag{2}$$

where T_0 is the equilibrium temperature of the surface body at the heliocentric distance 5 AU; $T_0 = 140\ K$; the heat-transfer coefficient ($\Lambda \approx 0.5$); λ, the heat conduction coefficient. It follows from (2) that $T_1 \approx 150$ K.

Considering the problem within the framework of approach of the boundary layer for equations of motion of ideally compressed gas and using the results of several authors (Stulov, 1972; Gershbejn *et al.*, 1978; Vislyj *et al.*, 1983) studying streamline of bodies by radiating gas at strong blowing in, average estimates were obtained as follows: contact surface moves apart from the body's surface at a distance of about 100 m; the shock layer, at the distance of 300 m; the thickness of the shock-wave layer is about 70 m. The radiating surface is 8×10^{10} cm^2. The intensity of bolide radiation (of shock-wave radiation) in integral light (at $T_U = 2 \times 10^4$ K, according to Stefan's law) is 7.2×10^{23} erg/s. It is the first phase – the phase of the fireball, when the fragment enters the atmosphere.

The changing meteoroid velocity, depending on height and other parameters, may be determined using the known formula:

$$E_i[\sigma(1-\mu)V_0^2/2] - E_i[\sigma(1-\mu)V^2/2] = 2\Gamma A_0 H^* \times$$

$$\times \exp[\sigma(1-\mu)V_0^2/2][\rho(H)-\rho(H_1)]/m_0^{1/3}\delta^{2/3}\cos Z_R,$$

where E_i is the exponential integral function; $\sigma = \Lambda_R/2\Gamma Q$, ablation coefficient; Γ, coefficient of drag; Q, specific ablation energy of the body; μ, A_0, parameter and coefficient of the body's shape; m_0, the initial mass of the meteoroid. It follows from this formula that a noticeable change in the body's velocity begins rather deep – in the region of the conventional null of height. At the site of about 100 km in height (to the height of $H \approx -110$ km) the velocity is reduced to 35 km/s. Therefore, we come to the following approximation:

$$V(H) = V_0 - 0.138\exp(-0.0473\,H),$$

where V is in km/s, H is in km and, for $\Lambda = 5\times 10^{-3}$, the coefficient of drag is 0.5, the heat of ablation is 8×10^{10} erg/g (evaporation), $Z_R = 0^0$, $H^* = 20$ km.

We calculated the motion of the cometary body, its deceleration and destruction in the atmosphere made using the technique described in the monograph by Voloshchuk *et al.* (1989). The calculations were carried out for cases of constant and variable cross-sections of the body (S = const, $S \neq$ const). We determined for such cases different values of the following parameters: the height H_* of the maximum deceleration; velocity V_* and deceleration dV_*/dt at this height; mass of the body at the height of maximum deceleration relative to its initial mass, m_*/m_0; kinetic energy E_* at this height; its loss $\Delta E = E_0 - E_*$ before this height.

1. $\boldsymbol{S}$ **= const.** Here, again, we see that for very large bodies this pattern is quite acceptable.

Maximum deceleration occurs at the velocity of

$$V_* = V_0\exp(-0.5)$$

and is equal to

$$dV_*/dt = -0.184\cos Z_R V_0^2/H^*.$$

We determine the maximum deceleration height from the equation of deceleration, written for H_*:

$$\rho(H_*) = m_0^{1/3}\delta^{2/3}\cos Z_R/2A_0\Gamma H^*.$$

2. $\boldsymbol{S \neq}$ **const.** Maximum deceleration occurs at the velocity

$$V_* = \{2\tanh[0.175\sigma(1-\mu)V_0^2]/\sigma(1-\mu)\}^{1/2}$$

and is equal to

$$\frac{dV_*}{dt} = -\frac{\tanh[0.175\sigma(1-\mu)V_0^2]\cos Z_R}{\{1-\tanh[0.175\sigma(1-\mu)V_0^2]\}H^*\sigma(1-\mu)}.$$

Table 1. The results of calculations of the cometary body parameters at the height of deceleration

	$S \neq const$						$S = const$			
	$Z_R = 45°$			$0°$			$45°$		$0°$	
	$\Lambda_R = 8 \times 10^{-3}$		10^{-2}	5×10^{-3}		10^{-3}				
H^*, km	20	25	20	20	25	20	20	25	20	25
H_*, km	–102	–121	–108	–110	–131	–111	–105	–125	–112	–134
V_*, km/s	35.2	35.2	35.1	35.3	35.3	35.5	36.4	36.4	36.4	36.4
dV_*/dt, km/s^2	27.7	22.1	41.5	35.9	28.7	32.1	23.4	18.7	33.1	26.5
m_*/m_0	0.31	0.31	0.23	0.48	0.48	0.86	1.0	1.0	1.0	1.0
E_*, erg(10^{27})	0.8	0.8	0.59	1.3	1.3	2.3	2.8	2.8	2.8	2.8
ΔE, erg(10^{27})	6.8	6.8	7.0	6.3	6.3	5.3	4.8	4.8	4.8	4.8

We determine the maximum deceleration height from the previous equation and from the equation of deceleration, written for H_*:

$$\begin{aligned}\rho(H_*) &= \frac{m_0^{1/3}}{2\Gamma A_0 H^*\{1-\tanh[0.175\sigma(1-\mu)V_0^2]\}}\\ &\times \frac{\delta^{2/3}\cos Z_R}{\exp\{0.5\sigma(1-\mu)V_0^2-\tanh[0.175\sigma(1-\mu)V_0^2]\}}.\end{aligned}$$

The results of calculations are presented in Table 1.

The fireball flight time before height H_* is 9–12 seconds. The aerodynamic load reaches 1.6×10^{11} dyne/cm^2 at the height of maximum deceleration exceeding the iron strength not only by tension but by compression as well. The loss of the body's kinetic energy by deceleration reached in that zone on the way of 200–300 m length is $\approx 10^{11}$ erg/g, exceeding the energy necessary for full evaporation of the body. The known stone, iron and comet bodies (Tungusskiy, Sikhote–Alin, Sterlitamak, Pribram, Innisfree, Lost City) exploded or were destroyed in the Earth's atmosphere when the aerodynamic resistance was 10^7–10^9 dyne/cm^2. By analogy with terrestrial phenomena, we believe that the cometary body in Jupiter's atmosphere will explode at the height no less than the height of maximum deceleration, i. e. not lower than the height ≈ -120 km. From power considerations, almost full evaporation of the remaining mass of the comet's fragment (the thermal explosion) in the region of the maximum deceleration may occur in the range of heights

$$\Delta H = m_* Q \cos Z_R / S_* \rho V_*^2 \approx 0.1 \text{ km},$$

which can be considered "the point of the explosion" (Here $Q = 8 \times 10^{10}$ erg/g is the average specific energy of the evaporation of the comet's material). Energy $E_* \approx 10^{27}$ erg will be released at that time (see Table 1) which will generate an originally spherical shock wave.

According to the theory (Grigorian, 1979; Hills and Goda, 1993; Svettsov, 1995), an ablating body behaves itself like an incompressible liquid. One may assume that fragmentation of the cometary body will begin when the aerodynamic pressure is $\approx 10^6$ dyne/cm^2, which corresponds to the height of $H_0 \approx 150$ km. From this point onward, the cross-section of the meteoroid will grow, and at the height of $H \leq H_0$ (with no account for evaporation) it will be equal to

$$S(H) = \pi \left[R_0 + \frac{H_0 - H}{\cos Z_R} \left(\frac{\delta}{\rho(H)} \right)^{1/2} \right]^2 ,$$

where R_0 is the initial radius of a body. The height of maximum deceleration (it equals the height of maximum energy release) is, in this case, by 50–100 km bigger as compared with data of Table 1.

On the basis of the theory of explosion in a heterogeneous atmosphere with exponential density distribution (Kompaneets, 1960; Zel'dovich and Rajzer, 1966), we determine main parameters of the shock wave coming out from the Jupiter atmosphere.

The spreading velocity of an explosive wave depends on its direction in a heterogeneous atmosphere: while moving down in the direction of the highest possible increase in density, the explosive wave accelerates and increases its energy to maximum values; while moving vertically upwards, in the direction of maximum density decrease, the explosive wave accelerates and, within a limited time, "breaks through" the atmosphere. The vertical upward explosive wave velocity can be written down as follows:

$$V_n = \left[\frac{(\gamma^2 - 1)\alpha}{2\pi} \right]^{1/2} \frac{E_*^{1/2}}{\rho_*^{1/2} r^{3/2}} \exp\left(\frac{r}{2H^*} \right) , \qquad (3)$$

where γ is the adibatic index; α, a constant, which, in our case, is equal to 1.25; $E_* = m_* V_*^2/2 \approx 10^{27}$ erg, explosion energy; r, distance from the explosion point.

It follows from Eq. (3) that for $r \to \infty$, the velocity V_n also tends to infinity. When $r = 3H^*$, the spreading velocity of the explosion wave has a minimum value. Table 2 shows values of V_n depending on the distance from the explosion site.

Table 2. The velocity of the explosion wave spreading in the vertical direction

r	V_n, km/s	r	V_n, km/s
H^*	0.41	15 H^*	7.8
2 H^*	0.24	20 H^*	61
3 H^*	0.21	21 H^*	94
4 H^*	0.23	22 H^*	140
6 H^*	0.4	24 H^*	340
10 H^*	1.2	25 H^*	530

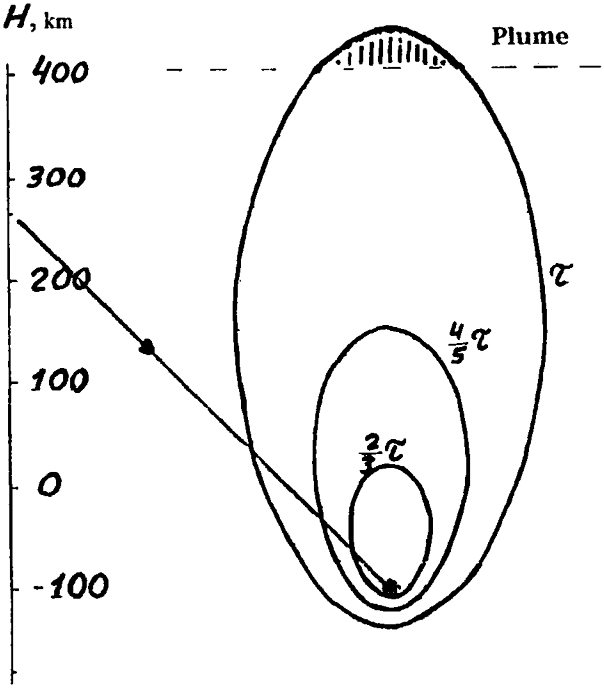

Figure 1 The section of the explosive wave surfaces in the vertical plane.

The time of explosive wave exit to infinity is limited,

$$\tau_\infty = \int_0^\infty \frac{dr}{V_n} = 6\pi \left[\frac{\rho_* H^{*5}}{(\gamma^2 - 1)\alpha E_*}\right]^{1/2}.$$

The adiabatic index being $\gamma = 1.2$, the time for the explosive wave to reach infinity equals $\tau \approx 10$ minutes; when $\gamma = 1.4$, $\tau \approx 7$ minutes.

It is the second phase – the phase of the Plume. In our case, the distance from the explosion point to upper layers of atmosphere, where the explosive wave was formed at entry of the body, is ≈ 500 km. The time for the explosive wave to cover this distance is virtually the same as for reaching infinity.

While leaving the surface of the Jupiter's atmosphere, the explosive wave will be approximately shaped as a rotation ellipsoid (see the Figure 1).

Based on the above, the estimated values are as follows: the total energy released is $\approx 2.5 \times 10^{26}$ erg; the area of the energy release surface is $\approx 5.6 \times 10^{14}$ cm^2; the time of basic energy release, $\approx$ 1s; the intensity of radiated energy in visible spectrum, $\approx 1.25 \times 10^{24}$ erg/s for the radiation intensity coefficient $\beta = 5 \times 10^{-3}$ (Opic, 1958); the effective stellar magnitude of the plume (for the total surface area), at the distance from the terrestrial observer, is $m_p \approx -1.5^m$ (when $\beta = 10^{-2}$, $m_p \approx -2.3^m$).

The obtained results are in complete agreement with the data of direct observations (Carlson *et al.*, 1995; Meadows *et al.*, 1995). If the thermal explosion occured on the maximum deceleration height, the velocity of the plume exit to the Jupiter's atmosphere surface, according to our calculation, may exceed 100 km/s. On the basis of the direct observations (Hammel, 1995), the velocity of the plume exit is smaller than ours ($\approx$ 10 km/s). It can mean that the explosion happened by several dozens of kilometers higher than the maximum deceleration height is.

The brightness increase of the nearest moons (Io or Europe) will reach the value of the order of 10^{-3} of the solar radiation, due to both the shock wave at the time of the fragment's entrance into the atmosphere (the first phase, fireball), and to the shock wave at the time of exit (the second phase, plume).

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